

Strategic Appraisal of Interdependent Infrastructure Provision

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Abstract

Infrastructure services are of fundamental importance to a country's economic and social well-being; however, decisions about such investments are complex, involving multiple actors, high levels of uncertainty and creating a multi-decadal lock-in to the choices made. Methodologies to assist with such decisions ('appraisal' methodologies) have developed to consider many of these complexities, yet they remain sector specific, ignoring interdependencies between infrastructure networks. Such methodologies thereby ignore the opportunities or vulnerabilities derived from these inter-relationships, simply assuming that cross-sectoral services will be provided, and ignoring the constraints created for future development. Furthermore, the siloed methodologies make calculation of the total system effects impossible, undermining strategic plans and obscuring any need (or ability to) prioritise across sectors. The work herein aimed to develop and demonstrate a strategic approach, capable of providing a more complete valuation of infrastructure investments by taking the interdependencies between the networks into account. In so doing, it examined the hypothesis that use of such a methodology could help deliver more robust outcomes.

The work is founded on development of a common, cross-sector appraisal methodology: fifteen common, monetised infrastructure performance metrics, developed by reviewing the strategic priorities of infrastructure and the existing sectoral cost benefit analyses. This was integrated with best practice from portfolio, pathway and real option approaches to create a longer term, system focused analysis of the decision space. Testing the framework through a case study (the Thames Hub Vision), chosen specifically for its high number of sectors, diversity of impacts and magnitude of its interdependencies, it examines the information gained by the increased methodological complexity.

The results demonstrate that current appraisal methods are indeed incomplete, with interdependencies creating additional value and the opportunity for increased robustness. Indeed, ignored system effects are found to be sufficient to reverse the result of the analysis and future effects enabled by the investments are found to be up to an order of magnitude greater than the direct impacts recorded by current appraisals. Furthermore, the response and sensitivity to uncertainty is shown to be affected by consideration of the system effects, both directly, through their application to multiple assets and indirectly, through interaction with the wider investment landscape. The proposed approach captures these values and relationships, allowing more informed decisions to be made. In addition, a decision support tool is developed providing the means to identify which opportunities stakeholders wish to maintain, how these can be created and which variables must be tracked to ensure the opportunities remain valid. The work therefore promotes a more active, strategic approach to infrastructure investment, allowing translation between national targets, regional stakeholder values and sector-specific technical requirements, to create a more holistic plan for a country's infrastructure networks.

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1 Infrastructure Decision Making: The Decision Context, Current Appraisal Practice and the Possible

1.1 Introduction

This chapter explains the context, problem domain and aim of this research. We start by outlining the complexity of all infrastructure investments, then consider how an existing system of infrastructure networks can further complicate these decisions in more mature economies, focusing on the UK case in particular. We consider the current methods used to support infrastructure decisions ('appraisal') and their shortcomings, before proposing a bounded body of research concentrated on incorporating interdependency and the value of flexibility into these methods. Finally we outline the structure of this thesis in presenting that body of research and summarise the key contributions of the work.

1.2 Infrastructure in a global setting: The importance and complexity of infrastructure decisions

1.2.1 The purpose of infrastructure and the need for investment

A country's energy, ICT¹, transport, water and waste networks are often referred to as its 'lifeline' (O'Rourke, 2007) or 'economic' (Marshall, 2013a) infrastructures. They form the foundation of welfare provision to a country's population, including sanitation, heat, light and access to social infrastructure such as healthcare and education. Furthermore they underpin a country's economic activities, providing communication and control, resources for industry and access to trade². More recently, infrastructure assets have been linked to country's wider

¹ Information and Communication Technologies.

² Infrastructure is described as the 'second pillar of competitiveness' by the World Economic Forum (Schwab, 2014).

economic health (Égert et al., 2009; Arslanalp et al., 2011; CBI and KPMG, 2011) . The five networks are therefore pivotal to the continued welfare of a country's population and its economy.

While the importance of access to high quality infrastructure is widely recognised, there are concerns that demand will exceed capacity, even in mature economies, such as that focused on in this thesis. This is due to many factors:

- Demand levels have increased due to growing populations and increasing standards of living;
- New environmental legislation has necessitated the closure or scaling back of some of the least cost solutions and older technologies;
- Infrastructure maintenance and repair have had a low political priority due to their 'invisibility' and high cost; and
- The recent economic climate has made the large investments necessitated by most infrastructure assets more challenging.

There is therefore a large shortfall in the forward plan for infrastructure, with \$57 trillion of global investment required from 2013 to 2030 (Dobbs et al., 2013). With commitments from many countries to strongly invest in both their existing infrastructure networks and a new generation of infrastructure assets, the next few years present a heretofore unseen opportunity to influence infrastructure planning practice.

1.2.2 Infrastructure investments as complex decisions

From Section 1.2.1 it is clear infrastructure decisions are important and urgent, but they are also multifaceted and made under high levels of uncertainty, presenting a complex decision problem. The services provided by the infrastructure networks are of fundamental importance to a country. Inappropriate or insufficient investment will reduce the population's welfare or the country's opportunity for economic growth. Yet the 'purpose' of infrastructure will vary between stakeholders, depending on whether they use it directly, live near it or invest in it. In addition, the lead time of the assets requires decisions to be made far in advance of knowledge of even the initial requirements (Dimitriou et al., 2013)³. The assets will then operate for decades, imposing decisions on future generations with potentially different values and whose environmental and economic climates are outside our ability to predict. Finally the high sunk costs, spatial footprints and resource requirements of infrastructure assets, make decisions difficult to reverse, creating lock-in to decisions despite any changes that occur. We can summarise these issues into three key factors:

- Multiple actors, with multiple valid perspectives;
- Planning in advance of knowledge of requirements and conditions; and
- Lock-in to a given technology and the resources, space and environmental costs required for its operation.

Taking each of these in turn, we can consider the necessary implications on the decision problem and any methodologies to be used for infrastructure decision making.

³ The OMEGA project found that the average time from political approval to construction for mega transport projects was 17 years.

In Section 1.2.1 we noted two inter-related functions of infrastructure: to provide a service to its users and to increase economic growth. We therefore have at least two perspectives on the purpose of infrastructure. Further interest groups must be added when we consider the design and operation of the infrastructure. Indeed work by de Neufville and Scholtes (2011) and Herder et al (2011) would suggest there were nine primary infrastructure actors, each with different priorities which may or may not align (see Table 1.1). Furthermore, the opinions of ‘secondary stakeholders’ such as environmental pressure groups, should also be considered (Rogers and Duffy, 2012) .

Table 1.1 – Actors of infrastructure investment decision making (adapted from de Neufville and Scholtes (2011) and Herder et al. (2011))

Actor	Priority
Political Decision Maker	Electoral promises; macro-economic and regional impacts
Controlling Authority	Ex ante economic evaluation is sufficiently positive; high access to services; appropriate minimum service levels
Financier	Adherence to budget; provision of revenues/dividends
Project Initiator	Project completion
Designer	Contractual requirements
Infrastructure Manager	Output delivery; operational cost
End Users	Personal cost of access to the infrastructure and quality provided
Tax Payer/General Public	Appropriateness of economic and social cost of the infrastructure
Local Residents	Externalities

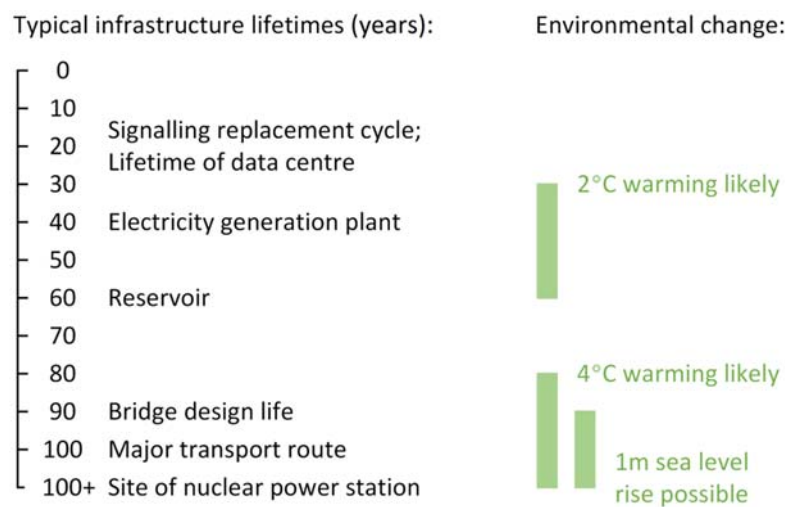
Where there are three or more opposing value systems, Arrow’s general possibility theorem tells us that we unlikely to be able to collate them into a single set of decision criteria (see Arrow (1950)). The possibility of making a group decision optimised against all priorities therefore becomes unlikely (French, 1986). In such situations, actors may choose to behave strategically rather than stating their true preferences, applying game theory mechanisms, negotiating and cooperating to ensure undesired events do not occur (Kørnørv and Thissen, 2000). In addition, many of the decision makers in Table 1.1 will be working on behalf of others, knowing that their decisions will be judged based on their future success. In such situations actors may make

decisions based on avoiding regret, choosing solutions which will be perceived more favourably rather than those with the greatest potential to succeed (Larrick, 1993).

All of the actors in Table 1.1 are either decision makers themselves or are able to influence the decisions made. Therefore while appraisal methodologies are often founded on the idea of a single decision maker, this will not be the case for infrastructure developments. Any decision making methodology proposed for such decisions must therefore be capable of capturing multiple perspectives and conveying the results in the context of different value systems. However, it must also encourage open discussion of the trade-offs created, with a focus on the strategic objectives of the developments rather than each actor's costs and benefits.

Our second attribute is that the investment decisions must be made years in advance. Decisions must be made about the future viability of a technology, about the resources it requires to operate and the externalities it induces. We must expect behaviour and legislative priorities to change over the decades in which the asset is likely to function and with them the values and priorities of our stakeholders. Furthermore, we can expect economic and environmental change over this time period (see Figure 1.1 for example). However, accurately predicting such change, the actions that will be taken under these conditions and their effects on our asset's operation is beyond our capabilities (Weaver et al., 2013; de Neufville and Scholtes, 2011) . We must therefore admit high levels of uncertainty, not only in the assumed demand profiles for our assets, but in the availability of resources, the operational requirements and in the values of our stakeholders. An infrastructure decision making methodology must therefore depict the high levels of uncertainty surrounding the results and help decision makers navigate this.

Figure 1.1 – Infrastructure lifetimes compared to environmental change (adapted from Defra (2011))



Our final attribute is the irreversibility of infrastructure investments. Infrastructure assets are expensive spatially and financially, producing a long-term footprint that creates a multifaceted lock-in to technologies, emission levels and land use (Weaver et al., 2013). The technological lock-in effects create a tendency for risk averse behaviour, with proven technologies appearing to be a lower risk and therefore being more likely to attract further investment. However, continued investment in a single technology can make transition to new innovations extremely difficult (Geels, 2012). Furthermore, reliance on a single technology and thereby a single set of resources will eventually undermine security of supply, particularly in a global marketplace, where all countries will be competing for these resources (Dawson et al., 2014). Similarly, lock-in to the outputs of a technology creates system vulnerabilities should they could become heavily regulated over the decadal lifetime of the asset. The greater the use of a single technology, the more difficult it will be to comply with these changing regulations. Finally the lock-in to land-use means that the location and opportunity value of the infrastructure site must be carefully considered. Once the asset is in operation it will start to affect land-use, through employees wishing to reside nearby and the delivery of resources and outputs to and from the site. As greater interconnections develop, the cost and risks involved in changing the land-use increase. When the asset needs replacing it is often too difficult to relocate and the new asset is

built on the site of the old asset. It is therefore important that the location be carefully considered along with its value (environmentally or for other land use) and its vulnerabilities (such as future resilience to flooding) as part of the investment decision. The methodology chosen to make such decisions must therefore convey the lock-in created by the investment.

1.2.3 The additional complexities of infrastructure investment in mature economies

The complexities discussed in Section 1.2.2 are common to all infrastructure investment decisions. However, for mature economies an additional level of complexity must be considered. This relates to the need to integrate new assets with an established (and often extensive) system of inter-related infrastructure networks that has developed over many decades, in particular their:

- Disparate governance and ownership;
- Legacy technologies and precedent levels of infrastructure provision; and
- Organic and uncoordinated interdependencies between and within the other infrastructure networks.

In mature economies, assets are likely to have been built in a piecemeal fashion over many decades, under differing governing conditions and priorities. The nine primary actors noted in the general infrastructure case are therefore likely to need further disaggregation. For example, while public funding, or funding through global development funds may be prevalent for less developed countries, the infrastructure in mature economies will have had decades to develop and change. The more secure economic environment of these countries may have allowed experimentation with various types of private investment and the opening up of these

investments to the global market place. In such cases, investors may have no interest in the welfare provision for the population, or have any technical knowledge of the asset. Indeed they may only see the asset as part of a portfolio investment interested simply in the risk and returns. Furthermore, government agencies and regulators may have been created under an entirely different set of Governmental priorities and asset technologies and developed separately in the different sectors. The diversity of actors between and within infrastructure sectors is therefore likely to be higher in mature economies.

The long history of infrastructure in these economies will also be visible through the range of technologies used. Given that infrastructure is expensive and long-lived, many of the technologies will be older or less efficient, or may be close to emission restrictions, yet these will constrain which future technologies can be used. Furthermore, over their operation, these assets will have created a precedent level of service, set when service demands were lower and restrictions on emissions were less severe. The expected level of service is therefore likely to be high compared to more emerging economies. In addition, any resilience to reduced service levels is likely to have been eroded over time as the infrastructure proved to be reliable. The reliance on high levels of service is therefore likely to be stronger in mature economies and may be founded on assets which are now reaching their design life or the limits of their usability given new restrictions.

The technological development and availability of infrastructure in mature economies will also affect the social and cultural norms of that country. For example, mature economies with the historically high levels of availability and reliability described above, may find it difficult to induce the behaviour changes required to move to more intermittent sources (such as wind power) and find their population wary of newer technologies, which are perceived as more dangerous (such as nuclear, see Slovic et al. (1980)), or environmentally damaging (such as fracking, see

Humphrey (2014)). Furthermore, the existing high levels of service may work against arguments for further investment, particularly where people have previously enjoyed the benefits of services while living remotely from externalities. Such preconceptions of danger or environmental damage are likely to affect public opinion of developments, causing resistance to proposals. In democracies, particularly where leaders are locally elected, this resistance is likely to strongly influence political campaigning and decision making, despite outcomes of appraisal analyses.

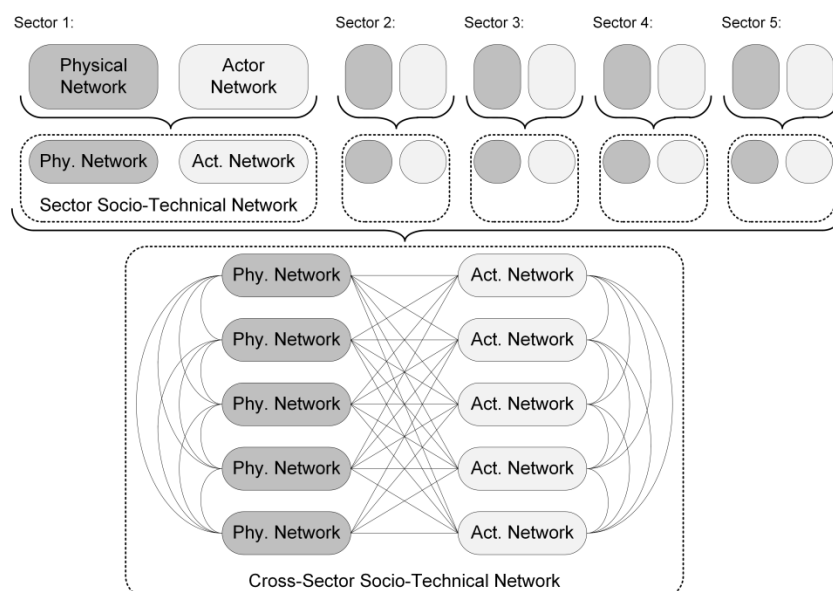
A significant proportion of each infrastructure's service requirement will be from the other infrastructure sectors, which over the development of the sectors and their proved service delivery will have become strongly interdependent both operationally (see Table 1.2) and spatially (O'Rourke, 2007). These interdependencies create a stronger lock-in to current land-uses and technologies than may be experienced in more emerging economies. They also create vulnerabilities, with the interdependencies leading to cascade failures throughout the other sectors and in different locations (see for example, Rinaldi (2004); Haimes et al. (2005); Apostolakis and Lemon (2005); Buldyrev et al. (2010)).

Complex in their own right, these additional actors, technologies and pressures interact to create a more complex infrastructure system of systems (see Figure 1.2). These interactions affect the performance of the infrastructure and therefore its perceived 'success'. Indeed, the meaning of 'success' is changing, taking consideration of an asset's performance over its full lifetime as part of this system of systems, rather than simple delivery to time and budget (Dimitriou et al., 2013) . It is therefore being recognised that if the infrastructure networks are to robustly meet the demands of stakeholders over the long-term, infrastructure decision making methods will need to consider these additional complexities.

Table 1.2 – A cause and effect mapping of functional infrastructure interdependencies (adapted from Rinaldi et al. (2001); Booth (2012); and Council for Science and Technology (2009))

Use of \ Use By	ICT	Energy	Transport	Waste	Water
ICT	Control and monitoring	Control, monitoring and demand management	Control, monitoring and public information system	Control and monitoring	Control and monitoring
Energy	Fuel	Fuel and maintenance (lubricants)	Fuel and maintenance (lubricants)	Fuel and maintenance (lubricants)	Fuel
Transport	Personnel (commuting) and maintenance (access)	Personnel (commuting), fuel (supply and distribution) and maintenance (access)	Personnel (commuting) and maintenance (access)	Personnel (commuting) and collection	Personnel (commuting) and maintenance (access)
Waste	Treatment of outputs	Fuel (energy from waste) and treatment of outputs	Treatment of outputs, resources for construction	Fuel (energy from waste)	Treatment of outputs and renewal of resource
Water	Protection (flooding) and cooling	Protection (flooding), cooling, production of fuels, and emission reduction	Protection (flooding) cleaning and safety (fire regulations)	Protection (flooding)	Protection (flooding)

Figure 1.2 – Infrastructure domains of complexity in infrastructures (adapted from Weijnen et al. (2008))



1.2.4 The UK case

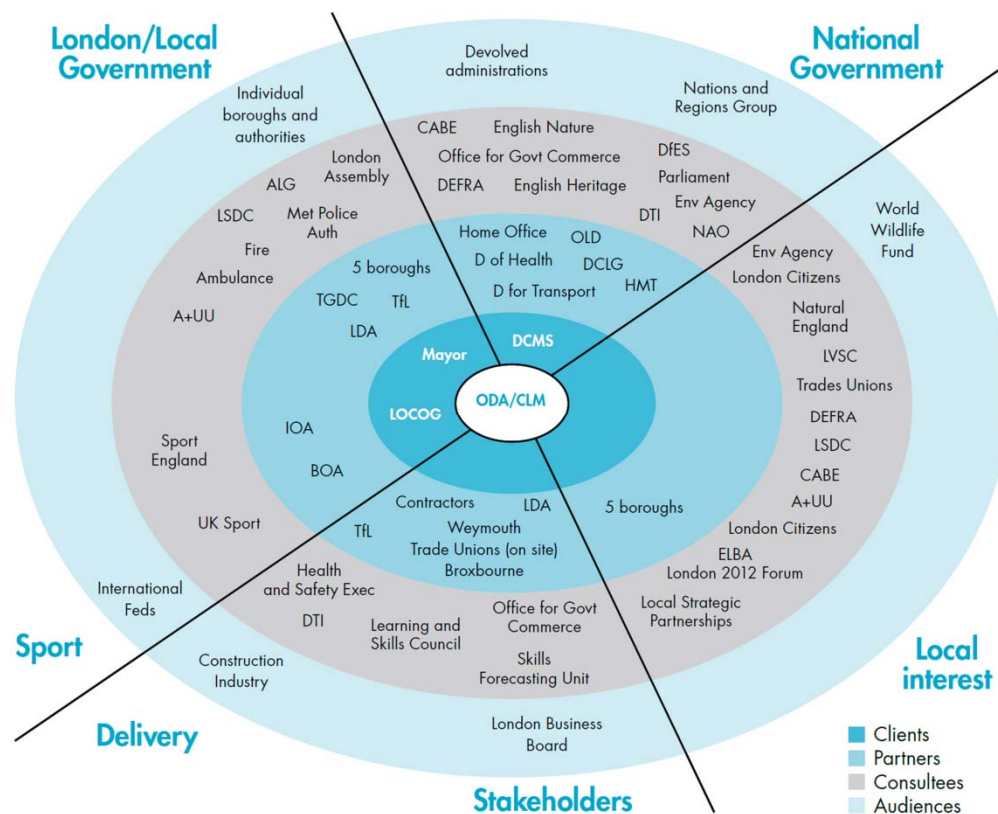
The UK presents a case of these mature economy complexities, with some of the most mature and interconnected infrastructure in the world (iBUILD, 2015a). The infrastructure system of systems is a complex mix of technologies, ages and states of repair, developed in segregated sectors over changing political and economic times. The long history of piecemeal investment has led to a “highly fragmented” ownership structure (Council for Science and Technology, 2009, p4), with different ownership types even within sector disciplines (see Table 1.3). However, following privatisation in the 1980s and 1990s approximately 60 per cent of the UK’s infrastructure is privately owned, almost double that of the next most privatised Country (Armitt, 2013). Furthermore, plans for future investment are focused on gaining additional private funding, with over 60 per cent aimed at private investors, and a further 23 per cent by public private partnership investment (Dobbs et al., 2013).

These privately owned and operated assets are overseen by Government regulators, with priorities to ensure innovation, competition/affordability, appropriate use of resources (financial and environmental) and minimum service provision. Their remits vary, being specific to geography (with different regulators for Northern Ireland and Scotland to England and Wales), sector (for example, Ofgem and Ofcom for electricity and ICT respectively), subsector (for example mode in transport, including the Office for Railway Regulation and the Civil Aviation Authority) and priority (for example, Ofwat, the Environment Agency and the Drinking Water Inspectorate regulate different aspects of the water sector in England and Wales). The stakeholder map for an infrastructure investment in the UK can therefore include a highly diverse set of priorities, pressures and areas of expertise (see Figure 1.3) and is likely to continue to do so into the future.

Table 1.3 – Infrastructure ownership in the UK (Infrastructure UK, 2010)

		Private Ownership	Private ownership (targeted support)	Regulated private ownership	Private ownership (regulated cashflow + government support)	Private ownership (public contracting for service delivery)	Public ownership (user charging)	Mutual ownership	Public Ownership
Energy	Electricity Generation		✓						
	Transmission and distribution networks			✓					
ICT	Cable and mobile phone networks	✓							
	BT Openreach			✓					
Transport	Roads								✓
	Network rail				✓				
	Some airports			✓					
	Ports and M6 toll	✓							
Waste	Local authority waste management					✓			
	Commercial waste operations by local authorities						✓		
	Commercial waste	✓							
Water	Water supply and sewerage in England			✓					
	Welsh water and British Waterways							✓	
	Scottish Water						✓		
	Flood management and Northern Ireland Water								✓

Figure 1.3 – Olympic Delivery Authority stakeholder map (Olympic Design Authority, 2011)



The UK's existing infrastructure networks are extensive with over 245,000 miles of roads, 500,000 miles of overhead and underground electricity cables and 186,000 miles of public sewers (Infrastructure UK, 2010). The railways are some of the busiest in Europe and the UK's hub airport (Heathrow) is the third busiest airport in the world (Airports Council International, 2014). These existing networks impact future development. For example in rail, future development is constrained by the mix of motive technologies used (restricting integration) and the available spatial envelope available between the rails, bridges and station platforms. Furthermore the increased accessibility provided by rail has, over many decades, attracted population growth in proximity to stations; therefore new rail connections to stations are limited by residential land-take.

Despite their age, the networks provide a high level of service (Schwab, 2014) and both the population and industry have become reliant on their reliability. Here, the older technologies

pose a risk having been developed when environmental requirements were less strict and resources more abundant. For example, the Climate Change Act (Great Britain, 2008) requires that greenhouse gas emissions in the UK be reduced by at least 80 per cent from 1990 levels by 2050. As the transport sector accounts for over 20 per cent of the UK's GHG emissions (DECC, 2011), decarbonisation could present an opportunity to meet these targets. Conversely, lock-in to current transport technologies could cause the UK to fail to meet its environmental obligations. Restrictions on new technologies, such as increased use of renewable energy technologies (EU, 2009), are also likely to impinge on service quality levels and reliability, reducing the sector's ability to provide the levels of service and capacity that the country's welfare system and industry have been built on.

Regulations in other sectors can also undermine strategic development. For example, approximately 20 per cent of the UK's electricity generating stations will close over the next decade (Infrastructure UK, 2011) due, in part, to European regulation on emissions from large combustion plants (EU, 2001). Without significant investment in further generation, this will limit the potential to decarbonise transport⁴ (hence meet the obligations of the Climate Change Act), but also to meet the increasing water quality standards, with the water sector already representing three per cent of the UK's energy demand (Rothausen and Conway, 2011).

Such interdependencies between the infrastructure networks have been highlighted by extreme weather events over the last decade. This has led to the importance of interdependencies being recognised at government level (Pitt, 2008; Council for Science and Technology, 2009; Infrastructure UK, 2010; Department for Environment Food and Rural Affairs, 2011; 2012a; Guthrie and Konaris, 2012). In turn, this has led to the creation of a number of initiatives to

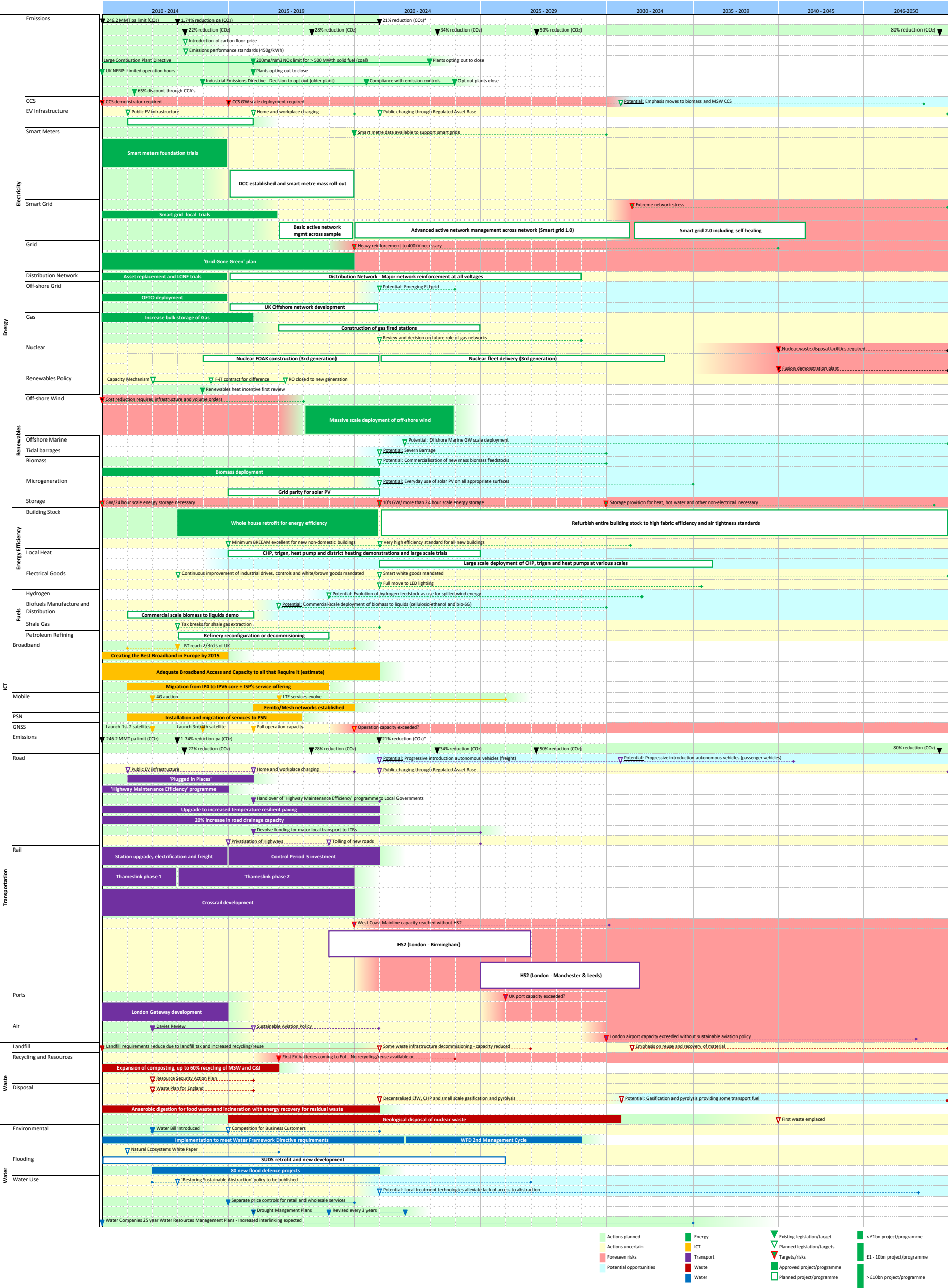
⁴ Estimated to increase demand by 29,000GWh/year by 2030 (Element Energy, 2010); transport already represents 34 per cent of UK energy consumption (Hall et al., 2012a).

investigate the effects of interdependence through the Engineering and Physical Sciences Research Council and the HM Treasury department 'Infrastructure UK'. In particular, these include:

- A study into the opportunities and risks of infrastructure interdependencies, which concluded that millions could be saved on one-off infrastructure projects through, for example, the sharing of infrastructure corridors (Frontier Economics, 2012);
- The investigation of the long-term national impacts of infrastructure interdependency, including a long-term systems assessment of capacity and demand requirements under different investment regimes and future projections (Tran et al., 2014) and a hot-spot analysis of infrastructure vulnerabilities (Hall et al., 2014);
- The creation of a cross-sectoral infrastructure investment pipeline (see Figure 1.4), to highlight gaps such as planning for disposal of electric vehicle battery components;
- Pilot studies for consideration of the interdependencies of infrastructure assets at their design stage through an 'Interdependency Planning and Management Framework', which concluded that there are a number of opportunities on existing projects such as the Lower Thames Crossing (University of Bristol, 2013); and
- The creation of cross-sectoral groups, such as the Infrastructure Operators Adaptation Forum, to encourage open discussion of opportunities and vulnerabilities between the sector specific agencies and regulators.

The outputs of these studies, suggest that infrastructure interdependencies can increase benefits and reduce costs if managed correctly, but can create system scale vulnerabilities if ignored. The UK's £466bn pipeline of infrastructure projects (Infrastructure UK, 2014) planned to meet increasing demand and replace aging infrastructure, therefore represents a substantial opportunity to secure additional benefits if planned with interdependency in mind.

Figure 1.4 – Planned UK infrastructure (adapted from Engineering the Future (2013))

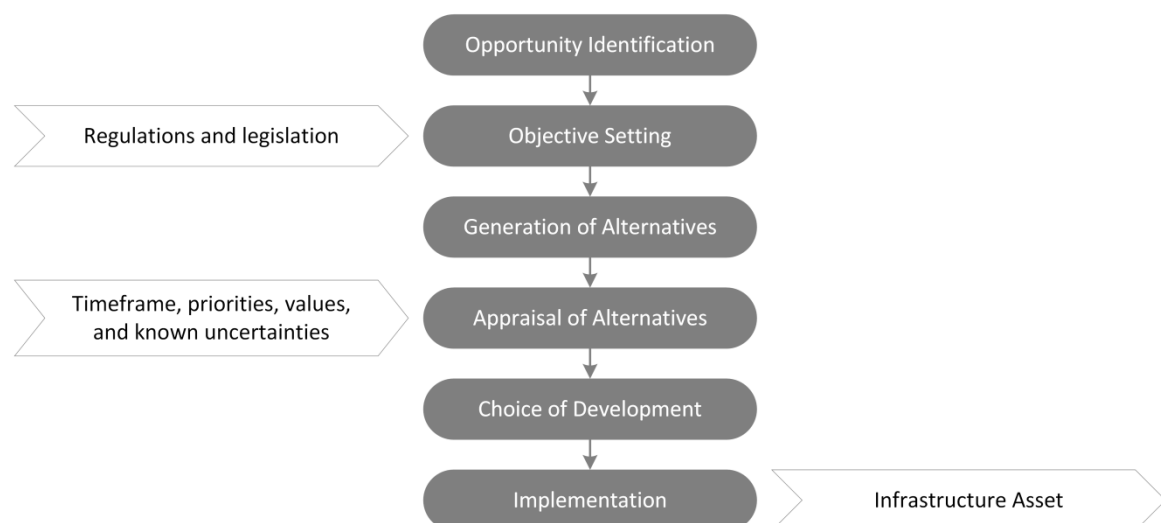


1.3 Infrastructure appraisal

1.3.1 The meaning and purpose of appraisal

As noted in the previous sections, infrastructure investment decisions are complex. Decision makers are therefore likely to require assistance in considering an investment's worth and/or comparing it against any alternatives available. An analysis used to assist in such decisions is an 'appraisal' of the investment(s). Townley defines appraisal as "the acquisition of information to aid a process of rational decision-making and resource allocation" (Townley, 1992, p186), where resources include funding, time, space and any other factor which limits our ability to build all alternatives available. The traditional engineering approach is to optimise designs against these resources (de Neufville et al., 2004) . In the language of decision analysis we 'maximise utility' for a given level of resource. An appraisal methodology is therefore traditionally a decision making tool that ranks investments based on their delivered utility, identifying that which gives the most value so that this can be implemented (see Figure 1.5 for a generalised framework)⁵.

Figure 1.5 – Generalised appraisal framework



⁵ The appraisal framework is sometimes considered a cycle (see, for example, Sayers et al. (2002)) with a review stage considering the results of the implemented asset and assessing these against the objectives of the investment. While there are significant benefits in a cyclic process, a formal review against project objectives is rarely undertaken for infrastructure investments (Dimitriou et al., 2013).

However, to 'optimise' or 'maximise' a decision output we must have either a single performance criterion, or a set of measures with relative utilities or weightings to allow trade-offs to be assessed. As discussed in Section 1.2.2, the presence of multiple legitimate but conflicting stakeholder viewpoints and values negates this possibility. With this in mind, most appraisal methodologies used by policy makers aim for 'procedural rationality' instead (Simon, 1976), standardising a methodology and applying it consistently for all potential investments. Without a single perspective on value, investment alternatives can no longer be ranked⁶. As such, most modern appraisal methodologies simply offer 'decision-support'⁷, highlighting the strengths and weaknesses of each investment over a number of performance criteria, encouraging a more universal understanding of the problem and enabling a more structured debate between stakeholders (French, 1986).

1.3.2 Appraisal methods used for UK infrastructure investment decisions

Infrastructure appraisal in the UK is guided by the 'Green Book' (HM Treasury, 2003) and the more recent supplementary guidance for infrastructure spend (HM Treasury, 2015). The Green Book is applicable for all appraisal and evaluation in central Government. It recommends use of Cost Benefit Analysis (CBA) and provides an outline of the stages required, a list of possible performance characteristics and a standard discount rate that should be applied. Performance characteristics and recommended valuation methods are routed in welfare economic approaches. The choice is made considering whether those who are made better off from the decision could theoretically compensate those who are made worse off⁸ and the distribution of

⁶ While ranking is not straightforward, it is possible for an investment to prove superior in all categories (Pareto optimal). However, given the numerous and conflicting priorities of stakeholders this is highly unlikely for infrastructure investments.

⁷ In comparison to decision making tools, which focus on results and optimisation, decision-support tools aim simply to provide greater transparency, counter subjectivity (OECD, 2011) and highlight the nature of trade-offs within the decision outputs (Faucheux et al., 1997).

⁸ The 'Kaldor Hicks criterion', note that whether the gainers compensate the losers in practice is not considered.

benefits. The supplementary guidance applies the Green Book recommendations to infrastructure. Previous editions simply outlined some of alternative investments that should be considered and additional values and risks that can be generated. In particular, recommending consideration of the more macro-economic impacts of infrastructure such as greater economic activity and economic growth through innovation. However, the 2015 edition has included some of the lessons learned on interdependence including the 'Interdependency Planning and Management Framework' noted in Section 1.2.4. Both the 'Green Book' and supplementary guidance recommend the application of additional analyses to consider the risk and opportunities associated with the investment. Furthermore, the supplementary guidance recommends consideration of interdependency and the risks of sharing resources and cascade failures; however, little guidance is given on practical application of the recommendations. Methodologies such as real options analysis are also mentioned, and while a very simplified example is given in the supplementary guidance for accounting for the effects of climate change (HM Treasury, 2009), little information is provided on application to real cases with higher levels of complexity. Indeed, neither set of guidance is prescriptive in how the recommendations should be applied and, with the exception of the discount rate, they do not specify values to be used.

The lack of a specified methodology allows appraisals to be tailored to the needs of the sector and relative complexity of the investment decision. Indeed, different methodologies have developed in each of the sectors and while each follows the Green Book guidance, each applies different timeframes, performance metrics and valuations. Table 1.4 outlines the similarities and differences between the water and transport sector methodologies as an example:

Table 1.4 – Comparison of water and transport sector appraisal methodologies

	Water Sector⁹ (Supply and Treatment)	Transport Sector
Timeframe	5 year Business Case and Asset Management Plan, 25 year Water Resource Management Plan	Maximum of a 60 year appraisal assessment, but limited to project's useful life
Focus	Least cost to attain minimum service levels (as set by the regulator)	Greatest benefit for available funding
Methodology	Mixture of CBA, quantified and qualified metrics presented in a sector specific appraisal summary table	Mixture of CBA, quantified and qualified metrics presented in a sector specific appraisal summary table
Monetised metrics	- Air quality - Carbon dioxide emissions - Fluvial change (operational) - Landscape and visual amenity - Recreation and navigation - Terrestrial biodiversity (operational) - Transport	- Accidents - Economic efficiency (providers and users) - Greenhouse gases - Interchange - Local air quality - Noise - Public health¹⁰
Other metrics (quantified, rated or qualified)	- Agriculture - Aquatic biodiversity - Community - Cultural heritage - Flooding - Fluvial change (construction) - Geodiversity (construction) - Land use efficiency - Local economy - Nuisance (noise, vibration, dust, odour etc) - Resource use - Risk perception - Social exclusion - Terrestrial biodiversity (construction) - Water quality - Water resources	- Biodiversity - Historic resources - Journey ambience - Landscape - Option values - Reliability - Security - Severance - Townscape - Water environment - Wider economic impacts
Consideration of cost bias	Through cross-company comparison by regulator	Application of reference class forecasting in accordance with Flyvbjerg and COWI (2004)
Residual value	Included	Excluded for all but rail projects
Spatiality/System effects	Scope limited to geographical remit of operator	Spatial modelling of effects on transport system 'desirable' at later stages of the assessment (once alternatives have been limited)
Uncertainty analysis	Monte Carlo analysis of supply and demand and scenario analysis of impacts of climate change	Sensitivity analysis of 'key' variables

⁹ Metrics based on Thames Water's 2010-2035 Water Resource Management Plan (Thames Water Utilities Ltd, 2009).

¹⁰ Active mode appraisal, for example for walking and cycling schemes.

In all sectors, appraisals tend to focus on a single project or asset, which is treated as a closed system (Dimitriou et al., 2013) against a sector specific, often static, development context. Developments and future demands from the other sectors are ignored.

1.3.3 Strengths and limitations of current appraisal methods

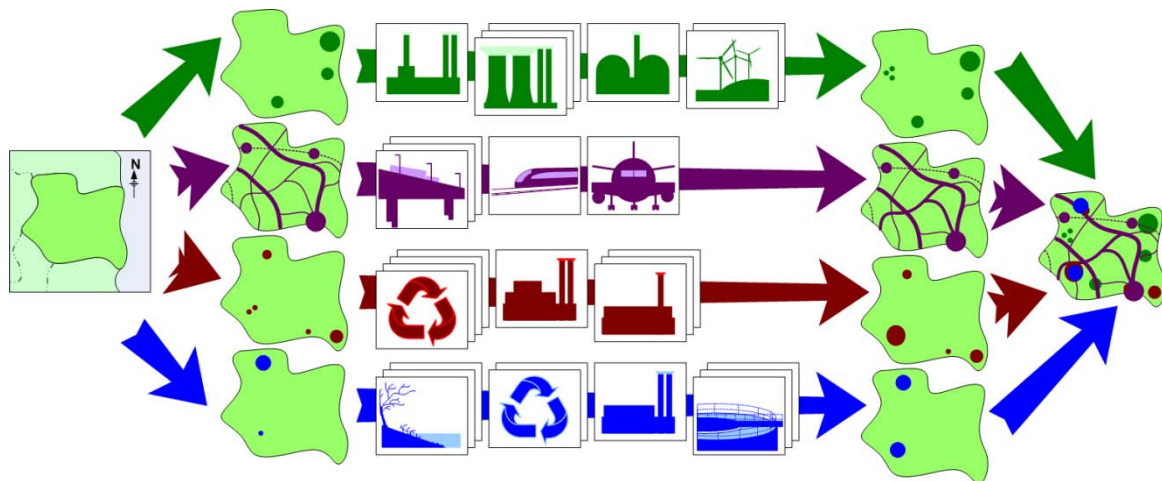
The methodologies provide procedural rationality for the investment decisions and focus on the timeframes, stakeholders and performance metrics relevant to the sector. Indeed the 'WebTAG' methodology used by the UK Department for Transport is one of the world's most comprehensive transport appraisal analyses (Sumner, 2011) forming the basis of the World Bank's Transport Appraisal Toolkit and considering wider economic impacts such as agglomeration. The sector specific methodologies therefore present a number of benefits:

- The methodologies have, in some cases, been used for decades providing a historic record that can be mined for consideration of uncertainty;
- By limiting the scope to a single sector, the counterfactual case ('do nothing'/'do minimum') is more obvious and the investments are more comparable;
- The concentration on sector specific performance metrics makes the analysis more straightforward and limits the number of stakeholders; and
- The resulting analysis is bounded, limiting the required skill set and experience of analyst and making the results easier to communicate.

However, the diversity in methodologies makes them incomparable across sectors. This has led to suspicions of underfunding in some sectors (Mackie, 2010) and means that appraisals cannot be combined to review the developments on a system scale. In particular, the performance metrics chosen tend to focus on sector specific outputs, presenting a siloed perspective of the

appraisal and ignoring wider effects. Indeed, even within a single sector, the stresses caused by planned projects on other parts of the network are not always considered. For example, the design for 'Crossrail', a rail service which is currently being built and will serve Heathrow airport, has been developed without consideration of expansion at Heathrow, despite such plans having been discussed for decades (Transport for London, 2014). Furthermore, the current plans for an expanded Heathrow note the need for provision of additional road capacity, assuming this will be provided, but with no allowance for additional costs (Airports Commission, 2013). Within and between sectors, appraisals are conducted in parallel without consideration, or in some cases knowledge, of the plans elsewhere (see Figure 1.6).

Figure 1.6 – Parallel sector specific appraisal



The use of disparate methodologies therefore conceals any system resource constraints created by parallel or future developments.¹¹ This eliminates the opportunity to strategically plan the use of such resources, instead relying on a first-come, first-served process until the resource becomes sufficiently scarce. Furthermore, interactions between the sectors are ignored (Squire, 1975). Without engagement between the sectors, assumed demand levels on an asset and by that asset on other sectors, are not validated, undermining the success of the investment. In

¹¹ For example the spatial conflict between the proposed waste and water developments in Figure 1.6 would only be realised when applying for planning permission, or once one investment was being implemented.

addition, the possibilities for cross-sector integration are ignored, restricting achievable benefits and those recognised. For example, benefits achieved through industrial symbiosis are only possible if integration is considered in the design stage, and more macro-scale economic benefits are only likely to develop where systems and policies are complementary (Bannister & Berechman, 2003).

Finally, despite high level awareness of the uncertainties associated with infrastructure appraisal and recommendations for the use of methods such as real options analysis in the Green book, current methodologies minimise consideration of uncertainties (Salling and Banister, 2010) .

Where uncertainties are considered they focus on negative impacts, aiming to ‘avoid’ or ‘mitigate’ this risk, with little formal consideration of potential benefits (Ford et al., 2002) .

While we noted in Section 1.2.2 that infrastructure investments create lock-in effects that can exceed their lifetimes, current appraisals often limit timeframes to twenty or thirty years, which can be significantly shorter than the life of the investment (OECD, 2011). This limits the uncertainty of projections, but inhibits our ability to consider the system effects of the investment, ignoring the relationship between current and future developments, including the effects of delay or speedier provisioning, or how one infrastructure development can invalidate or enable future investments. Given the deep uncertainty of the conditions the future infrastructures will be operating under, developments which offer flexibility could offer value, yet this cannot necessarily be captured under the short timeframes of the current methodologies.

We can conclude that the current methodologies constrain the opportunity to create cross-sector benefits, ignore possible system effects and constraints and do not convey the full uncertainty of investments. They thereby obscure much of the value that could be created by such investments as well as the risks and vulnerabilities associated with long-term interactions

between the networks. It is perhaps not surprising, therefore, that there have been calls for infrastructure developments to be considered as a system of systems (Beuthe, 2002; Raven and Verbong, 2009; Frischmann, 2012) and, more recently, for appraisal methods to be developed to more closely reflect this additional complexity (iBUILD, 2015a; International Symposium for Next Generation Infrastructure, 2013; Dimitriou et al., 2013; Booth, 2012).

1.3.4 Improving the practice of appraisal for UK infrastructure: Current best practice

Previous reviews of infrastructure appraisals have tended to concentrate on a single sector, often focusing on a single metric or problem and a single country. The physical connection of the transport networks across country boundaries has created an exception, with a number of research projects specifically aiming to understand international best practice across all performance criteria (see OECD (2011); HEATCO (2006); and Marcial Echenique and Partners Ltd (2001)). However, while the studies extend to recommendations for valuing wider economic impacts, indirect benefits and equity¹², their remit remains strongly within the transport sector, ignoring cross-sector effects. The sector specific lessons can, however, be translated to other sectors providing incremental improvements to the methodologies. Flyvbjerg et al.'s research into the inaccuracy of appraisal estimations, for example, originally concentrated on transport sector megaprojects (Flyvbjerg et al., 2002; 2003). However, the work later translated these inaccuracies for use in all transport sector appraisals (Flyvbjerg and COWI, 2004) and further for all public sector appraisals (HM Treasury, 2013). However, as can be seen in the Flyvbjerg case, the improvements tend to be adapted for the different sectors, maintaining the differences in methodologies and reinforcing their sector specific perspectives.

¹² We will return to such spatial considerations in Chapter 8.

The OMEGA project (see Dimitriou et al. (2013)) provides an exception to these sector specific and sector reinforcing reviews. While the study was originally focused on improving the planning, appraisal and delivery of mega transport projects¹³ in developed economies, the research concluded that the practice of appraising projects as ‘closed systems’ separate from the wider and more complex context of the infrastructure systems was fundamentally inaccurate. It suggested that such siloed practices were likely to cause impacts to be underestimated, significant opportunities to be lost and downside risk¹⁴ to be increased. Furthermore, that those projects which considered wider ‘agent of change’ objectives¹⁵ were more likely to garner higher levels of public sector support and funding from other sectors. The study also recommended that appraisal processes:

- Be transparent and capture the financial, institutional, personnel and legal resources required for the development;
- Recognise the long-term nature of infrastructure and therefore that effects may not manifest for many years;
- Acknowledge the uncertainty of projections and outputs, adopting flexible, adaptive strategies;
- Present results transparently against different timelines and within a multi-criteria framework to assist the understanding of trade-offs between priorities and stakeholders; and
- Analyse the critical variables and interdependencies surrounding the decisions and allow for review as these environmental, political and technological contexts change.

¹³ Projects with capital costs in excess of \$1bn or which were likely to attract high levels of public or political interest due to their environmental, social or financial impacts.

¹⁴ Particularly relating to stakeholder objection.

¹⁵ Objectives relating to strategic, societal or welfare benefits.

1.3.5 Improving the practice of appraisal for UK infrastructure: Decision making under uncertainty

Outside infrastructure appraisal, consideration of similar long-term decisions with vast unknowns have become the focus of a large body of literature termed ‘decisions under deep uncertainty’¹⁶ and led to significant methodological advances. Such decisions are defined by Hallegatte et al. (2012) as containing one or more of the following three elements:

- Multiple valid but divergent perspectives regarding value or success;
- ‘Knightian uncertainty’ i.e. uncertainty that cannot be reliably quantified; and
- Decisions which are complexly inter-related and can change over time.

Best practice suggests that decisions made under deep uncertainty be “reversible, corrigible, and flexible” (Collingridge, 1981, p12). However, as we have noted in Section 1.2.2, infrastructure assets have high sunk costs and create lock in; the ability to reverse or correct such decisions is limited¹⁷. To be relevant to infrastructure appraisal we therefore concentrate on the third recommendation of flexibility and the methods that have been developed to capture this aspect of future decisions.

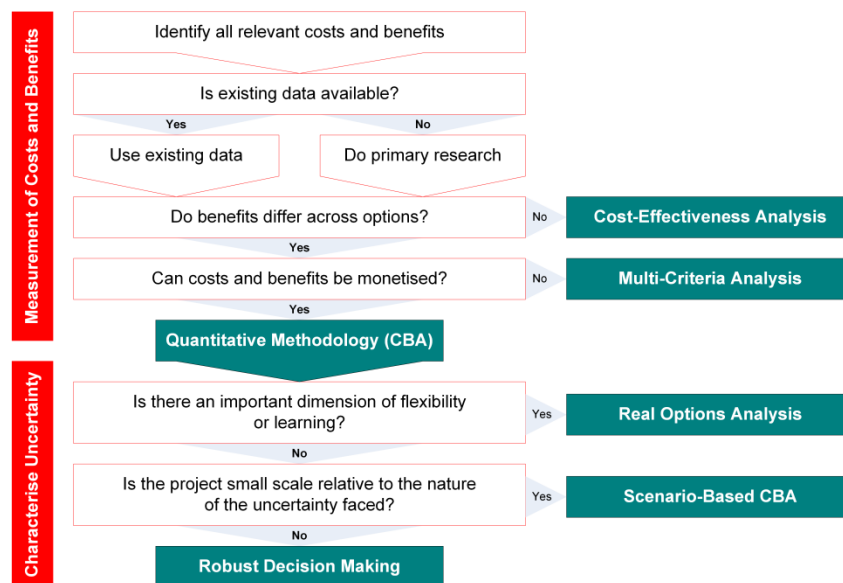
Advances in decision making under deep uncertainty have perhaps been most rapid in the field of adaptation to climate change. Here the brittle nature of optimised decisions has been realised and the need to instead consider robustness and flexibility widely recognised (World Bank Climate Change Group, 2014). To meet this demand, the field has generated a number of methods to consider the vulnerability or robustness of decisions over the long-term (see Figure

¹⁶ Phrase first used by Kenneth Arrow, but also referred to as decisions under severe, radical, or fundamental uncertainty, or decisions under ignorance (Wise et al., 2014).

¹⁷ A number of authors have explored opportunities to build less expensive, smaller, distributed infrastructure assets to reduce the cost of future changes (see, for example, Ansar (2010)).

1.7, developed for the UK Department for Environment, Food and Rural Affairs, for examples). We consider these methods further in Chapter 2. The methods are more computationally complex than traditional appraisal approaches, but their value has been formally recognised by governments with, the Intergovernmental Panel on Climate Change (IPCC) for example, stating that their aim “is not to find the best policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information” (IPCC, 1995, p5).

Figure 1.7 – Decision making methodology mapping for increasing uncertainty (Frontier Economics, 2013)



Two groups of analyses in Figure 1.7 offer the opportunity to quantitatively analyse the flexibility of development alternatives to ‘succeed’ in an uncertain future: Real Options Analysis (ROA) and Robust Decision Frameworks¹⁸ (RDF). ROA considers developments as decisions over time and allows for the inclusion of path dependency. ‘Real options’ are future investments that may be exercised if provision is made in the original design (at a given cost). An example would be buying additional land surrounding an infrastructure asset to allow expansion at a future date. By considering whether the options would be exercised under different futures, the benefit of the future flexibility provided can be compared to the additional provisioning cost. The use of

¹⁸ Weaver (2013) includes Robust Decision Making, Decision Scaling, Assess Risk of Policy, Info-gap and Context-First methods within this category. Herein we also include Computer Aided Reasoning.

real options for infrastructure investments has been explored, but only from sector specific perspectives (for example, Smit, 2003; de Neufville et al., 2006; Guo and Jiang, 2010; Suttinon and Nasu, 2010; Fernandes et al., 2011; Ashuri et al., 2011) . Furthermore, in most cases, only a single option is considered and a single uncertainty explored. However, such studies have reported benefits including increased value (particularly expected revenue), an improved risk profile and, in some cases a lower upfront cost (de Neufville and Scholtes, 2011). RDF, by contrast, tend to only consider complete development alternatives, but do so against an array of possible futures or against the field of uncertainty. While most applications remain in the field of climate change, examples can be found in the academic literature for infrastructure investments. The ITRC, for example, has created an interdependent set of infrastructure system models and is working to apply an adapted Computer Aided Reasoning approach¹⁹ to national infrastructure investments in the UK (Hall et al., 2012a; Tran et al., 2014). However, the complexity and computational expense of this group of methodologies has limited their use by industry.

To create an appraisal capable of considering many different combinations of investments, that can be reviewed and revised over time by the stakeholders themselves, a more simplistic approach is required. With such aims in mind and taking inspiration from ROA and RDF, the use of portfolio and pathway appraisal methods have been explored for complex climate change policy decisions. In the US, for example, portfolio appraisals have captured the wide range of investment options available and how these can be combined, (Coastal Protection and Restoration Authority of Louisiana, 2012) and considered uncertainty and vulnerability through thousands of plausible futures (Groves et al., 2013). Whereas, in the UK pathways appraisal has been used to consider the value of long-term flexibility (Reeder and Ranger, 2011) . The uses remain sector specific, concentrated in the adaptation of water sector resources for climate

¹⁹ See Lempert (2002).

change, but all three recognise some influence on wider infrastructure and, in the case of the Colorado study, the need to consider system effects between the investments. Furthermore, their inclusion of resource constraints and mutually exclusive events suggests that extension to the more advanced multi-criteria pathway analyses conducted academically (see, for example, Hasnoot et al (2012; 2013) and Kwakkel et al (2014)) may soon be realised for real-life policy making.

The extension of such portfolio and pathway methods to infrastructure appraisal, however, is not straightforward. The case studies above rely on having a clear priority to the investment, either to limit the decision space directly or to determine trigger points at which actions are no longer valid. No such single priority will exist for infrastructure investments and therefore a decision-support methodology must also help the user navigate and reduce the decision space.

Drawing on the limitations of current appraisal methods discussed in Section 1.3.3, the recommendations of the OMEGA project and the advances made in decisions under deep uncertainty, we can draw out five recommendations for more completely assessing infrastructure investments and providing a more strategic appraisal methodology:

- Provide a standardised assessment such that investments can be prioritised across sectors;
- Consider developments as cross-sector portfolios such that demand levels are captured and resource constraints are highlighted;
- Consider pathways of developments, the emergent system effects produced and the lock-in/opportunity provided by investments on those to come;
- Ensure that results convey the deep uncertainty of the decision and where robustness can be improved; and

- Present the results, such that the decision space can be navigated despite the absence of an overarching priority.

1.4 Research objectives

1.4.1 Hypothesis and aims of this research

This research will focus on the call for appraisal methods to be developed to more closely reflect the systems complexity of infrastructure. We have reviewed the aspects of this system complexity in this chapter and can characterise the interdependent infrastructure decision problem, as requiring consideration of:

- Valuation against a background of divergent priorities, and impacts which are large, long-term and can be non-marketable, non-marginal and at multiple scales;
- The resource requirements of developments from a whole system perspective;
- Prioritisation across sectors with different functions for the economy;
- The system effects of an investment, including its demand on other sectors, its ability to contribute to emergent effects and its constraint or enablement of future investments; and
- The robustness of investments over the long-term under conditions of deep uncertainty.

In particular, this research will investigate Rinaldi's (2004, p1) supposition that omitting system interdependencies will "at best limit the validity of analyses and at worse lead to bad or inappropriate policies". Applying this to appraisal, we test the hypothesis:

There is more scope for achieving robust outcomes in the long-term, if the interdependencies between infrastructure networks are taken into account; in contrast to the situation that exists at present where each network is addressed largely in isolation.

The aim will therefore be:

To develop and demonstrate a practical decision making methodology for multi-sector infrastructure investment, which is robust to future uncertainties and takes account of the system's interdependency.

Capturing the five recommendations derived from the OMEGA project and recent advances to decision making under deep uncertainty (see Section 1.3.4), the objectives of the research will be to:

- Develop a common appraisal framework that delivers a more complete valuation of infrastructure developments, capturing the multiple stakeholder perspectives and resources required, but also the cross-sector and systems effects created by the system as a whole; and
- Develop a policy level multi-sector decision-support tool focused on ensuring solutions are robust to future change by considering how future infrastructure investments are enabled and constrained by the decisions made, the potential total value of the system and the uncertainty of the results.

The hypothesis will be investigated by applying the developed framework and decision-support tool to a regional case study in five incremental stages of complexity:

- Assessment against a single attribute vs multi-attribute valuation;
- Investment in individual projects vs investment in groups of projects (portfolios);
- A specified single project/portfolio vs consideration of pathway flexibility;
- Single future projection vs valuation under an uncertain future (sensitivity analysis);
- Isolated predictions of change vs path dependency and feedback (incorporation of the interdependency between the development and the investment landscape).

Relevant to all complex, long-term, decisions under deep uncertainty, these increments will allow the benefit derived by the additional effort and the change in perspective provided by each level of analysis to be assessed.

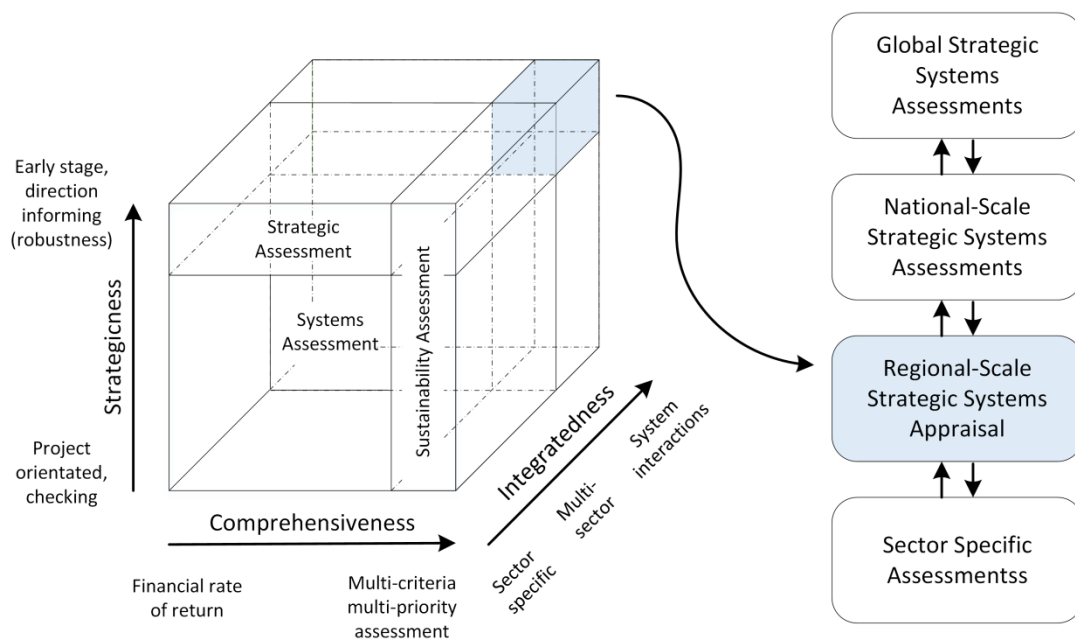
1.4.2 Scope of the research

The work will focus on use by UK policy makers, taking a strategic, regional perspective. The output, as shown in Figure 1.8 will be a multi-criteria, multi-priority appraisal from a systems perspective, presenting the opportunity to consider the robustness of investments as part of an integrated system. The aim is not, however, to replace either the shorter-term, more detailed sector specific assessments or higher level national/international strategies. Rather it forms a missing link, providing a more integrated assessment of resource constraints, potential systems effects, opportunities and risks to inform the high level strategies and a way to translate national strategy for regions and infrastructure sectors. In Figure 1.8 we show this assessment hierarchy, including a higher global/international strategy. This may have different priorities to that of the UK and is therefore only partially connected to the national assessments²⁰. Depending on interconnectivity with Europe and worldwide efforts on problems such as climate change, this

²⁰ For example, it may be economically or operationally beneficial for Europe to jointly promote one hub airport; however, if this is outside of the UK, it may not be economically beneficial for the UK.

relationship may be strengthened (or weakened) in the future. The framework and embedded appraisals must therefore be considered as context specific, with performance metrics representing a snapshot of the priorities at a given time. While the work holds a given level of robustness, focusing on those metrics which are thought to be long-term and strategic, these will need to be revised as contexts change.

Figure 1.8 – Scope of strategic regional appraisal and place within wider assessment hierarchy (adapted from Morrissey et al. (2012))



The methodology will initially assume a normative or ‘ideal’ approach to decision making²¹, with a single decision maker (assumed to be a Government agency akin to the National Infrastructure Commission). This will allow a single set of values to be developed, a necessary foundation to a system-wide appraisal. However, as we have noted herein, infrastructure decisions are made in a multi-actor context, with each actor holding individual perspectives on value. The resulting tool will therefore need to acknowledge uncertainty in valuation and highlight the trade-offs being made, aiming to enable and support an informed multi-stakeholder debate on the developments.

²¹ As opposed to a network model (see Kørnøv and Thissen, 2000).

To ensure the methodology can be updated and reviewed by sector stakeholders as contexts and priorities change, it will build on the 'bottom-up' welfare economics approaches currently undertaken. Therefore, while the regional case study presented may have macro-economic implications, the indirect and spatial effects of the development will not be included within the appraisal valuation. The potential effect on the uncertainty of the results will, however, be considered in increment five: the feedbacks between infrastructure development and the investment landscape. As the macro-economic effects of infrastructure are of increasing importance to policy makers, their integration into the proposed appraisal framework is left as an important extension to the work and is recognised as a limitation in the valuation.

Furthermore, the timeframe of this research only presents the opportunity to explore one complex case study. An important extension to the work herein is therefore to test the methodology on additional cases. In particular, the examination of smaller, less exceptional cases would test whether conclusions drawn regarding the additional value and understanding provided by the methodology applied more widely.

Finally, it has been recognised in this chapter that the uncertainty surrounding infrastructure appraisal is deep and multi-faceted, relating to technologies, environmental change, economies, social priorities and legislation. While consideration of the uncertainty of infrastructure appraisals is therefore central to the research, it will not be possible to pursue all avenues of uncertainty analysis. Given our focus on systems interactions, we will concentrate on the holistic sensitivity of key variables and the uncertainties surrounding feedbacks between the investments, the investment landscape and valuation. Drawing on methods such as Adaptation Pathways and Dynamic Adaptive Policy Pathways, a useful extension to the work would therefore be to consider the vulnerability of the pathways to ensembles of possible futures. In particular this could help derive legislative or sector specific tipping points that would enable dynamic decision making to be included within the methodology.

1.4.3 Content of thesis

The remainder of this thesis is structured to provide a walk-through of the development of the methodology; building a theoretical framework, determining a suitable case study and demonstrating the common sector specific, portfolio and pathways appraisals methodologies proposed. We then assess the uncertainty of the appraisal through a sensitivity analysis of key variables and review the feedbacks between the investments and land-use, before returning to our hypothesis to consider the information gained by a systems perspective. A more detailed outline of the chapters of this thesis is given in Table 1.5.

Table 1.5 – Outline of thesis chapters

Chapter	Title and Outline
2	<i>Current Practice for Infrastructure Appraisal and Deep Uncertainty Decision-Support</i> We review the strengths and weakness of current appraisal methods and through consideration of other decision making under deep uncertainty methods, identifying those most able to capture the complexity of infrastructure interdependencies. Centring on real options ‘in’ projects (Wang and de Neufville, 2005) and pathways appraisal, we explore the current use of such methods for infrastructure appraisal and consider the extensions necessary for the multi-sector, multi-criteria context. Finally, we propose an appraisal methodology capable of capturing both the interdependency and uncertainty of long-term infrastructure decisions.
3	<i>Developing a Framework and Methodology for Strategic Infrastructure Appraisal</i> Building on the methodological approach proposed in Chapter 2, we outline a new infrastructure appraisal framework capable of capturing the system perspective. Key cross-sector performance metrics are identified from a review of governmental, academic and industrial literature and brought together into a set of four attributes. Finally the multi-pathways methodology is formally defined.
4	<i>Case Study Choice: Cross-Sector Infrastructure Investment in a Mature Economy</i> Focusing on proposals, projects and programmes applicable to the UK, with complex interdependencies between multiple infrastructure sectors, we derive a suitable case study to test the framework developed in Chapter 3. We determine a single deviant case (see Flyvbjerg (2006)) will provide the most complete test of the methodology and select the Thames Hub Vision, a £50 billion infrastructure hub in South East England (Foster+Partners et al., 2011a). Exploring the case study, we consider parallel developments that will form the ‘do minimum’ development pathway.
5	<i>A Multi-Attribute Cost Benefit Approach to Valuing Infrastructure Impacts</i> Applying the appraisal framework we consider the methods available for quantification and valuation of the fifteen metrics and the uncertainties introduced by their use. We demonstrate the methodology, using the Thames Hub vision case study, determining the uncertainty of the measures used and their ability to completely and consistently value the impacts of individual infrastructure developments in different sectors.

Chapter	Title and Outline
6	<i>Cross-Sector and Systems Appraisal Through Pathway Analysis</i> Demonstrating the second stage of the cross-sector appraisal methodology, we identify three impacts undervalued by the standalone asset analysis (total resources, emergent system effects and the ‘opportunity’ value of an asset in its ability to enable future development). We investigate these impacts for the case study through a portfolio analysis before bringing these into the pathway analysis outlined in Chapter 3. Finally, we collate outputs into min-max opportunity ranges for infrastructure pathway families to create a decision-support tool for policy makers.
7	<i>Assessing System Uncertainty: A Sensitivity Analysis of Key Variables</i> We review the outputs of the pathway analysis through a sensitivity analysis of key variables. As one of the most controversial factors of CBA and a variable that affects all attribute valuations, we first consider the discount rate applied to the valuation. We apply both lower (Stern, 2006a) and higher (Weitzman, 2007) rates and consider the changes in value. Secondly we determine population to be a key variable, affecting estimations of both the demand for infrastructure and valuation of its impacts. We therefore review the effects of population uncertainties on our pathway analysis results and apply high and low projections to the case study to test the results.
8	<i>Assessing System Feedbacks: An Analysis of the Spatial Interdependency of Infrastructure Developments</i> As a final test of the uncertainty of the outputs we consider the interdependencies between infrastructure and the investment landscape through a Land Use Transport Interaction (LUTI) model. We investigate one such feedback, testing how the employment impacts of infrastructure can affect local population growth. We integrate our findings with the pathways analysis to understand how these changes affect both the inherent value of the assets and the opportunity provided through their pathways.
9	<i>Conclusions and Implications: The Information Gain of Appraising Infrastructure as a Systems of Systems</i> Returning to our hypothesis, aims and objectives we consider the outputs of our analysis. We review our five increments of complexity and consider the variation in results and the additional information provided at each stage. Finally, we reflect on the limitations of the work, implications for UK policy and investment, and the future work necessary.

1.4.4 Contributions of the thesis

The work herein builds upon the field of decision making under deep uncertainty. We extend the multi-stakeholder, multi-impact analyses developed for assessment of adaptation to climate change to the realm of interdependent infrastructure networks, creating a framework capable of more fully valuing the system impacts of developments over the long-term. Furthermore we explore the value of increasing the complexity of the analysis and the variation in outputs produced.

Additional contributions to the literature include²²:

- A set of standardised performance criteria for infrastructure investment, allowing consistent appraisal of infrastructure and thereby strategic prioritisation of investments across sectors;
- A pathways appraisal framework capable of more fully valuing infrastructure through the capturing system resource constraints, cross-sector demands and emergent system effects; and
- A decision-support tool that conveys the deep uncertainty of future investments and promotes robust decision making through the visualisation of infrastructure value as a sum of the inherent value, the systems value and the opportunity value provided for future developments. Furthermore, that promotes decision making based on flexibility (the opportunities we wish to leave open for the future), while identifying which factors need to be monitored, and which stakeholders engaged, to ensure benefits are realised.

The research herein has been presented at conferences and is published in the Proceedings of the International Symposium of Next Generation Infrastructure (Young and Hall, 2014) and the Journal of infrastructure Complexity (Young and Hall, 2015).

²² The contributions of the work are fully discussed in Chapter 9.

2 Current Practice for Infrastructure Appraisal and Deep Uncertainty Decision-Support

2.1 Introduction

In Chapter 1 we outlined the complexity of infrastructure decisions, focusing on UK case.

Infrastructure decisions were shown to be complex decisions made under deep uncertainty (Hallegatte et al., 2012). This complexity was due to a number of factors. Infrastructure investments have multiple stakeholders with differing perspectives on its purpose and value. Many of whom must make decisions on behalf of others, representing the opinions and values of their constituents, shareholders, or users. Long lead times mean that decision must be made far in advance of knowledge of their operational conditions, and their long operational lives mean that effects are felt for decades, locking in technologies and land-use beyond this lifespan. Furthermore, their long lifetime means that their substantial financial, environmental and social effects are felt by future generations whose socio-economic environment may be substantially different and whose values are unknown.

With a UK pipeline of over £466bn of projects (Infrastructure UK, 2014), large scale infrastructure investment was shown to be an imperative, but highly constrained problem with high expectations of service. Furthermore, that these investments were complex, being delivered into an existing extensive system of infrastructure systems which have been shown to be highly interdependent. The use of appraisal methodologies to analyse such decisions was introduced; however, their limited consideration of system of systems interactions was noted, with many calls for the methodologies to be further developed to consider this intrinsic complexity (iBUILD, 2015a; International Symposium for Next Generation Infrastructure, 2013; Dimitriou et al., 2013; Booth, 2012).

The main purpose of this chapter is to provide a greater understanding of the current state of the literature in both infrastructure appraisal and more widely for decision making under deep uncertainty, comparing these to our needs for strategic infrastructure appraisal. We start by reviewing the context of infrastructure decision making and the methods currently used to ensure decisions are made rationally, specifically Cost Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA). We continue by looking more widely at extensions to these methods, created for decisions under varying levels of uncertainty and the information provided by these analyses. We then consider how these methods have been extended to allow for sequential investments, before reviewing their capabilities for cross-sector strategic decision making. We conclude that while real option analysis, pathways methods and portfolio appraisals offer the opportunity to consider the interactions of multiple investments, none currently offer the flexibility to consider the long-term system perspectives inherent in cross-sector analysis. Further, that if a usable cross-sector appraisal methodology is to be developed, it will need to carefully balance the complexities of the individual investment appraisals, the number of investments (and portfolios of investments) considered and how the uncertainty is captured. Finally we propose how the methods can be brought together to realise a more complete appraisal of infrastructure investments.

2.2 The need for appraisal methodologies and the use of micro-economics

A ‘rational’¹ decision for infrastructure investment is likely to be considered one which maximises benefits and minimises cost, in accordance with ‘expected utility theory’ (Kahneman and Tversky, 1979). Such approaches are not always taken. For example, politicians are often

¹ A ‘rational’ decision maker, as defined by Pitcher (2008) is one who is immune to errors in judgement, adverse to risk and displays self-control.

accused of favouring large ‘ribbon-cutting’ projects over less visible ones for maintaining or adapting existing assets. In these cases, Soelberg (1967) notes that the appraisal process can also be used to justify decisions which have already been made, with criteria created to ensure the prominence of the favoured solution or details of the appraisal analysis concealed (see, for example, Ergas’ (2009) discussion of Infrastructure Australia’s guide to project evaluation). The political ‘prestige’ of developments is one aspect of the multi-actor decision problem discussed in Chapter 1. As noted, we concentrate herein on a rational strategic approach; however, the multiple perspectives of decision makers must be remembered. It is therefore important to ensure the appraisal methodology is consistent and transparent, so that limitations and biases are evident and can be discussed.

Even where rational approaches are taken, given the complexity described in Section 2.1, such choices are not straightforward. Decision makers are considered to have a ‘bounded rationality’; the problem is too complex to logically optimise either due to limited knowledge or the current ability to predict its impacts (Simon, 1972)². Decision making methods or decision-support techniques are therefore necessary to ensure the biases (Kahneman et al. (1982))³ and irrationalities (Pitcher, 2008)⁴ inherent in everyday decision making are ignored.

Micro-economics would suggest that a bottom-up account of all inputs and outputs could provide such a mechanism to compare investments. From a private company perspective a financial micro-economic appraisal of the costs and revenues of an investment may be sufficient, using one of the decision criteria in Table 2.1 to determine the optimal investment for them as a company. However, while such methods are consistent and rational, they do not capture the

² Hickman (2012) notes that policy makers have not historically moved beyond satisficing in such situations, seeking the ‘minimally acceptable’ outcomes and avoiding potentially risky innovations.

³ See Frischmann (2012), Glaeser (2011) and Gollier and Treich (2003) for examples.

⁴ Such as loss aversion, risk seeking, nonlinear preferences and source dependence.

multiple non-market social and environmental effects of infrastructure investments. They cannot, therefore, provide the societal perspective needed for policy making, capturing costs and benefits to the whole population, including those who neither invest in, nor make use of, the investment. For such an assessment we must instead look to welfare economics techniques, created to capture value under market failure conditions. In the next section we review the two most commonly applied methodologies, their benefits and limitations and consider their use in the deep uncertainty context.

Table 2.1 – Financial decision criteria

Method	Principle	Limitations
Minimax Regret	Lowest maximum opportunity loss	No account taken of total profit or distribution of profit/expenditure over time. Methods can also give different answers depending on application (French, 1986).
Maximin	Highest minimum opportunity gain	
Payback Period	Minimise period for return of the initial investment	
Annual Rate of Return (ARR)	Greatest percentage return per year	
Internal Rate of Return (IRR)	Least impacted by time preferences and inflation	Can give different ranking to net present value (de Neufville and Scholtes, 2011). Use explicitly advised against on UK central government evaluations (HM Treasury, 2003).

2.3 Current appraisal methodologies

2.3.1 An overview of cost benefit analysis

CBA extends financial micro-economic methods by estimating a monetised value for any non-market consequences of the investment and adding these to the market effects. The total ‘costs’ (negative impacts) and benefits (positive impacts) of potential investments can then be compared to produce a ranking. Similar decision criteria to those shown in Table 2.1 can be used to determine which investments provide the greatest benefit, but more commonly they are compared by calculating their Benefit Cost Ratio (BCR), produced by dividing the benefits by the

costs, or their Net Present Value (NPV), estimated by calculating the present value of all impacts and summing the result. A BCR greater than one or a NPV greater than zero suggests that the project benefits outweigh the costs and the investment should be considered. Options with a BCR of less than unity or a negative NPV can be assumed to provide a net loss and therefore should not be funded unless they provide “other, significant, redeeming features” (Ergas, 2009, p31). The greater the value of the BCR or the NPV, the greater the benefit received from the investment and the higher its ranking. However, it should be noted that by calculating BCRs, any differences in the size of investments are lost, making them difficult to compare to a given budget (Rogers and Duffy, 2012)⁵.

CBA has a number of limitations, which are considered below; however it is generally considered to be a transparent methodology and therefore more readily trusted than methods such as MCA (Rogers and Duffy, 2012). It has been used for infrastructure appraisal for over 150 years (OECD, 2011) and is currently used by most European countries, the United States and the World Bank⁶. There is therefore a wealth of experience in its application and data is available on its inaccuracies. Furthermore, results of CBA are more readily communicated and understood than newer or less used methods.

2.3.2 The assumptions of CBA and their limitations

CBA assumes impacts create marginal change and continue to do so over the appraisal period. It values the effects according to market prices or the ‘willingness to pay’ (WTP) of users/‘willingness to accept’ (WTA) of those affected. WTP and WTA must be estimated through

⁵ Can be considered by calculating the incremental BCR (recommended in the UK by the Department for Environment Food and Rural Affairs (Defra) and the Environment Agency (2009)).

⁶ Use on World Bank projects has, however, been declining. It is thought that this is due to difficulty of application (World Bank Independent Evaluation Group, 2010).

shadow pricing techniques, deriving value by directly asking people or by considering their current behaviour. However, it relies on all direct and indirect impacts being captured and existing markets being 'perfect' to ensure that valuations are accurate.

Should an NPV approach be taken, further assumptions must be made about the value of impacts over time. General behaviour would suggest that short-term benefits are valued more highly than similar benefits further into the future ('pure time preference'). Furthermore, it is normally assumed that the economy will grow and therefore future generations will be wealthier than the current one. The value future generations will ascribe to a given marginal change in utility would therefore be lower than that of the current population (the future 'marginal utility of consumption' will be lower). Finally, money not spent could accrue additional value and therefore the 'cost of capital' must be considered. To account for these three factors, discount rates are used to reduce the value of future benefits or costs. Equation 2.1 shows the value of a given benefit n years into the future. As the discount rate (r) increases⁷, short-term benefits are weighted more highly.

Equation 2.1 – Calculation of present values using a discount rate

$$V_0 = V_n \times \frac{1}{(1 + r)^n}$$

where V_0 = Present value (value in year 0) of V_n , if received half way through year n
 V_n = Value received in year n
 r = discount rate
 n = year benefit/cost is received

While many of the assumptions appear to be straightforward extensions of those from financial micro-economics, some limit the scope of the analysis. For example, as perfect markets will not hold in reality and the full extent of effects are unlikely to be captured (Beuthe, 2002), CBA is

⁷ Through increasing assumptions on pure time preference and/or weighted cost of capital and/or decreasing assumptions of the future marginal utility of consumption.

considered most accurate when comparing options intended to accomplish the same requirement, where inaccuracies are likely to be similar for all the alternatives considered (Rogers and Duffy, 2012). Furthermore, as infrastructure investments are known to cause large scale and long-term externalities and macro-economic change, the accuracy of marginal change assumptions will be limited as we increase the scale of the developments considered (Mackie, 2010)⁸. The valuation assumptions of CBA are of particular concern, and for some authors undermine its use altogether, questioning whether:

- Human life, that of other species and preservation of the environment can be given a monetary value (see, for example Mace et al. (2011) and Layard and Glaister (1994));
- Non- market effects can be fully and ‘accurately’ valued by shadow pricing techniques and can do so without inducing double counting (see, for example, Schipper (2004));
- Future value can be accurately captured through discounting;
- Estimations are sufficiently accurate that the appraisal process will determine the ‘best’ solution(s); and
- That societal benefit is sufficiently captured by a summation of all benefits and costs.

Some of these concerns have lessened as the CBA methodologies have developed over time. For example, reference class forecasting is now applied to reduce estimation inaccuracies (Flyvbjerg and COWI, 2004), impacts can be weighted to take account of differing marginalities of income (Mackie, 2010) and a ‘veto threshold’⁹ can be used to ensure impacts do not exceed reasonable levels. However, the first three points, and particularly the discount rate, remain controversial.

⁸ This has recently been recognised in the UK, where there have been attempts to perform macro-economic appraisals for the hub airport capacity (Frontier Economics, 2011) and investment in the High Speed 2 railway (HS2 Limited, 2013).

⁹ A minimum level of performance (or maximum negative impact), below (above) which the solution is declared unsuitable even if all other indicators show a good level of performance (Faucheux et al., 1997).

2.3.3 The controversies of CBA

Many authors reject the entire premise of CBA, stating that application of a value to a 'dignity' such as life is inherently wrong (Ackerman, 2008), or that the Earth is inherited by all species and the allocation of ecosystem resources should be decided by equity and democracy not market values (see Daly and Farley (2011)). While arguments have been made to justify the process (see, for example, Pearce et al. (1989)), little can be done to reverse such a belief. If, however, it is accepted that monetisation of values is a reasonable approach for decision making, there still remain two fundamental criticisms of CBA, our ability to find the full value of a non-market impact and our ability to value this over an extended timeframe. We consider these two aspects of the methodology further in this section.

Where market prices are not available, 'shadow pricing techniques', based on the principles of welfare economics must be used to estimate the value of a given social benefit or impact.

Navrud (2000) splits shadow pricing methods into revealed preference methods¹⁰ (RPM), where value is derived through existing behaviour and market valuations, and stated preference methods (SPM), where individuals are questioned about their current values or those under hypothetical futures (see Table 2.2).

Table 2.2 – Shadow pricing techniques (Navrud, 2000)

Value Estimator	Revealed Preference Methods	Stated Preference Methods
Individual	• Hedonic pricing¹¹ • Household production function (e.g. travel cost method or averting costs)	• Contingent valuation (e.g. choice experiments such as conjoint analysis)
Decision Maker, Expert or Interest Group	• Production function methods (e.g. averting costs/damage cost avoided, replacement cost) • Implicit evaluation	• Delphi technique

¹⁰ Also referred to as 'surrogate market prices'.

¹¹ Use of the variations in market price to estimate an element of the purchase, for example comparison of house prices in quieter and more noisy neighbourhoods to value the avoidance of noise.

An overview of these two types of methodology is given in Table 2.3 and described further in the paragraphs below¹². The methodologies are most commonly applied by considering the behaviour of individuals; however, valuations are then reliant on those individuals being well informed¹³, consistent and honest, assumptions which are often proved incorrect in practice. The effect of these assumptions can be reduced by instead asking experts to value the behaviours (for example, using the Delphi technique). However, bias can still be introduced and the values obtained may not reflect those of the general public.

Table 2.3 – Summary of benefits and limitations of stated preference and revealed preference methods

Characteristic	Revealed Preference Methods	Stated Preference Methods
Valuation	Use values only; valuation of current experiences/alternatives only	Use and non-use (option, bequest, existence) values; valuation of experiences/ alternatives currently unavailable
Scope	Restricted by data available; likely to be only one data point per respondent	Adjustable through questions asked; multiple observations possible from single respondent
Cost	Cheap if data is available or can be collected automatically, otherwise can be more expensive than SPM as more respondents required	Expensive: Mail and postal surveys are cheaper but suffer from sample selection bias and can inhibit communication of the scenarios
Biases	Assumes that users have complete information about their choices, and that they are buying the measured variable in isolation (can require regression analysis, depending on data series, therefore can be affected by colinearity); scope of data used can be questioned, for example use of a national dataset for value in a specific location	Requires careful design, so as not to introduce bias through phrasing and to maintain realistic market conditions (see Rogers and Duffy (2012) for an explanation of types of bias); tends to produce a large number of 'protest' responses, and is sensitive to the treatment of these responses
Validation	Individual methods reflect demonstrated behaviour	Only through reference to other studies; particularly difficult for non-use or new experiences
Equity	Assumes that value is equivalent to a consumer's ability to pay for it, devaluing benefits to the poor	Willingness to pay questions assume value is equivalent to a consumer's ability to pay for it, devaluing benefits to the poor, but use of choice methods can avoid this

¹² For full descriptions of the methods, their strengths, limitations and how they should be applied, see Pearce et al. (1989); Pearce and Turner (1990); Layard and Glaister (1994); Rogers and Duffy (2012); Hanley and Barbier (2009); Kroes and Sheldon (1988); Adamowicz et al. (1994); and Louviere (2000)).

¹³ Both in the options available and in their own preferences. Uncertainty surrounding an individual's preferences is thought to be one of the hardest to quantify (Marcial Echenique and Partners Ltd, 2001).

As noted above, RPMs rely on valuing behaviour and relating this to a factor of interest. An example might be using the time and cost spent travelling to a park to approximate its recreational value, or the additional cost of housing in quiet areas to approximate the value of peace and quiet. Values can therefore be validated against actual behaviour and have been shown to produce relatively consistent relationships between effects and behaviour (Smith and Huang, 1993; Navrud, 2000). Actual behaviour, however, may not only reflect a single variable. As such, the methods are reliant on the ability to disassociate variables and can be subject to 'omitted variable bias' if all applicable variables are not identified. They also only reflect current behaviour, so cannot be used to value non-use values¹⁴ (Hanley and Barbier, 2009). The travel cost method is the oldest and most extensively used RPM; however, its assumptions that travel time is not productive (or valued) and that all saved time is beneficial have recently received criticism (Lyons et al., 2007). In contrast, expert informed RPMs rely on valuing behaviour that could be taken, such as the cost of double glazing to estimate the value of peace and quiet; assuming an individual's willingness to pay based on market prices. It therefore suffers from a lack of behavioural evidence to support the valuation (Navrud, 2000).

SPMs simply ask individuals for valuations, either directly or through comparison with other activities. Unlike RPMs they can therefore be used to estimate non-use values (Department for Environment Food and Rural Affairs, 2007) and behaviour change. They are, however, more subject to biases, particularly 'hypothetical bias' where the alternatives described are not suitably realistic hypothetical situations and 'strategic bias' where individuals purposely falsify value to protest against a proposition or support their beliefs¹⁵. To avoid hypothetical bias, the studies often require personal presentation and therefore tend to be more expensive to conduct than RPM. The Delphi technique can be used to seek expert judgement and thereby reduce

¹⁴ Option values, bequest values and existence values (European Commission, 2002).

¹⁵ See Hanley (1991) for a study on the strategic bias ('protest voting') in six similar contingent valuation studies and how interviewer assumptions affect the results.

some of the biases of individual assessments; however, results may not be repeatable (Powell et al., 1997).

The quantity of data required for RPMs, the cost of collecting it for SPMs and the restricted time available for conducting appraisals have led to a wish to reuse past information, often from different locations. Such 'benefits transfer' allows estimations of value to be conducted in a timely and cost-effective manner; however, it significantly increases error margins, and care is required in both choosing applicable previous studies and in applying the data at the new location (Navrud, 2000). It is generally accepted, however, that it provides useful advice on the magnitude of valuations (Entec, 2004) as long as data is not transferred between countries¹⁶.

Caution is advised with the use of SPM and RPM valuations as they can be strongly reliant on data availability and practitioner judgement (see Pearce et al. (1989)). The methods have also been shown to produce substantially different valuations (see, Schipper (2004); Carson and Groves (2007); and Stevens et al. (2000)), often attributed to the limited scope of RPM and the biases of SPM¹⁷. The uncertainties of the valuation process will therefore vary with each variable measured, depending on how closely they reflect market assumptions¹⁸, the exact methods and data used. It is therefore likely that variables requiring approximation by shadow pricing will be more uncertain than those which have market values.

¹⁶ Variations in the socio-economic and environmental backgrounds of different countries have been noted to make benefits transfer unreliable (Ready et al., 2004).

¹⁷ Integration of the two methodologies has been found to remove some of the limitations of each method, providing a grounding for valuations (RPM), but allowing elimination of colinearity and valuation of non-use values (SPM), see for example Englin and Cameron (1996), Adamowicz (1994) and Kroes and Sheldon (1988).

¹⁸ Ecosystem services, for example, are known to have threshold effects where behaviour change is no longer marginal, therefore CBA valuation assumptions are undermined (Hanley and Barbier, 2009).

Over the decadal life of infrastructure assets the socio-economic environment will change and the values expressed through SPM or assessed through RPM will become inaccurate. In the absence of known future values, the question of intergenerational equity arises, trying to ethically balance short and long-term gains and losses (Broome, 2008). However, even in the absence of behavioural or value change, the estimation of future values are not straightforward. While valuations may include 'bequest' values for future generations, most of the future value is generated by discounting current valuations and it is here that the strongest disagreements lie.

A number of problems exist with use of discounting as a simplification of time preference, for example it assumes borrowing rates are constant over time and amounts borrowed, and it ignores changes in risk profile over time (de Neufville and Scholtes, 2011). However, more fundamentally, there is strong disagreement on how the rate should be calculated. Indeed, the importance and value of each of the three factors contributing to the discount rate¹⁹ are strongly debated. Rates based on the weighted average cost of capital are likely to be between 5 and 12 per cent (Pearce and Turner, 1990), see Weitzman (2007) for example, while, those aiming to balance the impact of effects in the short and long-term, will be much lower (Stern (2006a), for example, recommended a rate of 1.4 per cent, calculated by using a very low rate of time preference). Lower rates are particularly promoted for climate change mitigation, where the effects could be catastrophic, but where such effects are likely to be very far in the future and may be felt by those in poorer countries (with a higher marginal utility of income than current 'rich' polluters). High discount rates put individual preference over the importance of avoiding such events or even species preservation²⁰, suggesting a low rate promotes more sustainable investments. However, it is also argued that lower discount rates encourage greater investment

¹⁹ Pure time preference, changing marginality of consumption and cost of capital.

²⁰ This creates further questions. For example, if actions create climate change effects that reduce the population, should the values of people who will now no longer exist be taken into account and how should these be compared to people who currently exist (see Hanley and Barbier (2009))?

and greater use of resources, leaving fewer for future generations (Pearce et al., 1989). The ‘sustainability’ and ‘equity’ benefits of low discount rates are therefore not as clear cut as it may first seem.

Small changes in discount rate can substantially change the result of the analysis (Bickel et al., 2006)²¹, see Table 2.4. Therefore an approved, standard discount rate is required for CBA to be effective. In the UK, for example, a reducing rate starting at 3.5 per cent (see Table 2.5) is applied to all public sector investments. Such reducing rates balance short-term preferences and long-term effects on future generations (Rogers and Duffy, 2012). However, even with standardised discount rates, as timescales are extended, the effects of the chosen discount rate (on both resources and long-term costs/benefits) need to be explored if solutions are to be sustainable and robust to future changes in preferences and values. The US takes this approach, requiring investments be assessed against both a 3 per cent and 7 per cent discount rate (World Bank Climate Change Group, 2014).

Table 2.4 – Present value of £100 received in the future using different discount rates

Discount Rate	Year Received				
	0	10	20	30	40
3.0%	£100	£74	£41	£17	£5
4.0%	£100	£68	£31	£10	£2
5.0%	£100	£61	£23	£5	£1
6.0%	£100	£56	£17	£3	£0
7.0%	£100	£51	£13	£2	£0

²¹ The HEATCO project found that the 0.5 per cent difference between the UK and European average discount rates decreased overall NPV by 19% (Bickel et al 2006).

Table 2.5 – HM Treasury discount rates (HM Treasury, 2003)

Period (years)	Discount Rate (%)
0-30	3.5
31-75	3.0
76-125	2.5
126-200	2.0
201-300	1.5
301+	1.0

The final concern raised in Section 2.3.1 is that of double counting. CBA requires rigorous checks to ensure that transferred benefits are not counted twice and that effects are attributed to the appropriate source. As a simple example, a passenger on a train must value their journey at at least the cost of their ticket. Valuing the service provided as the cost of the ticket would therefore provide a simple lower bound. However, should the passenger actually value the journey as the cost of their ticket, they would receive no net benefit (having received a service and paid a fare of equal value). The only benefit is that received by the operator through selling a ticket. Similarly, increased economic growth in one area of a country, experienced after an investment is made, may be at the expense of another area. Attribution becomes particularly difficult when multiple projects are involved. Despite effects emerging from the interactions of various investments, their benefit or cost is generally accrued to the most recent (latterly implemented) project. For benefits this undervalues prior projects, reducing the long-term systems opportunity and focusing on short-term standalone benefits.

2.3.4 Avoiding monetisation: Multi-criteria analysis

The strongest controversies of CBA centre around the need for valuation. MCA takes a similar bottom-up approach to CBA, but simply quantifies effects in their natural units (see Table 2.6 for a summary of the two main types of MCA). Any aspect that can be quantified (however

approximately) can be included in the decision²². MCA thereby removes the need for a single value perspective and the uncertainty surrounding value and value change over time, making it more appropriate for multi-actor, highly uncertain decision making. However, it can only provide a list of results, making it difficult to assess worth against a budget (Beuthe, 2002), or to provide a ranking in the absence of a non-dominated ('pareto optimal') solution. In its purest ('non-compensatory', see Table 2.6) form it therefore only provides decision-support.

Table 2.6 – Non-monetised appraisal: Types of MCA

Type of MCA	Principle	Limitations
No weighting applied ('non-compensatory')	Several criteria evaluated, but measurements left in the most applicable units	Pareto optimal set will require further analysis/trade-off; difficult to compare between studies
Composite indicators or dominance ²³	Several criteria evaluated, with measurements made in most applicable units then combined through preference weighting functions	Weightings reflect decision maker's unique preferences, therefore 'incorrect' weightings will result in sub-optimal solutions; method is unique to decision maker therefore can be inaccessible and incomparable.

The metrics can be brought together through composite factors, or optimised through, for example, evolutionary algorithms, but both require the assignment of preferences. It therefore introduces the opportunity for 'arbitrary assessments' regarding weightings (Beuthe, 2002) and can encourage the creation of irrational preferences (Ergas, 2009). Not only can these weightings be critical to the outcome, but they tend to be hidden in the detail of the analysis (OECD, 2011), making them difficult to compare (Ackerman and Heinzerling, 2004; Rogers and Duffy, 2012) and the analysis difficult to validate after the fact (Ergas, 2009). This has led to a perception that results could easily have been manipulated (Kuik et al., 2013) and a distrust of the outcomes.

²² Although the analysis can become overly complex and inefficient if too many indicators are used (Sebastian et al., 2013).

²³ Includes Simple Additive Weighting Method, Analytic Hierarchy Process and Concordance Analysis techniques.

2.3.5 Combining CBA and MCA: Strengths and limitations

While developed as separate methods, there is considerable overlap and synergy between CBA and MCA (OECD, 2011) and the two methods may be effectively combined. Taking the example of valuation of transport infrastructure; impacts are often calculated using a core CBA approach complemented or extended by an MCA (Bickel et al., 2006; Hayashi and Morisugi, 2000; Grant-Muller et al., 2001). Such methods provide a financial basis to compare alternative developments, but do not restrict assessment to impacts that can be monetised. Monetised impacts can be summed to minimise the number of variables for consideration, making comparison of alternatives more straightforward (and transparent) than MCA. Variables where monetisation is difficult or highly uncertain can be left in their natural units, providing a more complete assessment than CBA alone.

2.3.6 The use of combined CBA and MCA methods for strategic appraisal

While combined methods may overcome many of the shortcomings of the individual methodologies and be adequate for limited scope individual projects, their appropriateness for infrastructure plans or programs is questioned (López et al., 2008). Firstly, they do not intrinsically address the uncertainty prevalent in both the quantification and monetisation of effects and of the future in which the infrastructure will be operating in. Secondly, they ignore the spatiality of effects, an understanding of which becomes increasingly important if macro-economic benefits are to be achieved (Banister and Berechman, 2003). Finally, projects are judged as standalone investments, ignoring which are mutually exclusive due to resource limitations or function and which can be combined for greater benefit. Such analyses ignore the emergent effects that can be achieved through portfolio investments, or how a lower 'value' standalone project may provide the opportunity for greater benefits as part of a future system.

For a more complete appraisal of infrastructure investment we must therefore look to these three issues: Uncertainty; spatiality; and systems analysis.

2.4 An overview of uncertainty methods

Not only is the monetary value of an impact uncertain under long timeframes, but also the degree to which the impact will be felt. Taking the example of a flood barrier, its value is likely to be estimated through the people, property and environment it protects; however, population growth, economic development and changes in environmental protection policy will alter this 'value' over time. Emergent conditions such as economic development and climate change must therefore be included in the decision making process (Martinez et al., 2012) as these will change the value of impacts making investments more or less worthwhile. The provision of new services can also cause a change in behaviour, undermining future projections and the analysis produced under these assumptions (see, for example, de Neufville and Scholtes' (2011) review of the Boston sewage system or Glaeser's (2011) discussion of Jevon's paradox in reference to greater broadband speeds and car engine efficiency).

If the results of these uncertainties are relatively minor, the considered future will be reasonably predictable. In these cases CBA and MCA can be extended using Bayesian decision trees and defined probability distributions to assess the most likely best outcome (see Table 2.7). As the methods capture sequential decisions, they present the opportunity to consider further investments or changes to the original investment over time. However, the methods carry forward the same limitations as the simpler assessments regarding monetisation and bias. Furthermore, they require accurate probability distributions for each of the outcomes, which will not be available for long-term infrastructure investments.

Table 2.7 – Extending CBA and MCA where uncertainty is quantifiable: Probability methods

Method	Principle	Limitations
Expected Monetary Value	Decision pathway analysis using the probability and payout of each outcome to define the best decision route	Monetisation of benefits required; needs well characterised system models with confirmed probability distributions
Expected Utility	Decision pathway analysis using the probability and ‘value’ of each outcome to define the best decision route	‘Value’ will be dependent on perspective of decision maker and consistency of results is dependent on their ‘rationality’; needs well characterised system models with confirmed probability distributions
Multi-Attribute Utility Analysis	Decision pathway analysis using the probability of outcome and benefits under a number of criteria to define the best decision route (see Haimes et al. (1990))	Pareto-optimal set will require further analysis/trade-off; difficult to compare between studies; needs well characterised system models with confirmed probability distributions.

Where probabilities cannot be predicted, further analysis of the potential investments may be possible using bounds of uncertainty (see Table 2.8). These methods move away from sequential decision based analyses, tending to examine the effects of uncertainty on the final investment/system as a whole. Input values are varied between the identified bounds to determine which have the greatest effect and to quantify the uncertainty of the appraisal result. While it is generally accepted that infrastructure decisions are made under deep uncertainty and therefore estimated bounds are unlikely to be accurate (see Chapter 1), current infrastructure appraisal in the UK has tended to use these analyses to explore uncertainties. Indeed HM Treasury states that sensitivity analysis is ‘fundamental’ to the appraisal of UK public projects and should be ‘dispensed with only in exceptional cases’ (HM Treasury, 2003, p32).

Table 2.8 – Extending CBA and MCA where uncertainty is quantifiable: Bounds of uncertainty methods

Method	Principle	Limitations
Sensitivity Analysis	Variation of individual factors within a simpler methodology (for example CBA) to determine the impact of their uncertainty on the assessment	Carries forward limitations of the simpler methodology (for example monetisation); variation of combinations of factors may be necessary and will be dependent on time and computational processing power

Method	Principle	Limitations
Interval Analysis	Combination of all lowest and then all highest input variables to give error bounds to the result	Carries forward limitations of the simpler methodology (for example monetisation) and assumes inputs are not linked; probability is not defined therefore range has limited meaning
Monte Carlo Analysis	Mathematical application of sensitivity analysis to multiple input parameters; estimates the range, distribution and expected return on investment	Carries forward limitations of the simpler methodology (for example monetisation); dependant on accuracy of predicted uncertainty distributions

Methods for the consideration of ‘deep uncertainty’ (where even the bounds of uncertainty cannot be estimated) have been created, (see Table 2.9 for a summary, or Weaver et al. (2013) and Lempert (2002) for a fuller discussion). Such methods work on the principle of ‘robust satisficing’, assuming that sustaining a given level of performance, or a lower level of sensitivity to assumptions, over a range of future scenarios is preferable to optimisation under a given future (Hall, 2012b; Weaver 2013). They therefore investigate the investments under a diverse range of future conditions, without estimating the likelihood of these futures. The methods are time consuming to construct and undertake, and ranking of results is not possible (in the absence of pareto optimals), due to the lack of data on probabilities of the future. Furthermore, the results of such analyses are more complex than other uncertainty methods and therefore more difficult to interpret and communicate.

Table 2.9 – Appraisal methods to consider unknown levels of uncertainty (deep uncertainty)

Method	Principle	Limitations
Scenario Analysis	Assesses value/resilience of investment under well-defined narrative futures, often chosen to explore the extremes of the uncertainty space	Scenarios are time consuming to construct therefore normally limited to 2-4; analysis is limited by initial selection of scenarios, which is often arbitrary; methods cannot rank investments and are reliant on human reasoning
Robust Decision Frameworks ²⁴	Mathematically assesses the robustness or vulnerability of a solution over a set of plausible views of the future	Can require significant computational effort; model outputs require ‘translating’ for non-domain experts

²⁴ Includes Robust Decision Making, Decision Scaling, Assess Risk of Policy, Info-gap and Context-First methods (Weaver et al., 2013).

Method	Principle	Limitations
Computer Assisted Reasoning (CAR) (Lempert, 2002)	Computationally implements hundreds of possible futures, applying one of the simpler economic analyses in each case to test resilience of investment to all futures	Computationally very challenging and time consuming; huge volume of results that require exploration via genetic search algorithms
Backcasting	Works backwards from a particular desirable end-point to the present in order to determine the physical suitability of that future and what policy measures would be required to reach that point	Requires an aim to work towards, factors outside of this aim must be compared using separate analyses; impacts of policy measures are subject to uncertainty; tends to produce groups of policy measures rather than prioritised rankings

The least complex of these techniques (scenario analysis) has been used quite widely for policy review. It is recommended in the UK (HM Treasury, 2003) and mandated in the US for certain public projects (Schroeder and Lambert, 2011). Use of the three more complex methods is extremely computationally expensive and, therefore, is predominantly limited to academic study. Use to date has mainly been in application to climate change adaptation, producing some infrastructure appraisal and planning studies where assets are strongly affected by climate change (for example, assets under the remit of Southern California's Inland Empire Utilities Agency, the Metropolitan Water District of Southern California, Denver Water and the California Department of Water Resources, see Weaver et al. (2013)). More recently, the Infrastructure Transitions Research Consortium has applied a CAR analysis to national infrastructure appraisal in the UK (Tran et al., 2014), providing both a systems and a deep uncertainty perspective. The models required for this analysis, however, have taken years to develop, requiring vast quantities of data and processing power to accomplish. The methodology is therefore not easily adaptable to smaller scales or changing priorities and is not suitable for iterative decision-support by non-experts.

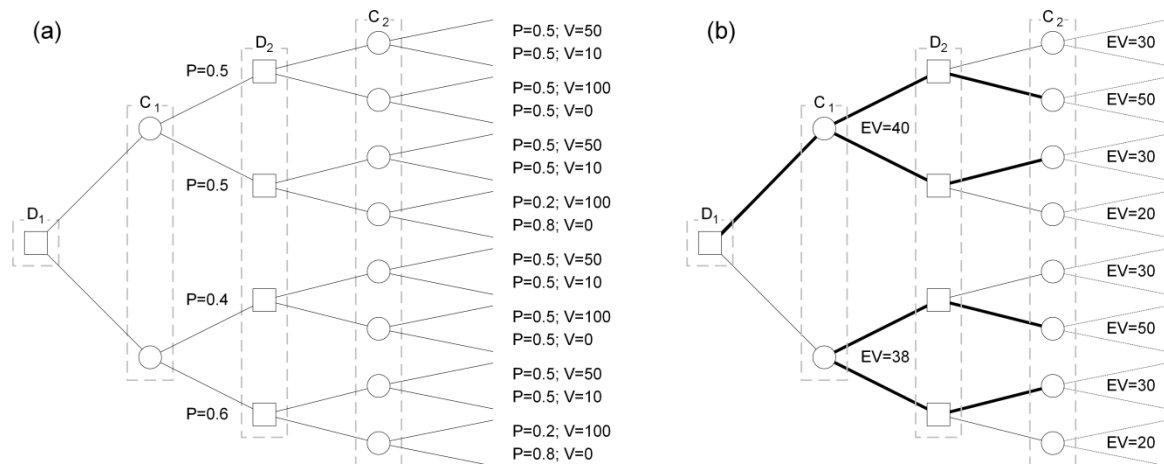
2.5 Sequential systems decisions under uncertainty

Similar to the uncertainty methods in Section 2.4, as we increase the complexity of system models, there is a tendency for them to become prohibitively large (Golub et al., 2011). As such, existing research has tended to focus on the case of a single, non-interacting network (Buldyrev et al., 2010). Examples of cross-system analyses are severely limited to date; however, a number of methodologies have been adapted to consider multiple investments, their interactions and some of the uncertainties involved. We discuss these below.

2.5.1 Decision tree analysis and expected value

The most basic sequential decision analysis is decision tree analysis (DTA), first comprehensively reviewed by Raiffa in the 1960's (see Raiffa (1968)). DTA has since been widely used for analysis of multi-stage decision problems. The decision tree itself provides a graphical presentation of the problem. Branches represent alternative states of the system (see Figure 2.1), created either by decisions (squares) or by chance (circles). The final branches represent the possible outputs of the system. By multiplying outputs by their probabilities we get the 'expected value' of the decision or choice node preceding it. In the case of a pure *decision* tree, we could use these expected values to determine the optimal approach. However, most trees are created to consider uncertainty and therefore also include chance nodes. In the presence of chance nodes, we cannot determine the whole route; however, we can iterate the averaging process back to each decision point, selecting the choices that provide the greatest average value. We therefore create a forward plan of actions taking into account the uncertainty of the chance nodes. By continuing this process back to the stem of the decision tree ('averaging-out and folding-back') we calculate the expected value of the whole decision under uncertainty (see Figure 2.1b).

Figure 2.1 – Example decision tree



(a) Represents two sequential decisions (D_1 and D_2) with chance events (C_1 and C_2) dictating the probability of which decision will be available in the second instance and the payout of that second decision. We calculate the expected value (EV) in (b) by multiplying the probability and value of each output of the C_2 chance event. The second decision is then assumed to take the highest value route (emboldened). We then repeat with the C_1 chance event to determine which D_1 decision should be taken and its expected value.

Decision trees therefore translate a complex decision into a number of sequential decisions that can be easily understood and, in the presence of known probabilities, provide an optimum route or valuation for the decision. Furthermore they assist in designing a proactive approach to planning, with actions chosen dependant on the outcomes of future events. Without such probabilities DTA provide little provision for considering robustness in their original state; however, they form the basis of most sequential decision analyses and have been extended in a number of ways to consider decisions under greater uncertainty. We proceed by considering two of these extensions.

2.5.2 Real options analysis

The more complex uncertainty methods in Table 2.9 determine robustness by searching a vast decision space; however, most consider the investments as fixed, unable to change over time.

Building on the decision tree analysis described in Section 2.5.1 an alternative is possible:

delivering robust solutions by taking a fallibilist viewpoint and looking at the flexibility of

decisions (Kuik et al., 2013)²⁵. By considering the investment over time, actions can be strategically planned as information becomes available and uncertainty decreases, allowing a proactive approach as conditions change.

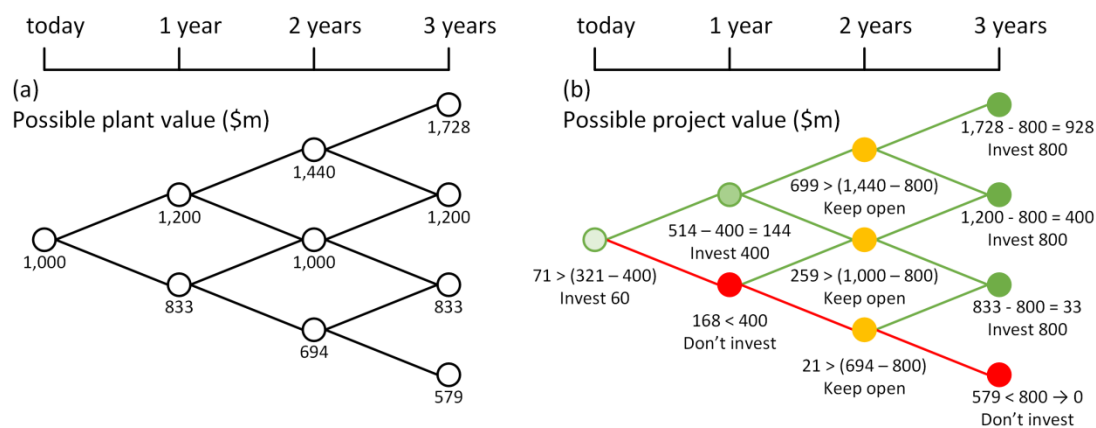
The most common method for valuing the flexibility of decisions over time is Real Options Analysis (ROA). The method was developed from 'option' pricing methodologies in the financial sector (see Myers (1977)), where a 'real option' is an investment that increases flexibility (or the range of decisions) in the future. This option can be exercised if conditions are favourable or ignored if not. It therefore creates the opportunity for greater benefits, but has a lower risk than a full upfront investment. An example would be the purchase of additional land to allow later expansion of a plant. Should demand increase, the land is available and construction may begin as necessary. However, should demand remain constant or fall, no additional construction will be undertaken, indeed, the land could be resold further reducing the risk to investors. The method therefore has the potential to increase project value, or potential returns while limiting risk (de Neufville and Scholtes, 2011; Ford et al., 2002), producing improvements in NPV of the order of 10-20 per cent (Weijnen et al., 2008). Furthermore, it has been found to produce useful insights (Pachamanova and Fabozzi, 2010), highlighting which information should be sought and monitored to ensure decisions are made at the appropriate time.

Wang and de Neufville (2005) define two types of ROA, real options 'on' projects and real options 'in' projects. The former has been more commonly applied to date. It is more strongly linked to financial options analysis, treating the investment as a black box and calculating its value by mirroring a stock price or through an assumed elasticity. It is therefore considered most suitable for investigating investment opportunities and estimating shareholder value

²⁵ De Neufville describes this as 'active' protection against uncertainty, as opposed to the 'passive' protection of RDFs or 'controlled' protection through demand management (de Neufville et al., 2004).

(Wang and de Neufville, 2005). Option values are calculated based on equivalent financial transactions using, for example the Black-Scholes formula (see Borison (2003) for a topology of ROA approaches). An example calculation, taken from Copeland and Tufano (2004) can be seen in Figure 2.2. It uses assumed elasticities to value a plant over time and a replicating portfolio technique to value an option to expand.

Figure 2.2 – Real options ‘on’ projects analysis of expansion of a plant (Copeland and Tufano, 2004)



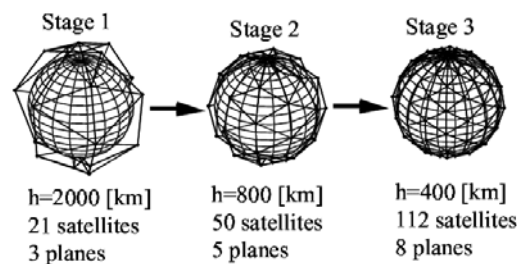
Creation of an event tree of the future values of an asset (a) and valuation of an option to expand, at an initial cost of \$60,000, followed by two compound options of \$400,000 and \$800,000 respectively (b). Values in (a) are calculated from left to right assuming an initial value of \$1bn and a volatility of 18.23 per cent. Values in (b) are calculated from right to left, with results indicating the value of keeping the option open for the future²⁶ calculated using a risk-free rate of 8 per cent.

Criticisms have been made of the foundational assumptions of the ‘on’ projects methodology and the use of financial calculations when riskless arbitrage opportunities could be available. More generally critics note that assets cannot be sold at will and links to stock prices are only loosely applicable (Borison, 2003; Wang and de Neufville, 2005; Pachamanova and Fabozzi, 2010; de Neufville and Scholtes, 2011).

²⁶ Equivalent to an investment portfolio of risk-free par-value bonds and shares with outputs equivalent to the two resulting event tree valuations; calculated by solving the simultaneous equations of $m(Av) - (1 + r)(B) = Iv$ for each of the two resulting asset values, then reinserting values to find Iv for the prior investment; where m = the proportion of plant value; Av = final asset value; r = risk-free rate; B = the number of par-value bonds; Iv = final investment value.

Real options 'in' projects allows the design and function of elements within the investment to be altered, focusing on the interactions between elements and how these change over time to deliver benefit. De Weck et al (2004), for example, use the methodology to test the option to reconfigure on-orbit communication satellites to allow formation of new constellations and thereby create greater capacity in the future if demand requires (see Figure 2.3). The option was found to lower life cycle costs by more than 20 per cent, delaying upfront expenditure and allowing managers to tailor future expenditure to market demands, reducing the risk of investment.

Figure 2.3 – Satellite reconfiguration, an example of real options 'in' projects (de Weck et al., 2004)



Options 'in' projects require a much more detailed understanding of the asset and can be difficult to identify and design (Wang and de Neufville, 2005). Furthermore, as elements of the asset can change, value must be derived from its outputs, using CBA, MCA or a similar measure of performance to compare the flexible investment to its non-flexible alternative. Such valuations may not relate to share value and therefore the method is considered more appropriate for evaluating flexibility, path dependency and go/no go decisions, than financial worth (Wang and de Neufville, 2005).

While criticisms of both types of ROA remain, its use for public investments has been recommended by a number of governments including the UK (HM Treasury, 2003; 2009; 2015)²⁷.

²⁷ Other governments recommending the approach include Australia, New Zealand and the Netherlands.

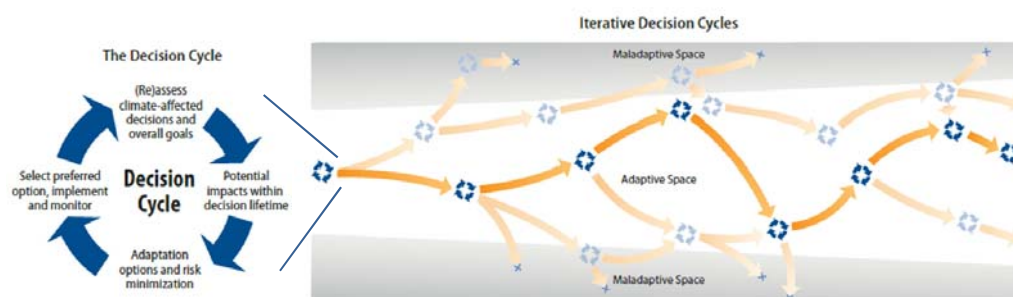
However, despite different ROA approaches producing ‘dramatically’ different valuations depending on the assumptions made (Borison, 2003), guidance on how to apply the methodology is limited. This perhaps explains why the application of ROA to infrastructure to date has remained mainly in the academic domain, in sector specific and often asset specific case studies, for example: Smit (2003), de Weck et al. (2004), de Neufville et al. (2006), Guo and Jiang (2010), Suttinon and Nasu (2010), Fernandes et al. (2011) and Ashuri et al. (2011). Quantified application to real-world infrastructure decision making is rare (Herder et al., 2011; Farrow, 2004), although an ex post analysis was conducted on the Tagus River Bridge, Lisbon (see Gesner and Jardim (1998)), concluding that the provision of flexibility was valuable in this case.

From the perspective of strategic cross-sector infrastructure appraisal, the method suffers from a number of factors, primarily its reliance on understanding the probability of value change. Secondly, as can be seen from Figure 2.2, the computation required grows exponentially as the number of time steps/decision points are increased. Applications therefore tend to strongly restrict the number of decision points/time steps, to limit the complexity of the analysis, but in so doing reduce the potential to consider large portfolios of investments. While the method does allow for ‘compound options’ or ‘options on options’, particularly if the binomial tree is used, this further complicates this process, potentially requiring additional stages or breaks in the recombination. Finally, adaptation of the methodology from a purely financial to a multi-attribute analysis can cause conflicted results (Krüger, 2012), suggesting it may not be suitable for MCA approaches.

2.5.3 Pathways analysis

Extrapolating ideas from ROA, multi criteria decision analysis methods have also been developed for robust decision making. Referred to as ‘adaptive decision making’, ‘adaptation pathways’ or ‘pathways analysis’, these methods build on assumption based planning techniques such as ‘iterative risk review’ (Panel on America's Climate Choices, 2010), but also allow forward planning of actions. The focus moves from justification of the initial decision to continual review for error (or new information) and response when this is found (Collingridge, 1981; Klein and Meckling, 1958), see Figure 2.4. Decision makers only commit to a set of initial investments and create a strategic plan for those that must follow.

Figure 2.4 – Pathways approach to decision making (adapted from Wise et al. (2014))



Plans present future investments as sequential decisions, considering their ability to meet the requirements under different conditions. They note which investments can be grouped, which are mutually exclusive, when further investment will be necessary and which investments should be considered at this time. Methods have seen increasing use in the context of adaptation to climate change, with related water sector infrastructure being included as part of such analyses. Examples include analysis of flood protection in the Thames Estuary, UK (see Figure 2.5) and water supply provision in the Rhine Delta, Netherlands (see Figure 2.6).

Figure 2.5 – Pathways analysis of flood provision in the Thames Estuary (Reeder and Ranger, 2011)

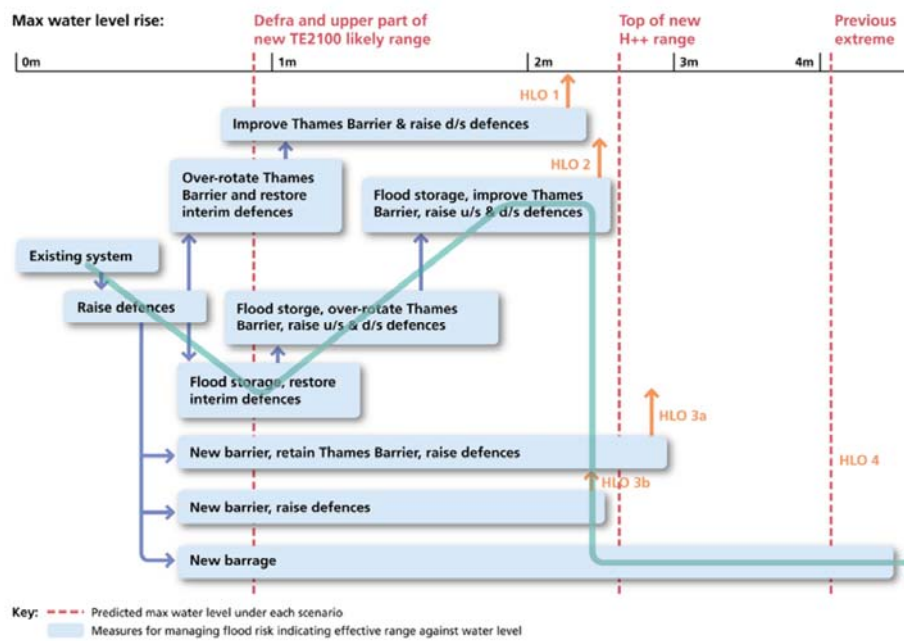
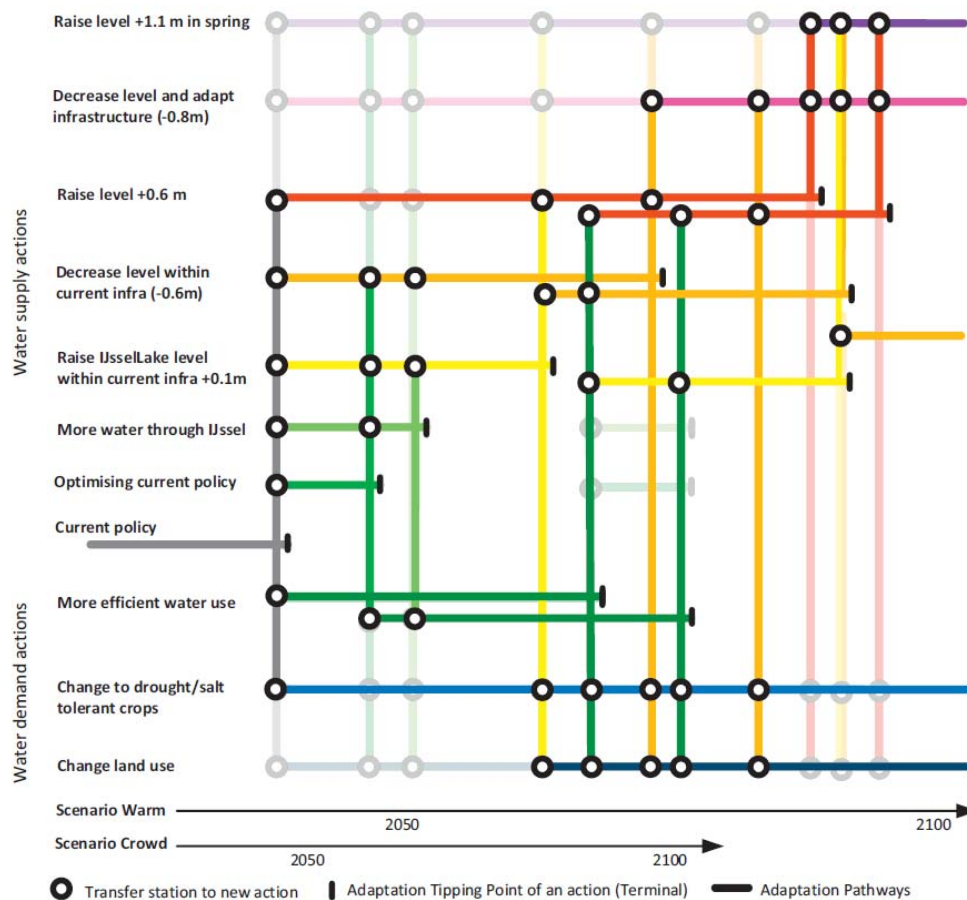


Figure 2.6 – Pathways analysis of fresh water supply from the IJsselmeer area of the Rhine Delta (Haasnoot et al., 2013)



The methods accept a higher level of uncertainty than ROA, often not requiring full monetisation or even quantification and have therefore been able to consider much longer timeframes (often 50-100 years, or even longer) and larger portfolios of investments. Furthermore, by depicting each investment as part of a portfolio over time, they provide the opportunity to consider each development's effects on future investments, the lock in created and any path dependencies. However, to balance this complexity further simplification of the problem domain is required. Such analyses have therefore, to date, required a clearly defined single objective to determine when investments are no longer valid²⁸ (Wise et al., 2014). As well as simplifying the analysis, this objective factor can be used instead of a timeframe to overcome uncertainty in predictions (note the horizontal axis in Figure 2.5 is sea level rise, not time). However, without such a threshold or tipping point, the analysis cannot be completed: the decision space cannot be reduced and, in the absence of further appraisal, the benefits of alternative pathways cannot be compared.

2.5.4 Portfolio analysis and scenarios

Use of some of the more complex bounded uncertainty and deep uncertainty methods for multi-asset infrastructure appraisal is possible, but requires further simplification of the problem domain. Examples again emanate from climate change studies and tend to restrict the analysis to a defined objective as seen in the pathway analyses, but also show shorter timeframes, a very restricted exploration of the uncertainty, or a more limited set of developments. A clear trade-off is made between the complexity of the investment appraisal (number of criteria considered, timeframe, number of investments compared, whether grouping is allowed and whether system effects are captured) and that of the future projections or scenarios considered. Two

²⁸ Maximum sea level rise in the case of Figure 2.5 and sufficient drinking water in the case of Figure 2.6.

applications of the methods to complex water policy decisions in the US demonstrate this balance:

Louisiana's 'comprehensive master plan for a sustainable coast' (see Coastal Protection and Restoration Authority of Louisiana (2012)), considered land loss and flooding, using a scenario analysis over a 50 year period, with a commitment to review the analysis every five years. Only two future scenarios were considered; however, hundreds of candidate ideas were combined into portfolios, with combinations limited only by mutual exclusivity, budget and resources. Furthermore, while the portfolio results were simply considered to be the additive result of the individual elements, the presence of system effects was recognised and will form the basis for future work.

The Colorado River Basin study, took the same 50 year perspective, considering management of the river's resources and how key vulnerabilities could be reduced over this timeframe to ensure water supply objectives could be met (see Groves et al. (2013)). The study used a more complex Robust Decision Making (RDM) analysis²⁹, comparing alternative developments to thousands of future scenarios; however, only a small set of dynamic development portfolios could be tested³⁰. The analysis focused on what future conditions led to the basin not meeting water delivery objectives, identifying the actions most commonly necessary in all future conditions.

While the studies focused their computation on different sides of the analysis, both considered multiple sequential investments and, although strongly focused on a single sector specific objective, both undertook a multi-criteria analysis of the performance of the system, providing more quantified information than a typical pathways analysis and allowing for a greater number

²⁹ A robust decision framework, see Lempert et al. (2003).

³⁰ Four supply scenarios, six demand scenarios and two river operation scenarios.

of criteria than ROA. Indeed both studies recognised a level of influence on other infrastructure sectors, suggesting some level of cross-sector thinking (although the priorities of the affected sectors were not included). Furthermore the Louisiana study considered system constraints, dismissing portfolios where these were exceeded. Finally, while not as long-term as the pathways analyses, more time steps/decision points can be included than in ROA, providing the opportunity for a multi-decadal quantified appraisal.

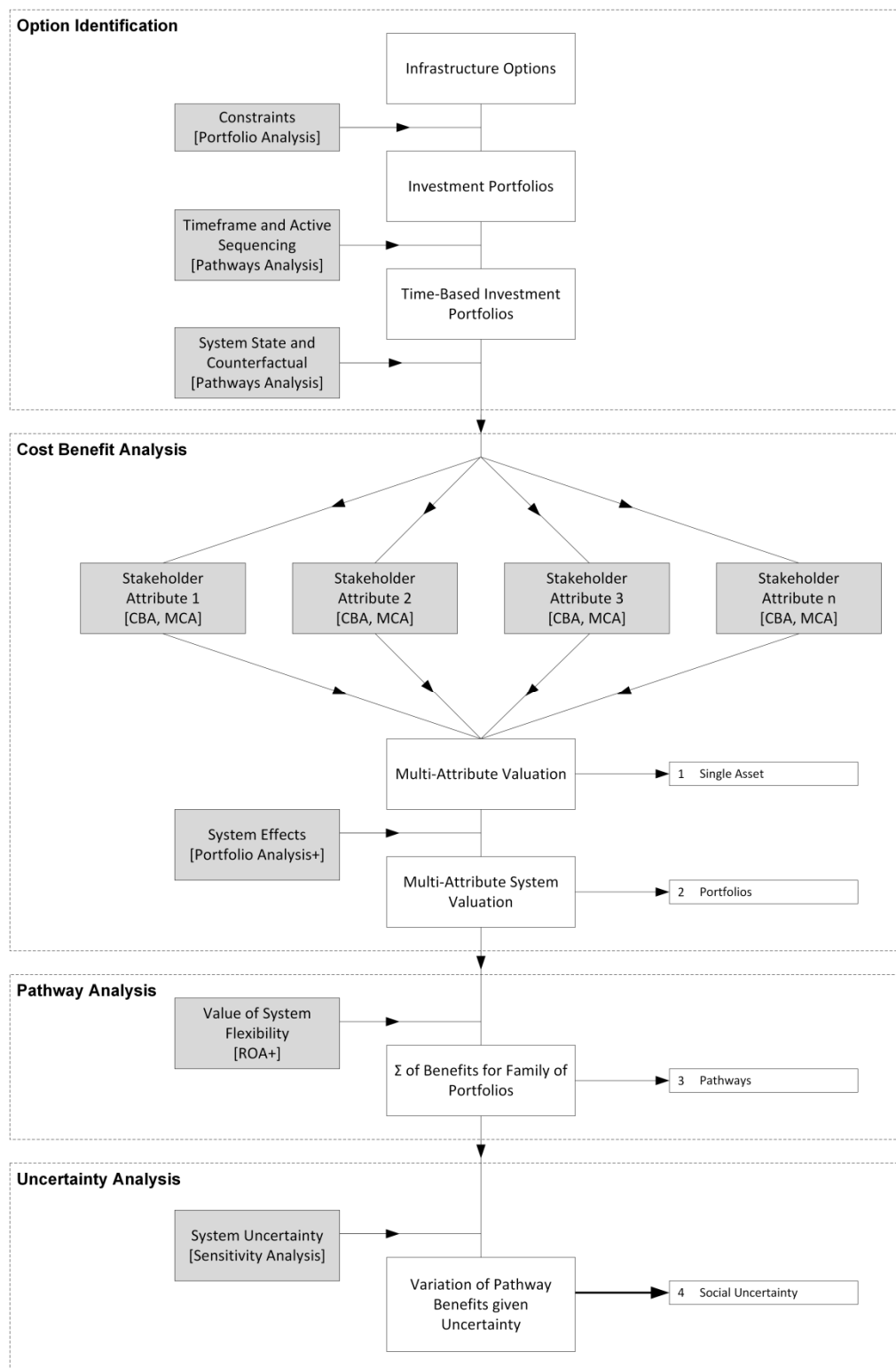
2.6 Extension of existing methods for strategic infrastructure appraisal

Each of the appraisal methods considered in this chapter has benefits that could contribute to a more complete assessment of infrastructure investments as part of a developing system of systems. However, none yet can individually quantify pathway and system effects over the long-term. CBA and MCA are well understood methodologies and when combined can overcome many of their limitations, creating a relatively transparent and comparable result that more fully values the effects of an investment. However, they have no inherent way to consider groups of investments or uncertainty. ‘Deep uncertainty’ methods provide an opportunity to consider uncertainty; however, their need to consider vast arrays of futures makes them very computationally expensive. Considering robustness through flexibility (using ROA) and adaptation (using pathways analysis) instead, limits this computational expense, while capturing path dependency, lock in and mutual exclusivity. ROA provides the opportunity to quantify and value flexibility; however, it is limited in the number criteria considered, the number of time steps that can be included and in its need for quantified probabilities. It is therefore not appropriate for large numbers of sequential decisions (i.e. large portfolios) or deep uncertainty. Pathways analysis allows for a longer timeframe, greater uncertainty and multiple criteria, but does so at the expense of quantification and hinges on a clearly defined single priority, which will not be present in multi-sector infrastructure appraisal. Furthermore, real world use of these

techniques is limited, therefore expertise may not be sufficiently available for stakeholders to manage and update such an analysis. Portfolio methods have been proven as useable tools for both stakeholder analysis and communication, having been applied to real world climate change adaptation policy. In addition, they provide an opportunity to capture total system requirements, such that mutually exclusive developments can be removed. However, they cannot display pathway impacts of an investment, tend to be shorter term and only consider a defined primary priority. Furthermore, they have not, to date, considered system effects. For a more complete assessment of infrastructure as a system, we must therefore combine the aspects of the analyses discussed. Our proposal is outlined in Figure 2.7.

As we have seen in this chapter, as the methods increase in complexity they incur a substantial cost in the form of time and analytical effort to undertake, making the results more difficult to understand and communicate. Therefore if we are to allow for an increase in the complexity of the appraisal (through inclusion of systems effects) we must first reduce the complexity of the decision problem. We do this in two stages. First we apply a portfolio analysis understanding of total system constraints to reduce the decision space, removing any potential portfolios with mutually exclusive investments. Secondly we chose to take an active approach to robustness (from pathways analysis and ROA), considering that all decisions are changeable and concentrating on initial decisions and their lock-in for the future. This removes the need to consider a vast array of possible futures (as used in RDF). However, as it will still be useful to understand uncertainty over the long-term, we propose a sensitivity analysis of key variables on the outputs of the system as a whole.

Figure 2.7 – Proposed appraisal methodology and outputs



With these reductions to the decision problem, we can increase the complexity of the analysis.

Firstly we can consider a long-term timeframe, recognising the changes this creates in the

counterfactual case in line with pathways analysis. We can then extend two of the methodologies, building on the portfolio analysis approach to consider emergent system effects of the investments and drawing on ROA to create a quantified understanding of the value of system flexibility. To allow this valuation, the appraisal will be based on CBA, drawing on the known transparency benefits of this approach. However, accepting the uncertainties of shadow pricing methods and differences in stakeholder priorities, the outputs will be segregated into attributes that capture these features.

Returning to our five incremental stages of complexity from Chapter 1:

- Assessment against a single attribute vs multi-attribute valuation;
- Investment in individual projects vs investment in groups of projects (portfolios);
- A specified single project/portfolio vs consideration of pathway flexibility;
- Single future projection vs valuation under an uncertain future (sensitivity analysis); and
- Isolated predictions of change vs path dependency and feedback (incorporation of the interdependency between the development and the investment landscape).

We see that our proposed approach will allow investigation of the first four stages, but it will be necessary to further consider analysis of the wider effects of infrastructure if we are to investigate the path dependencies and feedbacks with and from its environment. This is outside of the scope of the appraisal and deep uncertainty methods considered within this chapter. We will therefore return to this in Chapter 8 after conducting the systems appraisal.

2.7 Conclusions

In this chapter we have reviewed the current state of the literature in both infrastructure appraisal and more widely for decision making under deep uncertainty. Decision making methods and decision-support techniques have been used for decades to help ensure infrastructure decisions are made rationally. Current approaches centre around CBA and MCA; however, they have limited consideration of uncertainty or systems effects. More complex methods, specifically targeted at understanding uncertainty and interactions between investments have been created through consideration of other 'decisions under deep uncertainty'; however, no one methodology is currently sufficient to be applied directly. The methods that most closely depict the flexibility of investment pathways are sector specific and limited in their consideration of time or the number of priorities of the investment. Those that consider a larger number investments or their interactions as a system can have a more complete consideration of uncertainty and consider effects more widely, but ignore the pathway interdependencies. If we are to more fully capture the value of infrastructure, we must create a methodology that builds on the strengths of these methods, but is capable of multi-priority long-term assessments and depicting the interactions of investments as part of a pathway while capturing the emergent effects of the system as a whole. Yet the complexity must be constrained if the resulting methodology is usable and maintainable by stakeholders.

We have therefore proposed to build a strategic infrastructure appraisal methodology based on the strengths of each of the methodologies discussed, taking:

- The whole systems understanding of resource constraints from portfolio analysis, to develop possible portfolios of investments;
- An active approach to robustness and an understanding of the sequence of investments from pathways analysis and ROA;

- Timeframes from the pathways analyses; and
- Simple and easy to understand quantification from CBA, but maintaining some segregation of results to reflect both stakeholder perspectives and the uncertainty of the valuations.

Furthermore, we aim to build on two of the analyses, considering the system effects of the investments (portfolio analysis) and the value of system flexibility (ROA). The aim of Chapter 3 will be to develop a methodology for strategic appraisal of infrastructure, based this outline.

3 Developing a Framework and Methodology for Strategic Infrastructure Appraisal

3.1 Introduction

In Chapter 1 we outlined the complexity of infrastructure decisions and, given this complexity, the need for decision-support through appraisal. Reviewing how current infrastructure decisions were appraised, we drew the conclusion that there was a lack a consideration of the system of system interactions. Furthermore, that this oversimplification hides much of the value of infrastructure investments, particularly regarding long-term resilience to change. In Chapter 2 we reviewed the strengths and limitations of both current appraisal methodologies and decisions under deep uncertainty techniques. We concluded that no one methodology can sufficiently capture the pathway and system effects over the long-term, instead proposing that the methodologies be combined and extended to achieve this result.

The aim of the chapter is to fully outline such a methodology, that can complete the two objectives of this research:

- To develop a common appraisal framework that delivers a more complete valuation of infrastructure developments, capturing the multiple stakeholder perspectives and resources required, but also the cross-sector and systems effects created by the system as a whole; and
- To develop a policy level multi-sector decision-support tool focused on ensuring solutions are robust to future change, by considering, how future infrastructure investments are enabled and constrained by the decisions made, the potential total value of the system, and the uncertainty of the results.

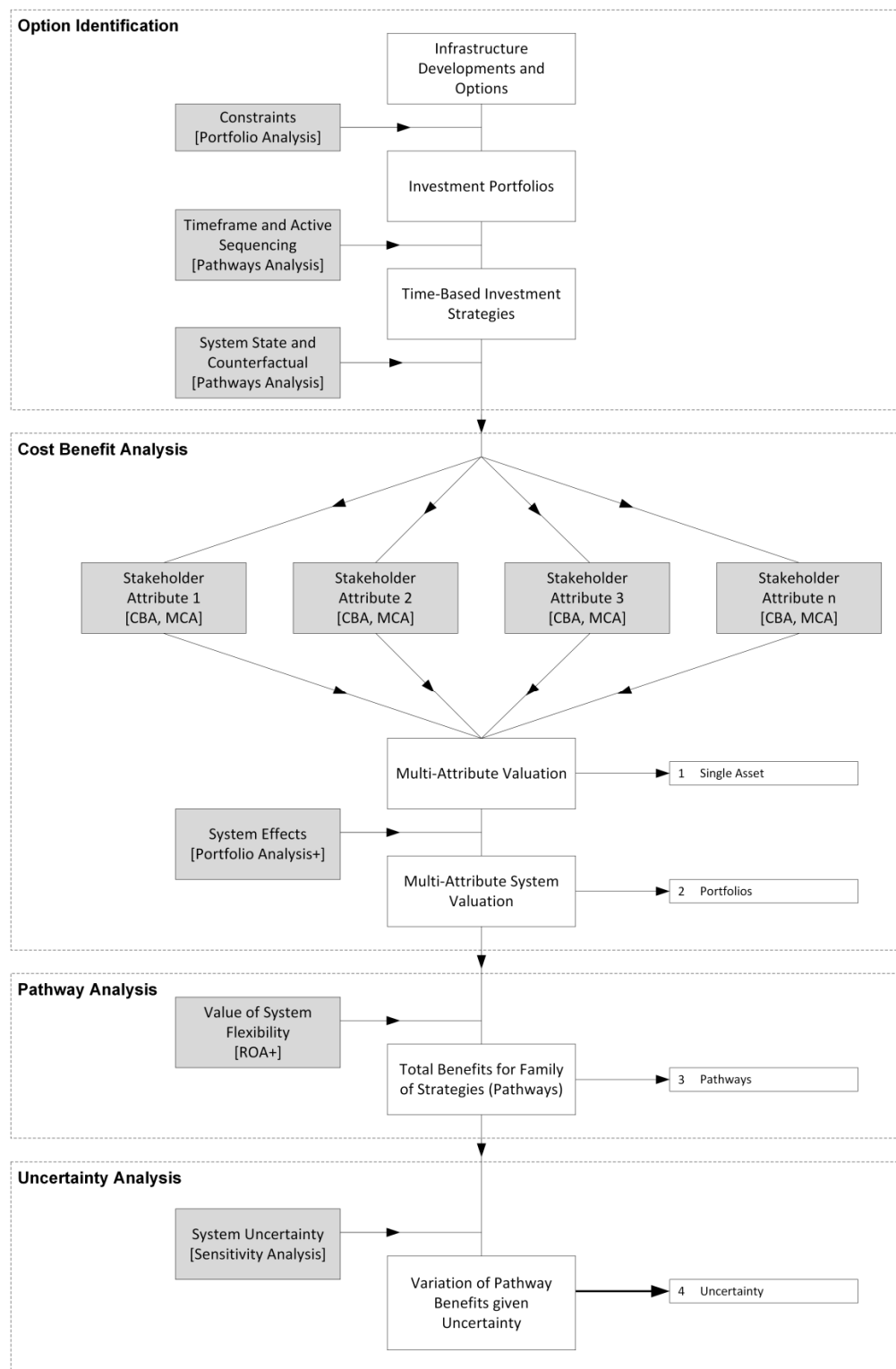
We start by considering the framework necessary for implementing the proactive robustness approach, drawing on the lessons learned in Chapter 1 from the OMEGA project (Dimitriou et al., 2013) and decision making under deep uncertainty frameworks. We split the framework into four stages, outlining each of these in turn. Stage 1 starts with a strategic review of cross-sector objectives, allowing us to define a common set of performance metrics. Stage 2 is the pathway creation stage, used to initially generate potential developments and options before combining these into portfolios, then reducing the resulting decision space by identifying constraints and prerequisites. Stage 3 requires the completion of the strategic appraisal, bringing together the methodologies discussed in Chapter 2. Finally, Stage 4 defines the forward plan for actions and review. Having outlined the framework, we provide a formal definition of the methodology. We review the methodology's benefits and limitations, before identifying the actions necessary to test the framework and therefore the objectives of the next four chapters.

3.2 The strategic infrastructure appraisal framework

In Chapter 2 we proposed a methodology capable of more fully appraising infrastructure as a system of systems, while considering its robustness to deep uncertainty. This is shown in Figure 3.1. We can compare this to the five recommendations derived in Chapter 1 for a more complete systemic and strategic assessment of infrastructure value, specifically that it should:

- Provide a standardised assessment such that investments can be prioritised across sectors;
- Consider developments as cross-sector portfolios such that demand levels are captured and resource constraints are highlighted;
- Consider pathways of developments, the emergent system effects produced and the lock-in/opportunity provided by investments on those to come;

Figure 3.1 – Proposed appraisal methodology and basis for each stage



- Ensure that results convey the deep uncertainty of the decision and where robustness can be improved; and
- Present the results, such that the decision space can be navigated despite the absence of an overarching priority.

Most of the recommendations are included directly; however the wider perspective (the creation of inputs and translation of outputs into useful decision-support) is currently missing.

In its current state, the methodology requires a number of inputs to be supplied to it and, while it provides a number of outputs, it does not suggest how these should be used to drive infrastructure planning. We therefore start this chapter by considering the framework in which our new appraisal will sit. In particular, how this framework must differ from that currently used, what information it must provide to the proposed appraisal method and what it must deliver to enable robust system decision-support.

3.2.1 Existing frameworks

The generalised appraisal framework outlined in Chapter 1 is shown again in Figure 3.2¹.

It takes a ‘predict and provide’ approach² to infrastructure delivery, choosing and implementing the optimal development when measured against a specific set of assumptions and priorities.

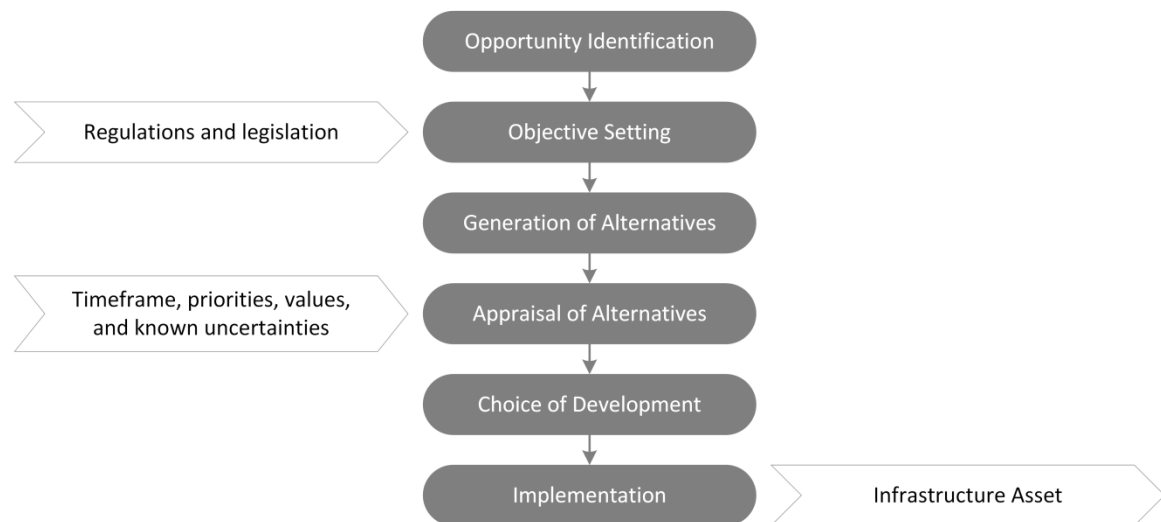
We can strongly correlate this framework with the decision making under deep uncertainty methodologies which take a passive approach to robustness (see Chapter 2). In these cases, the ‘appraisal of alternatives’ stage requires an array of alternative futures and the ‘choice of

¹ See, for example Environment Agency (2013). As noted in Chapter 1, while sometimes shown as a cycle with monitoring and review (see HM Treasury (2003) for general approach, or Sayers et al. (2002) for a specific example), this is often not conducted in practice.

² See Weaver et al. (2013).

development’ is made based on robust satisfying; however, once the most robust development is found, this is implemented and assumed to be a fixed, static choice.

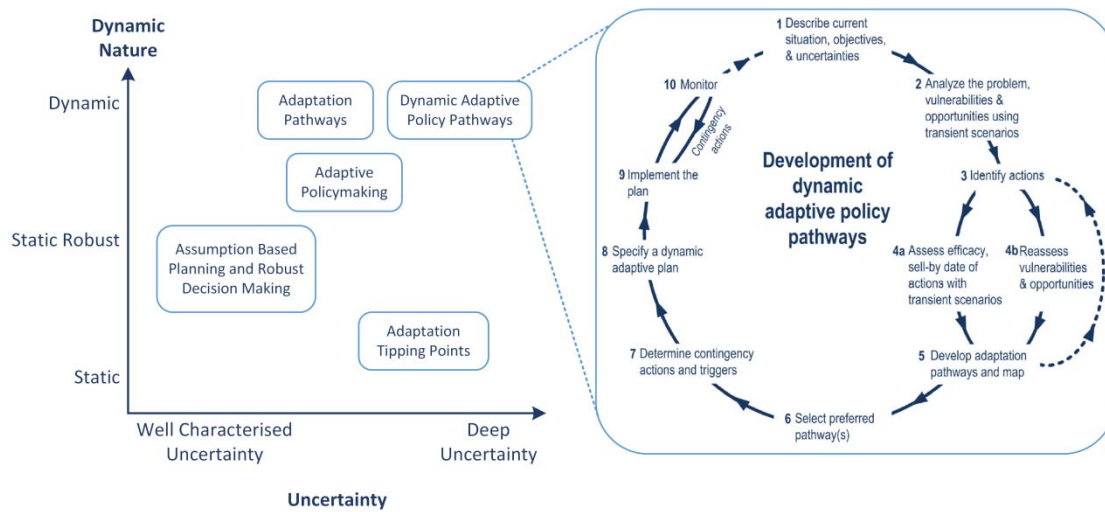
Figure 3.2 – Generalised current appraisal framework



Having chosen to take a systems approach to appraisal and an active approach to robustness, our output will not be a single asset choice, but rather an assessment of the pathways we wish to enable, the flexibility they will provide to meet future uncertainty and the system effects that may emerge. While this pathway will help define the initial investments that should be made (similar to the approach in Figure 3.2), it will also provide a forward plan of developments and a list of assumptions that should be monitored to ensure the plan continues to be appropriate. Our framework must therefore be more akin to the dynamic adaptive planning approaches described by Haasnoot et al. (2013), requiring iterative review of a plan for future actions to ensure their continued progress towards a given strategic vision (see Figure 3.3, for an example). However, unlike climate change adaptation, we must accept this strategic vision may vary from stakeholder to stakeholder, without an over-riding priority³. We must therefore open up the focus of the framework beyond that of a single sector or priority, looking more widely for our alternatives, priorities and impacts.

³ Such as maximum sea level rise, or availability of environmental resources (see Chapter 2).

Figure 3.3 – Dynamic adaptation policy pathways framework (adapted from Walker et al. (2013))



3.2.2 Building a new framework for strategic infrastructure appraisal

Considering first the inputs to the appraisal process (see Figure 3.1), we can determine four factors that our framework must define:

- The infrastructure developments and options to be considered;
- Constraints that can limit the decision space of these developments;
- The future system state and dynamic development background; and
- A common set of assumptions and performance metrics.

If we return to the five Chapter 1 recommendations, one issue relates directly to these inputs, that: investments should be considered and prioritised across sectors. Applying this recommendation to the four inputs, each must have a whole system focus, therefore our appraisal framework we must consider:

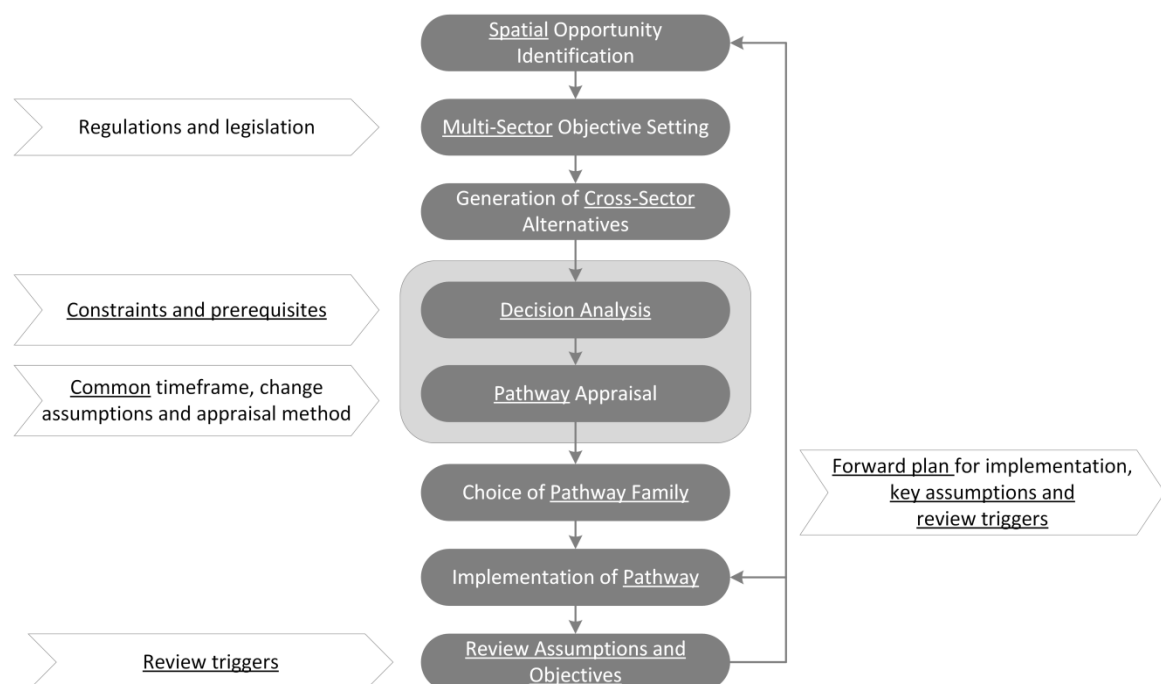
- Opportunities over the *whole system*;
- Potential developments *from all sectors* and whether they can be combined;

- What *system* developments and environmental changes will occur; and
- How cost and benefit can be *measured in a standard way* while representing differing perspectives on the purpose of the infrastructure investments.

If we next consider the outputs of the appraisal, again one of our five recommendations relates directly, that: results should allow the decision space to be navigated despite the absence of an overarching priority. This suggests that our framework must include the iterative review process seen in the dynamic adaptive planning frameworks, allowing decisions to be adapted over time as uncertainty is diminished. Our appraisal framework must therefore indicate how these reviews will take place and the resulting actions from them.

Taking these inputs and outputs into account, we must make a number of changes to the standard appraisal framework. This adapted framework is shown in Figure 3.4, with changes underlined and the appraisal methodology highlighted in light grey.

Figure 3.4 – Proposed strategic appraisal framework for infrastructure (adapted from Young and Hall (2014))



We can divide this framework into four stages:

- Stage 1 - Strategic review: The identification of cross-sectoral opportunities and objectives to create a common language for the analysis;
- Stage 2 - Pathway creation: Generation of potential developments and application of interdependencies (constraints and prerequisites) to reduce the decision space for the appraisal;
- Stage 3 - Analysis: The multi-attribute cost benefit analysis (CBA) proposed in Chapter 2 (see Figure 3.1), combining welfare economics, with a mixed portfolios, pathways and options analysis methodology; and
- Stage 4 - Review: Active testing of assumptions, objectives and the planned decision pathway as uncertainty diminishes.

We will consider each of these stages in turn over the next four sections to further define the framework and methodology.

3.3 Stage 1: Strategic review

For the current sector specific appraisals, opportunities may simply be identified by looking for areas where performance has deteriorated over time, creating a notable reduction in service provision⁴, or where service provision is lower than elsewhere in the country⁵. However, for a cross-sector strategic review, there may be hundreds of such opportunities and given the interdependency of the infrastructure networks, potential solutions could be found in any of the

⁴ Or where this service deterioration is likely to occur in the near future, for example due to increasing demand or existing assets being decommissioned.

⁵ A recent example is the Lower Thames Crossing which is being considered due to congestion on the existing Thames crossings and to provide greater connectivity in eastern London (Carhart, 2014).

sectors. We must therefore focus the analysis. We do this in two stages, firstly by limiting the scope of the assessment and secondly by considering the strategic objectives of the infrastructure from a policy maker's perspective.

For the sector specific analyses, the scope of possible opportunities is primarily limited by the remit of the sector. National priorities such as reduced emissions and pollution, will be met by different proposals in each sector, for example investment into cycle routes or electric vehicles in the transport sector, a switch to renewables in the energy sector, increasing quality standards for water treatment, or recycling schemes for waste. However, as we have noted in Chapter 1, a siloed sector approach can undermine the schemes. For example, increasing water quality standards and a movement to electric vehicles would both significantly increase demands for electricity, meanwhile a move to renewables would make electricity generation intermittent. To ensure we maintain this system perspective, we instead propose to limit the scope of opportunities and solutions spatially. This spatial scale must be set at sufficient resolution to allow changes to be perceived⁶, without overly restricting the number of potential developments to be considered. We therefore propose a regional perspective. This has resonance for the UK case where there has been an increasing realisation of the importance of cities and a push for their devolution and autonomy. Furthermore, the UK is already regionally divided into 'Local Authorities', whose role includes managing the publically owned infrastructure services and approving or rejecting planning applications. They therefore have a level of control, a knowledge of some of the current infrastructure operations and an interest in ensuring long-term service delivery.

⁶ Oswald et al. (2011) notes the problems of considering even large regional projects from a national perspective.

Having reduced the scope of our analysis, we next consider the system-wide strategic objectives of infrastructure and focus on the opportunities to deliver these objectives. However, defining a set of common objectives for our five infrastructure sectors, will not be straightforward. As we noted in Chapter 1, the perceived ‘purpose’ of infrastructure varies from stakeholder to stakeholder, depending on whether they are investing in it, using it or just experiencing its impacts. Taking our policy maker’s perspective, it will be important to reflect all these viewpoints when decision making. In the remainder of this section we therefore consider what the system-wide strategic objectives of infrastructure are from a policy-maker’s perspective and how these can be brought together in a ‘standardised assessment’.

3.3.1 Moving from objectives to performance

If we are to discern whether a development has the potential to deliver on strategic objectives, we must first define those objectives as they relate to infrastructure. Here, if we take Hall et al.’s definition of performance i.e. ‘those aspects of system behaviour that are relevant to meeting objectives’ (Hall et al., 2004, p56), we realise that we must define the performance we wish our system to achieve, or at least, which aspects we believe are significant strategically. However, it is important that we note a number of complications in the conversion from objectives to performance. We can summarise these as:

- Alternate and changing viewpoints;
- Abstract concepts and contradicting approaches;
- Causality of indirect impacts and system effects; and
- Standardisation across sectors.

We have already considered the first of these in our first two chapters; that stakeholders have different viewpoints, that these may change over the lifetime of the asset, and that they may be contradictory. However, even where our actors agree on objectives, they can often be abstract concepts such as ‘security’ or ‘connectivity’ (Stern, 2006a) which can be measured in a number of ways, some of which will give very different results. For example, Doganis’ (1992) review of US domestic air passenger capacity and demand from 1971 to 1986 showed that passenger increases from 1971 to 1982 were met by higher load factors and increased aircraft size while those from 1982 to 1986 were met almost entirely by increasing the number of departures. Both methods created the desired effect (increasing capacity to meet demand); however, our specific performance criteria will determine how we perceive these changes. We review these perceptions in Table 3.1: one metric suggests performance increases throughout the period, one shows a partial increase and the third suggests performance remains static.

Table 3.1 – Dependence between performance characteristics and noted results

Performance Characteristic	Noted Result
Number of departures	Performance increased only in the latter part of the study; capacity increases due to higher load factors/larger aircraft not recognised
Total passengers served	Performance increased throughout the study; however, dependant on and proportional to demand, despite capacity available
Demand met	Performance relatively constant despite significant increases in passenger demand and a varying rate of change of demand over time

In some cases, methods to improve performance can be contradictory, for example, in the waste sector, two ways we can reduce waste to landfill are by increasing reusability, or through improving waste management and recycling rates (see Ugwu et al. (2006)). However, by increasing one of these methods we reduce the other. We must therefore ensure our designated performance criteria capture the effects of all methods without unintentionally prioritising one form over another. We must concentrate on the desired final effect and understand any limitations of our performance criteria.

Once we move away from the direct effects and sector specific assessments, causality can also become difficult to ascertain. Glaeser gives the example of poverty rates in American cities, which generally increase in locations where new rapid-transit stops have been built (Glaeser, 2011). The causality is not obvious, it is unlikely that rapid-transit stops cause poverty; however, their proximity could be negatively impacting on house prices, or could be positively attracting those for whom car travel is unaffordable. Again we must be careful of our performance criteria: in the former case the effects are negative, a hedonic price approach (see Chapter 2) would suggest that welfare had decreased, perhaps due to increased noise or reduced safety; whereas, in the latter case, welfare may have improved, with increased accessibility and/or connectivity.

When we consider the system as a whole, effects become even more difficult to attribute, manifesting from the interactions of multiple investments. One of the benefits of our pathway approach to appraisal is that we do not need to disaggregate these effects between the constituent developments, instead acknowledging that they are a property of the system (or pathway) as a whole. However, it necessitates standardisation across sectors which may have previously used very different timeframes and scales of analysis. For example, a failure in the electricity network will be felt more keenly and recognised far more quickly than a similar failure in the waste network. Users are thus likely to want energy reliability objectives to be measured at a higher temporal resolution than those in the waste sector. This presents another trade-off of the analysis. While annual or monthly figures dilute daily or hourly fluctuations that may be helpful for decision making, the data volume and demand of the latter may be restrictive (de Neufville and Scholtes, 2011). When recording performance we may therefore need to allow some flexibility to reflect the differences between the sectors and consider the computational expense we are creating.

Reviewing these complexities, our regional focus and multi-attribute pathways approach inherently requires standardisation and will allow us to capture multiple viewpoints while avoiding attribution. However, as we progress to considering how the performance changes could be measured within an appraisal framework, we must maintain a focus on high level end effects, preserving some flexibility for differences between the sectors, while considering the complexity of the analysis as a whole.

3.3.2 Defining infrastructure performance: Performance metrics

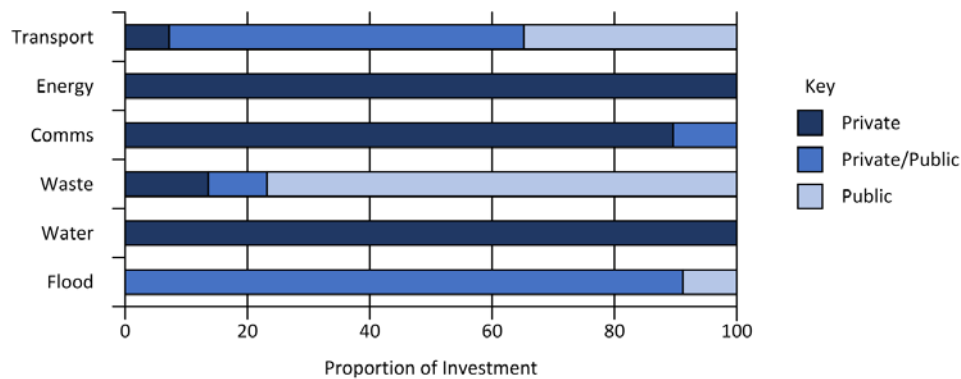
Measures of performance or ‘performance metrics’ are used for two main purposes:

- For decision making (assessment of alternative actions and strategies, evaluations of financing for capital projects and changes in public policy); or
- For monitoring and evaluation (measuring technical progress and ranking against competitors).

The first of these reflects our perspective and, indeed, many studies consider this the most important role of performance metrics (see, for example, Hermans et al. (2009), or Gillen and Lall (1997)). However, we must also remember the second purpose as this can also create value. For example, the UK’s ranking in the European Commission’s Eurostats or in the World Economic Forum’s Global Competitiveness Report, may affect future investment in the country. Such investments will affect whether developments can be funded privately, a priority for the UK given its aim for achieving high private investment (see Figure 3.5). While this is not directly relevant to the welfare of the population, it will still be of interest to policy makers. In Section 3.3.3 we return to such alternative perspectives, considering the current metrics used in

governance, industry and academia. However, we first consider the characteristics necessary for strategic appraisal performance metrics.

Figure 3.5 – Planned Public and Private Investment in UK Infrastructure (Infrastructure UK, 2011)



Reviewing the literature of infrastructure performance assessment⁷ we can derive a number of lessons learned for our strategic decision making perspective. In particular, this narrative focuses on:

- The use of multiple objectives;
- The ability of metrics to reflect actual performance; and
- The temporal stability of metrics, such that the historical information continues to inform decisions in the future.

We consider each of these in turn.

As we discussed in Chapter 2, the presence of multiple perspectives promotes the use of multi-criteria approaches, but such approaches are often seen as opaque and easily biased. These concerns are echoed in the performance metric literature, requiring any applied weightings and

⁷ Section 3.3.3 includes a full list of the studies reviewed, but particular conclusions are drawn from Ugwu et al. (2006); Lambert et al. (2013), Bhargava et al. (1994) and Rogers and Duffy (2012).

assumed interactions to be understood and well communicated (Marshall, 2013b). However, this is further complicated by our need to measure abstract performance criteria, particularly if composite indicators, combining several performance metrics⁸ are used to quantify these criteria. These composite indicators can condense complex information making it easier to present (Morrissey et al., 2012). However, they also add a second tier of weightings and make both the methods and the results more opaque to stakeholders. Ugwu et al. (2006) and Lambert et al. (2013) note the importance of stakeholder's being able to understand the metrics, with Lambert et al. specifically recommending outputs be compared against known levels of performance or disruption to aid stakeholder comprehension of the results.

The alternative to composite indicators is to use proxy measures for our abstract performance criteria. However, this presents problems as well. For example, road congestion causes significant pollution and therefore could be used to indicate emission levels; however, removing congestion will also remove disincentives for travelling on that road, which in turn is likely to increase traffic increasing emissions again (see Marshall (2013b)). Proxy metrics therefore require us to consider the system effects more fully. Furthermore, such metrics may be useful for indicating a number of performance criteria, see Hall et al. (2004); however, by allowing them to be used more than once we increase the probability of double counting. Where we recognise that they should only be included once, we must make a judgement about their relative importance for each of the performance criteria they represent, again introducing the opportunity for bias.

Finally we must consider the longevity of the performance metrics and our ability to record them, particularly given the decadal life of infrastructure assets (Bhargava et al., 1994). Performance criteria may change over this time period, so we must strive for metrics that will

⁸ See for example Lopez's measure of the 'cohesive' effects of transport projects (López et al., 2008).

continue to be recordable, but are also fundamental to operation, such that even if criteria change over time, we still have a useful historic data source, that is either directly relevant or can perhaps be used as a proxy indicator. Furthermore, if we are reliant on others for the data collection, that these data sources are likely to continue to be available for the lifetime of the investment.

Adding the recommendations above to our concerns from Section 3.3.1 we can determine a full list of recommendations for our performance metrics from a strategic decision making perspective. These are that metrics should be:

- A reflection of the multiple viewpoints of the stakeholders;
- Understandable and useable by the community of stakeholders;
- Quantifiable but relevant (to the performance/objective being measured);
- Focused on high level, mutually exclusive, end effects;
- Standardised, but with some flexibility across the sectors;
- Appropriate to the temporal and spatial scales of the developments; and
- Suitable for the lifetime of the infrastructure and calculated from data that will be consistently available.

Having derived this list we now review the infrastructure performance assessment literature to determine the metrics most commonly used and those which most strongly reflect the foci of our assessment, namely the UK policy maker's perspective.

3.3.3 Review of current infrastructure performance metrics

We consider three sources of literature: international guidance and best practice, UK guidance and current practice, and academic studies. International guidance and best practice includes measures from the European Commission's 'Eurostats' (European statistics) for the infrastructure sectors, the World Economic Forum's 'Global competitiveness report', the World Bank's 'Handbook for evaluating infrastructure regulatory systems' and the OECD's 2011 review into transport project appraisal. The UK guidance and current practice includes measures from Infrastructure UK's 'National Infrastructure Plan', HM Treasury's 'Supplementary guidance to the Green Book: Valuing infrastructure spend', current programmes such as the Thames Estuary 2100 project and sector specific current practice. The academic studies were found through a keyword database search on the word 'infrastructure' and any of the terms 'performance metric', 'performance indicator' 'performance measure' or KPI. The returned list was then reviewed to find those papers of relevance to the five infrastructure sectors considered within this research and which undertook some form of performance appraisal as part of the work. A full list of the studies considered for each of the three literature sets is shown in Table 3.2.

Table 3.2 – Infrastructure performance studies considered in literature review

Literature	References
International Guidance and Best Practice	• Global competitiveness report (Schwab, 2012) • Eurostat – energy, ICT, transport (European Commission, 2012a; 2012b; 2012c) • Handbook for evaluating infrastructure regulatory systems (Stern, 2006b) • Improving the practice of transport project appraisal (OECD, 2011)
UK Guidance and Current Practice	• National Infrastructure Plan (Infrastructure UK, 2011) • Green Book Supplementary Guidance (HM Treasury, 2011) • Sector guidance – transport, water (Department for Transport, 2011a; Halcrow Group Limited, 2013; Passenger Focus, 2012; Southern Water, 2013; Ofwat, 2008) • Programmes (Airports Commission, 2014a; Airports Commission, 2014b; Environment Agency, 2009)

Literature	References
Academic Studies	• Energy – policy in England, Scotland, Wales (Stagl, 2006) • ICT – general, routing, surveillance, wireless networks, WSN (Bharadwaj, 2000; Chung et al., 2005; Jyoti and Soni, 2013; Zaréa et al., 2013; McLoughlin and Prakash, 2013; Çalhan and Çeken, 2013; Alhadidi et al., 2013; Mamun, 2012) • Transport – general, airports, cohesion, liveability, ports, road, sustainability (Marshall, 2013b)(Oswald et al., 2011; Schroeder and Lambert, 2011; Gillen and Lall, 1997; López et al., 2008; Marshall, 2013b; Pallis and Syriopoulos, 2007; Hermans et al., 2009; Lambert et al., 2013) • Water – supply, coastal management (Hall et al., 2004; Marques et al., 2013; Roca et al., 2008) • Other – construction, marketing, sustainability (Sebastian et al., 2013; Bhargava et al., 1994; Fernández-Sánchez and Rodríguez-López, 2010; Ugwu et al., 2006; Ugwu and Haupt, 2007; Van Den Bergh et al., 2001)

Once identified from the literature, the metrics were translated into general cross-sector metrics by removing any sector specificity in their description, for example ‘total household energy consumption’ would become ‘demand’. However, where specification was not due to the sector (for example, carbon dioxide emissions rather than air pollution), the granularity was maintained. This review resulted in 78 cross-sector metrics. The metrics were then further grouped into attributes to form the basis of the multi-attribute CBA approach. Drawing on the conclusions of Chapter 1 and 2, the purpose of these attributes were two-fold. Firstly, to represent different stakeholder viewpoints, avoiding the need to make assumptions about trade-off preferences between attributes. Secondly, to segregate metrics requiring shadow pricing techniques from those with a current market value, avoiding the aggregation of values with large differences in certainty and allowing the decision maker to draw their own conclusions regarding the value of trade-offs.

The groups were initially defined using the ‘three pillars’ (United Nations General Assembly, 2005) or ‘triple bottom line’ (Elkington, 1997) of sustainable development, splitting metrics into economic (referred to herein as ‘monetary’ to segregate from factors which provide ‘economic’ benefit through increases in welfare), environmental and social attributes. This approach separates the market factors and the investor perspective (monetary attribute) from the metrics

requiring shadow pricing techniques and the perspective of the general population (environmental and social attributes). However, it does not differentiate between those who use the development and those who merely experience its externalities. It therefore ignores an important set of stakeholders for infrastructure developments. To capture this set of stakeholders, we adopt Rogers and Duffy's (2012) segregation of the infrastructure appraisal approach, including a fourth category for the technical (designed or engineering) aspects of the investment, referred to herein as 'service'. Service is not a 'pillar' in its own right but rather draws on the other three pillars, for example water and waste services could be classified as environmental, while accessibility could be classified as social. Some metrics could therefore belong more than one attribute. Given our wish to present the 'user' stakeholder perspective, we have assigned any costs and benefits that occur due to direct use of the infrastructure to the service attribute. Table 3.3 lists the 78 cross-sector metrics and their designated attributes. Table 3.4 shows the distribution of metrics between the four attributes for each of the three literature sets.

Table 3.3 – Attributes and constituent cross-sector performance metrics

Monetary	Social
Amalgamated economic benefits	Amalgamated social benefits
Capital cost	British inputs
Cost efficiency and ratios of costs	Community
Employment/Training	Crime
Financial resilience	Equity
Investment (types, market, subsidies available)	Health (disease)
Life Cycle Cost/Whole Life Cost	Quality of Life
Losses/Debt/Fines	Safety (accidents/injuries)
Market ranking/share	Security
Operational costs	Social standards met
Price (rate of return and affordability)	Toxic materials
R&D	
Relationship to GDP or economy	Service
Remaining value/Salvage/Redevelopment	Accessibility/Connectivity
Stock market performance	Additional facilities
Tariffs/Service market	Aggregated service benefit
Tax/Government revenue	Ambience

Environmental	Service (Continued)
Air quality Amalgamated environmental cost/benefit Biodiversity Carbon dioxide emissions Community/Townscape Ecosystems/Habitats Environmental inputs eg rainfall Environmental management Environmental standards met Heritage Landscape/Land use/Visual amenity Noise Pollution (General) Renewable energy percentage/production/consumption Resilience to climate change Sustainability of resources/consumption Use of public transport Vibration Waste Water quality	Availability Capacity/Production/Quantity Choice/Competition Cohesion Condition/Integrity/Cleanliness Demand/Utilisation Disruption/Losses/Resilience Ease/Risk of deployment Flexibility Frequency Information provision Innovation Lifetime Measurability Mobility Quality of service Reliability/Delay Reuseability Scalability Service efficiency Storage Time/Speed of service Waste management
Other	
Long-term planning/management; Engagement, and 'Other' (Useful by-products; Project declaration of general interest; Barrier effect of the project; Respect for local customs; and Type of contract)	

Table 3.4 – Recorded metrics for international, UK and academic literature reviews

Attribute	Instances of Metrics (Percentage of Total)			
	International	UK	Academic	Total
Environmental	18 (13%)	58 (18%)	59 (18%)	135 (17%)
Monetary	43 (32%)	54 (17%)	68 (20%)	165 (21%)
Social	8 (6%)	21 (6%)	50 (15%)	79 (10%)
Service	66 (49%)	183 (56%)	140 (42%)	389 (50%)
Other	0 (0%)	8 (2%)	17 (5%)	25 (3%)
Total	135	324	334	785

As can be seen from Table 3.4, very few metrics did not fit into one of the main four attributes, with the 'other' attribute representing only 3 per cent of the total metrics captured, varying from zero per cent in the case of the international studies to 5 per cent in the case of the academic literature. Furthermore, as detailed in Table 3.3, most of these 'other' metrics are not quantifiable, noting a discrete alternative (such as the type of contract) or a qualified statement (such as the level of engagement). As there are only a small number of these 'other' metrics and

their appropriateness for a CBA is limited, our strategic assessment will concentrate on the main four attributes identified.

The social attribute is the smallest, with only 11 cross-sector metrics (Table 3.3) and 6 per cent of the recorded instances in both the international and UK studies (Table 3.4). The result is significantly higher for academic studies, with 15 per cent of instances, but it still represents the smallest attribute. In all cases, 'safety (accidents/injuries)' is the most frequently occurring metric, representing approximately half of all social metrics recorded. 'Security' and 'equity' are also in the top five for all three studies. With the exception of 'health' and 'social standards met', the remainder of the metrics record a maximum of 2 occurrences in any literature set, suggesting they are of limited general interest. 'Health' and 'social standards met' record 9 and 7 metrics respectively, but all 9 of the former and 5 of the latter are in the academic literature set suggesting that these could be focused studies.

While the environment attribute has the second largest number of cross-sector metrics, it is the second smallest attribute in terms of recorded instances, with only 13 per cent for the international studies and 18 per cent for the UK and academic studies. All studies have 'ecosystems/habitats', 'landscape/land use/visual amenity' and 'water quality' in their top five most frequently recorded metrics. 'Air quality' is also quite frequently recorded, being one of the top five metrics when all three studies are totalled as well as in the top five for both the international and UK cases. The low number of recorded results compared to the large number of metrics, along with the use of amalgamated metrics, dilutes much of the remainder of the results; however specific concerns are visible. For example, 33 per cent of the international metrics are focused on renewables, 17 per cent of the UK metrics are focused on carbon dioxide emissions and 14 per cent of the academic metrics are focused on sustainability of resources, but, in each case, low numbers are recorded in the other two categories. While the

‘ecosystems/habitats’ metric receives the highest total results, ‘biodiversity’, which could be assumed to be similar, receives far fewer (8 compared to 22 recorded occurrences). This could be because of the difficulty in recording wildlife stocks and understanding their decline patterns, as highlighted by the UK National Ecosystem Assessment (Bateman et al., 2011).

The monetary attribute has less metrics (17 compared to 20 for environment), but averages 21 per cent of the total metrics recorded. While studies of infrastructure companies have shown a reliance on financial metrics alone⁹, this has clearly not translated into academic or UK current practice, with only 20 and 17 per cent of the occurrences respectively. The international study, however, shows a greater focus on this attribute with 32 per cent of the metrics recorded.

‘Price (rate of return and affordability)’ and ‘life cycle cost/whole life cost’ rank highly in all three studies with two other cost metrics (‘cost efficiency’ and ‘operational costs’) ranking in the top five overall. The international and UK studies also show a focus on macro-economic and investment concerns with ‘relationship to GDP or economy’ being ranked first and second, and the ‘investments (types, market, subsidies available)’ metric being in their top five.

The service attribute is the largest for all three studies with 27 cross-sector metrics and 42-56 per cent of the total metrics recorded. While the ‘demand’ metric shows the most use over all, its use is dependent on the literature set, ranging from most used for international to only seventh most used for academic studies. ‘Capacity’ and ‘accessibility/connectivity’ are also seen as important, being among the joint most commonly used metrics for both the UK and academic studies, and deriving second and third rankings from the international perspective respectively. The use of capacity and demand varies between studies, with some considering totals separately and others combining the metrics to look at the capacity utilised or the ‘headroom’¹⁰ remaining.

⁹ See, for example, Bhargava et al. (1994) for ICT and Gillen and Lall (1997) for airports.

¹⁰ Non-utilised capacity.

A difficulty is highlighted in recording such metrics, namely that the provision of additional capacity can provide a service in a number of ways¹¹, or not provide any service (if it is unnecessary). It therefore not only requires an understanding of whether the capacity is useful, but also several methods to capture this use. Use of the remaining metrics is spread between the studies; however the UK shows a strong focus on ‘disruption/losses/resilience’, ranking this equally with ‘capacity’ and ‘accessibility’, with sufficient use to give it fourth place when the metrics are totalled despite lower rankings (fifth and eighth) in the other two studies.

Summarising our analysis above, the most widely used metrics in our studies are shown in Table 3.5. We therefore consider these as a baseline of metrics for our analysis.

Table 3.5 – Infrastructure performance metrics most commonly used in previous studies and guidance

Attribute	Most Common Metrics
Environmental	Habitats, landscape, water quality and air quality
Monetary	Cost, rate of return (revenues)
Social	Safety, security and equity
Service	Demand, capacity and accessibility

Equity and accessibility require a spatial understanding. This will not be possible with the appraisal methodology proposed thus far; however, we will return to such attributes in Chapter 8 when we consider incorporating spatial models within the analysis.

As we have noted above, the relationship between capacity and demand can be measured in a number of ways and it would be useful to disaggregate benefits, we can therefore convert the these two metrics to ‘utilised capacity’, ‘reliability’ and ‘protection’ in the case of failures or extreme events. This captures benefits from normal operations and those from infrastructure

¹¹ Allowing for greater numbers of users, greater usage by existing users, providing a more reliable service quality or more resilience in the face of extreme conditions.

assets which provide protection against failures or extreme events (such as flood barriers). This latter factor was noted to be of particular importance to the UK ('disruption/loss/resilience').

We also choose to incorporate the other two UK specific concerns that were brought out by the analysis; including carbon dioxide emissions within the environment attribute, and the wider economy (through including changes to tax income and employment) in the monetary attribute.

Finally, while the metrics capture most of the environmental footprint of infrastructure, noise externalities are currently missing. Noise nuisance is particularly relevant to transport infrastructure¹² and is included within their standard appraisal process (Department for Transport, 2011a), but has also created opposition to energy generation projects such as wind turbines. While the noise effects of assets in the other sectors are limited (perhaps explaining why the metric was not one of the most used in our analysis), we will include noise within our appraisal under the environmental attribute, to allow effects for transport and energy infrastructure to be captured. We therefore propose the 15 metrics and 4 attributes in Table 3.6 for our appraisal methodology, but will re-review the completeness of this list in comparison to our case study in Chapter 5.

Table 3.6 – Attributes and metrics to be used within the strategic infrastructure appraisal methodology

Attribute	Infrastructure Performance Metrics
Environmental	Habitats, landscape, water quality, air quality, carbon dioxide emissions and noise
Monetary	Cost, revenues, tax and employment
Social	Safety and security
Service	Capacity utilised, reliability and protection

Comparing the list in Table 3.6 against the recommendations derived at the end of Section 3.3.2 we can see that proposed metrics appear to have addressed all suggestions. By maintaining

¹² Studies show that noise represents approximately 75 per cent of total environmental cost of transport infrastructure developments (see OECD (2010) and Schipper (2004)).

segregation of the results and including the service attribute, the results will present multiple stakeholder viewpoints. Furthermore, by using commonly applied metrics, the results should be understandable by these stakeholder groups and sustainable over the long-term. Each metric is applicable across all sectors but offers some flexibility in how they are recorded temporally and spatially. They are all quantifiable and directly relevant to the attributes, but address different facets, suggesting that they are mutually exclusive (although, again, we will return to this when we assess how they are quantified in Chapter 5). Finally they are focused on end effects that are applicable at the national (UK) and international level as well as being applied in the more specialised academic studies. We must remember, however, that some of our metrics were almost entirely derived from UK studies and therefore the approach may not be appropriate for other countries or from an international perspective. Furthermore, we have focused on strategic high-level effects; therefore, further analysis will be necessary to fully evaluate individual assets. This is entirely in line with the proposed scope of this research outlined in Chapter 1, where we stated that our appraisal would form a link between the international and sector/asset specific assessments, but was not intended to be a replacement for either.

3.4 Stage 2: Pathway creation

Having restricted our analysis to a Local Authority spatial region and the set of 15 system-wide performance metrics, we can start to review the different ways these objectives could be met within this spatial area. We have noted that, given the interdependence of infrastructure networks, this review must consider all five infrastructure sectors if we wish to develop a full list of potential infrastructure development opportunities. However, given that we wish to consider development pathways, we must look past the individual assets and, building on climate change pathway and portfolio analyses in Chapter 2, consider how each development enables or restricts future infrastructure investments. We must therefore review which constraints will

cause developments to become mutually exclusive and allow our decision space of potential assets and portfolios to be narrowed.

3.4.1 Creation of options

First we must define a full list of potential infrastructure developments within our spatial region.

Keeney (1992) suggests there are two ways to undertake such an analysis: an ‘alternative-focused’ approach and a ‘value-focused’ approach. While Keeney favours the latter, there is merit in both methods. The ‘alternative-focused’ approach starts with what is readily available.

In the case of infrastructure in the UK, a wealth of information already exists in the country, regional and sector specific strategic plans and in the planning applications made to the local authorities. Furthermore, infrastructure owners and operators may have already considered the future flexibility of their assets and included provisions for future development. While these may not be contained within sector specific plans, it is likely they could be captured through engagement of these stakeholders. Lastly, drawing on stakeholder experience of previous developments elsewhere may offer some valuable alternatives.

‘Value-focused’ thinking starts with the desired priorities or traits of the outputs of a decision and works backwards from this point. It presents a less constrained environment for thinking of alternatives and avoids biasing the results towards the more memorable, previously considered alternatives¹³. Engaging stakeholders collectively with the objectives identified in Section 3.3.3 provides the opportunity for more unusual and collaborative projects to be proposed and allows the consideration of potentially useful (and cross-sectoral) real options on the proposed projects.

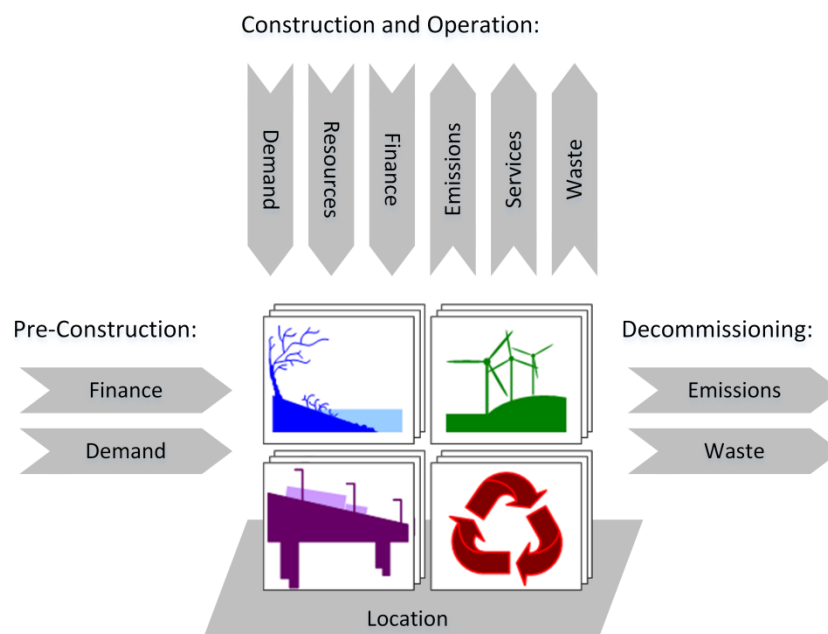
¹³ See ‘availability’ and ‘anchoring’ biases in decision analysis literature.

The ‘creation of options’ process should therefore include a literature review of strategic plans, individual interviews with asset owners and operators and a cross-sectoral stakeholder engagement and brainstorming exercise.

3.4.2 Determining pathway constraints and prerequisites

Once a full list of developments has been generated, we must consider whether, and how, they can be combined into full development paths. For each asset we must therefore determine the essential elements for its construction and operation and which other developments are needed to enable this (prerequisites), or could create a barrier to it (constraints). Our first step is to consider the system model of an infrastructure asset (see Figure 3.6).

Figure 3.6 – Simple system model for infrastructure



For an infrastructure development to be viable it needs a suitable location and a business case that encourages investment, that is, one where benefits are sufficient to justify the costs. For private investments this ‘benefit’ will manifest as suitable revenues and for public investments, a sufficient increase in welfare. In both cases, we can translate this business case into having

sufficient financing to afford the investment and demand to justify it. During construction and operation of the asset, further financing will be necessary, but other input resources will also be needed. These may be outputs from other infrastructure assets (for example electricity), resources for processes (for example, construction materials or replacement parts for equipment repair), or could be suitably skilled staff to operate the asset. A loss of any one of these fundamental resources will stop the asset from being built or operated. Considering the outputs of the system model, the asset must be able to operate (and be decommissioned) within legislated requirements. The outputs must therefore conform to national emission/impact targets and restrictions. Furthermore, it must do so when the sum of existing system emissions/impacts are taken into account. Assets with the same impacts therefore have the potential to constrain each other's development.

From the above we can identify four key resources that are applicable across the infrastructure sectors and must be considered within our appraisal methodology (see Table 3.7). The spatial and operational constraints apply to each development as it is implemented, while the financial and impact constraints apply to the pathway as a whole. We can therefore apply the spatial and operational constraints to reduce our potential asset and portfolio decision space, while we must apply the financial and impact constraints at the end of the pathway analysis stage.

Table 3.7 – Cross-sector constraints

Interdependence	Resource Limitation
Spatial	Geographical location and access
Operational	Functional resource such as electricity, or skills
Financial	Funding available and revenue realisable
Impact	Outputs such as emissions, noise or habitat loss

Of all the portfolios developed, one should be identified that describes the currently proposed (or approved) set of developments. This will form our counterfactual case for the pathway analysis (referred to herein as the 'do minimum' case). The constraints in Table 3.7, present a

first pass check of this portfolio, ensuring that the system resources needed for its development are plausible.

3.5 Stage 3: Analysis

Having narrowed the list of potential developments and portfolios, we can implement the appraisal methodology proposed in Chapter 2. Returning to Figure 3.1, we must first complete the 'option identification' phase. We must therefore set the portfolios developed in Stage 2 against time. To do this, we determine all possible implementation strategies for each portfolio, deriving the sequencing and grouping of implementation using the constraints and prerequisites derived in Stage 2. Next, we set these against a future timeline, taking account of the necessary construction time for each development and the 'implementation policy', that is, the earliest start date considered and the delay between implementation groups. We model each of these time-based investment portfolios ('development pathways') using common assumptions and socio-economic conditions to ensure they are comparable.

Next we must consider if there are developments that will occur in parallel or in preference to our development pathway. We can do this by comparing the development pathway to the 'do minimum' pathway. The 'do minimum' pathway represents the currently proposed investment pathway; therefore, if no countermanding action is taken, it is assumed this pathway will go ahead. Some elements of this pathway may complement, or may not affect the investments within development pathway, these can be assumed to go ahead as parallel projects. However, other elements may be mutually exclusive, negating the benefits, or somehow constraining the development pathway. Where such elements occur we must choose which set of investments go ahead, those in the 'do minimum' pathway, or those in the development pathway. Herein, we will assume that the assets which are implemented first are given priority. The result of this

process is therefore a final set of time-based 'strategies', each set against a pathway dependent baseline of developments derived from the 'do minimum' set of infrastructure investments¹⁴.

Once the strategies are modelled we can conduct the multi-attribute cost benefit analysis. We value the investment strategies against the fifteen performance metrics derived in Section 3.3.3, aggregating these effects into the four attributes¹⁵. We then subtract the benefits of the 'do minimum' pathway to find the net costs or benefits for each attribute. Strategies with only one asset produce results equivalent to current infrastructure appraisal, but by using the common appraisal method, allow comparison and prioritisation of the investments ('single asset' results). Those strategies with more than one asset capture the system effects of the assets as well as the effects of ordering and delay caused by different sequencing and implementation policies ('portfolios' result).

By deriving four attribute values for each implementation of each portfolio, we produce an extensive set of results, which will need further analysis if we are to provide decision-support. We therefore draw the results into family groupings based on the assets they contain. We present family results as ranges between the minimum and maximum results for the entire family, representing the uncertainty of the scheduling and implementation policies. The resulting ranges of pathway families can be compared to understand the opportunity and robustness provided by the assets, in a similar vein to single asset real options analysis.

Pathways which do not provide sufficient opportunity for benefit, or final systems which create too great an impact can be removed from the decision space. Alternatively, where thresholds are not appropriate or not available, pathway outputs can be compared, to enable decision makers to (i) decide which opportunities they wish to maintain for the future and (ii) consider

¹⁴ The set of potential baseline infrastructures derived from the 'do minimum' pathway shall be referred to herein as the 'dynamic baseline'. This is further detailed in Section 3.7.1.

¹⁵ Environmental, monetary, service and social.

the uncertainty of different paths and whether an investment is worthwhile based on the additional (or reduced) risk produced.

Given that we intend to update and review our analysis as uncertainty diminishes, the need to apply an extensive number of futures is reduced. However, we must review the uncertainty of our key assumptions if we wish to understand their effects on the system as a whole. Once the pathway analysis has been completed, the last stage of the analysis is therefore to conduct a systems sensitivity analysis on the key variables. Applying similar threshold and comparator decision criteria to this result, the decision maker can choose between initial investments to determine the 'optimal' pathway family from a robustness and flexibility perspective. By choosing a pathway family, the decision maker can determine which initial investments should be made. However, it is essential that the decision maker also notes the factors that make these investments favourable and those which make further decisions difficult to differentiate between. These factors will constitute the assessments necessary in the review stage of the analysis.

3.6 Stage 4: Review

The forward plan created by the pathway analysis outlined in Section 3.5 is strongly dependant on the assumptions within the system state conditions used and the objectives of the decision maker. The aim of the review stage is therefore to consider whether the assumptions and objectives are still accurate and plan for future asset developments as uncertainty decreases.

Review point triggers should therefore be set:

- After any change in strategic objectives;

- If there is a deviation in assumptions outside of those considered in the sensitivity analysis; and
- In sufficient time to allow the pathway's future infrastructure developments to be implemented.

Where objectives change, it may be necessary to reconsider the opportunities available within the spatial remit and/or include further metrics within the four attributes. Where assumptions have been inaccurate, it may be necessary to deviate within the current pathway, taking advantage of flexibility contained within the future developments, or consider the 'option to abort' the pathway and consider a different route entirely.

The final purpose of the review stage is to ensure that the flexibility contained within the pathways is maintained and not lost unintentionally through:

- Ignorance, as those who created the flexibility leave the company or project (e.g. Bluewater shopping centre car park in the UK (see de Neufville and Scholtes (2011));
- Stakeholder block, where the flexibility is reliant on one stakeholder but the benefit experienced by another, therefore action is not taken forward (Krüger (2012) noted that this was particularly relevant to PPP¹⁶ infrastructure);
- Insufficient internal planning; or
- External developments (such as new regulations or development of other assets).

¹⁶ Public private partnership.

Therefore, should no reviews be necessary due to the triggers identified, regular updates should still be provided to ensure stakeholders are aware of the forward plan and the provisions necessary to ensure flexibility is maintained.

3.7 Implementing the framework: A formalised methodological approach

Having defined our objectives and understood what information is necessary for our review in Stage 4 we are now in a position to formally define the standard methodological approach and the decision criteria for our pathway choice and onward review process.

Drawing together our proposed methodological approach (see Figure 3.1), and the performance attributes defined in Section 3.3.3, we can derive the appraisal methodology set out in Figure 3.7. Over the next four sub-sections, we therefore define the stages set out this figure.

3.7.1 Deriving the infrastructure pathways

To develop our investment portfolios, we start by splitting our time domain into a number of discrete intervals. The start of each interval is nominated as a delivery point, noted by the vector D :

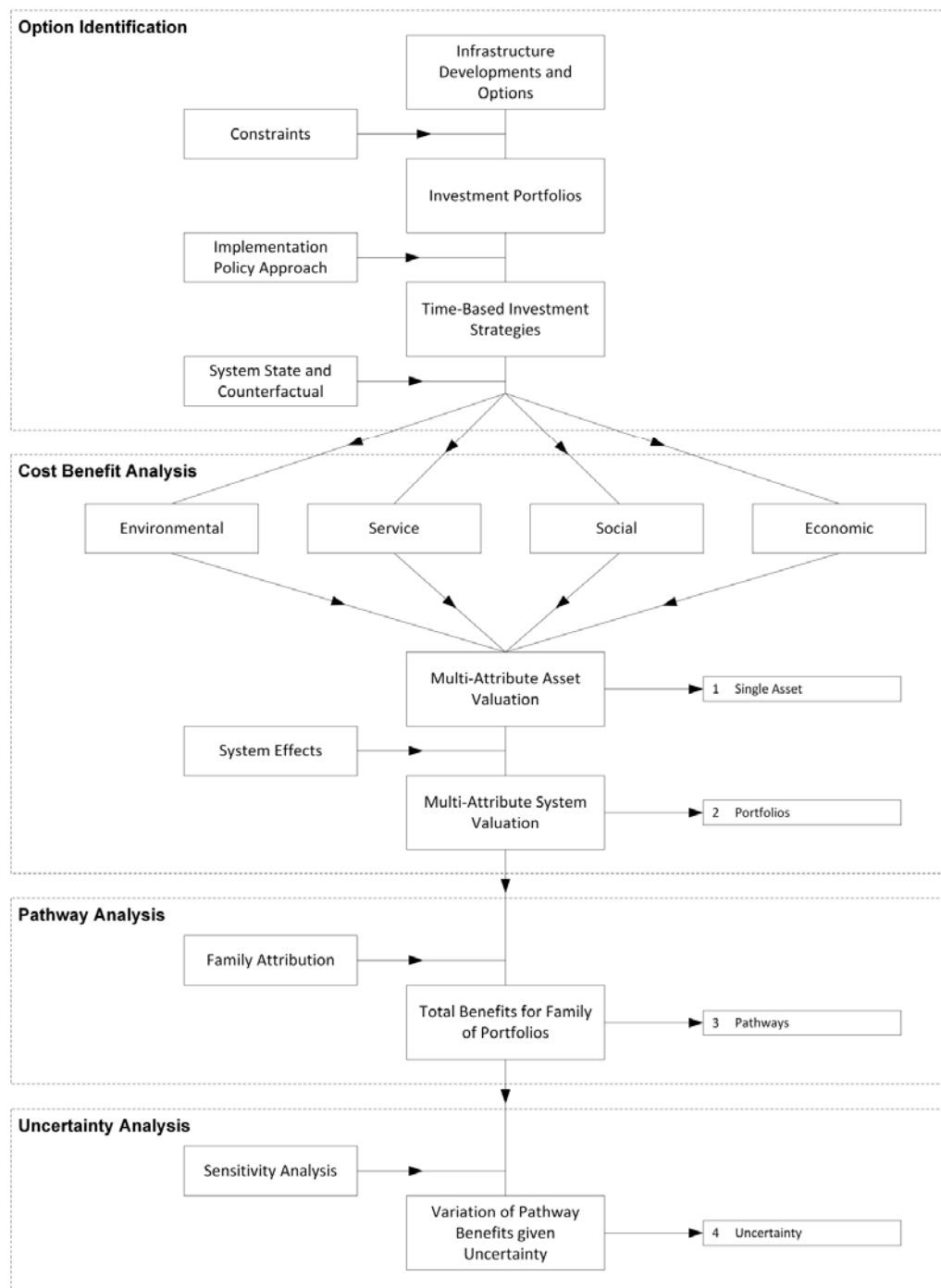
$$D = \{d_0, d_1, d_2, \dots d_i\}$$

At each delivery point in D there is the opportunity to implement any number of available infrastructure developments. All infrastructure developments are captured by the vector A :

$$A = \{a_0, a_1, a_2, a_3, \dots a_j\}$$

where $\{a_0 : a_j\}$ are all available infrastructure developments

Figure 3.7 – Outline of appraisal methodology (adapted from Young and Hall (2015))



Note that D are not *decision* points since the required planning time for infrastructure is highly uncertain. Instead, D are the points at which the infrastructure is implemented and becomes operational. Construction costs and impacts are accrued prior to D , while in-service and end-of-service effects accrue after D . Therefore each infrastructure development in A has an earliest

possible implementation date associated with it, according to its assumed minimum construction time.

To develop a full list of potential portfolios of developments we create an array P of all possible combinations of infrastructure investments A , such that:

$$P = \{a_0, a_1, a_2, \dots a_i, a_0+a_1, a_0+a_2, \dots a_0+a_j, a_1+a_2, a_1+a_3, \dots a_1+a_j, \dots a_0+a_1+a_2+a_3+\dots+a_j\}$$

Each element of P is a potential portfolio containing one or more infrastructure investments, but without any indication of implementation sequence or grouping. Our first step in applying the time domain is therefore to disaggregate each portfolio into its possible implementation paths. For each portfolio, all possible permutations of ordering and grouping are calculated. We shall refer to each of these permutations as a 'strategy'. A portfolio of two assets ($a_\beta, a_{\beta+1}$), for example, would have three strategies:

$s_\alpha = \{a_{\beta,t}, a_{\beta+1,t}\}$	where infrastructure developments a_β and $a_{\beta+1}$ are implemented together in a single group at time 't';
$s_{\alpha+1} = \{a_{\beta,t}, a_{\beta+1,t+n}\}$	where a_β should be implemented first (at time 't'), with infrastructure development $a_{\beta+1}$ implemented at the next delivery point (time 't+n'); and
$s_{\alpha+2} = \{a_{\beta+1,t}, a_{\beta,t+n}\}$	where $a_{\beta+1}$ should be implemented first (at time 't'), with infrastructure development a_β implemented at the next delivery point (time 't+n').

We therefore create an array of *potential* strategies S :

$$S = \{s_0, s_1, s_2, \dots s_i\}$$

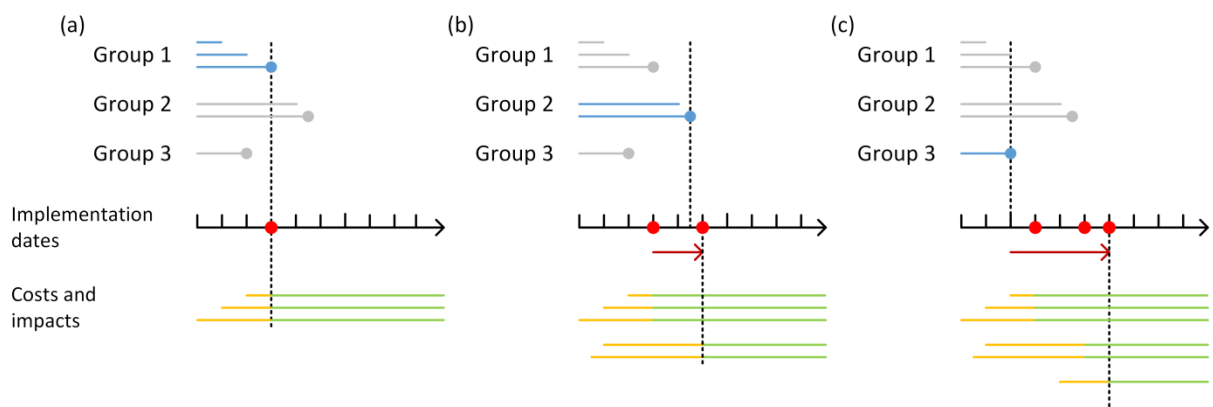
An array of system constraints C , is then applied to S , removing strategies with mutually exclusive developments (spatial and operational constraints, see Section 3.4.2) and those where prerequisite conditions have not been met (for example, where a development requires supportive infrastructure in order for it to be built or to function). This gives an array of *possible*

strategies S' :

$$S' = \{s'_0, s'_1, s'_2, \dots, s'_k\} \quad S' \subseteq S$$

To set each possible strategy in S' against the array delivery points D , we choose an ‘implementation policy’ (see Section 3.5) to define the earliest starting date for delivery and the minimum delay between each group of investments. This is combined with each asset’s earliest possible implementation date to determine the group delivery point. This process is shown in Figure 3.8, through an example strategy with three groups of investments. The delivery point of Group 1 is given by the longest of the three asset construction times (shown in blue), see part (a). This could be further delayed by the implementation policy’s earliest start date, but is not in this case. As noted above, construction costs and impacts (orange) accrue prior to this delivery point and implementation costs and impacts accrue after (green). Following the same method, the implementation date of Group 2 is two delivery points after that of Group 1, see part (b). Group 3 consists of only one asset with a construction time shorter than the delivery points of Groups 1 and 2. Its delivery date is therefore determined by the implementation policy, which in this case requires a single delivery point delay.

Figure 3.8 – Calculation of starting dates for asset groups



Having determined the delivery schedule of each strategy under a given implementation policy, we can start to quantify the impacts of each against future socio-economic conditions. Taking W

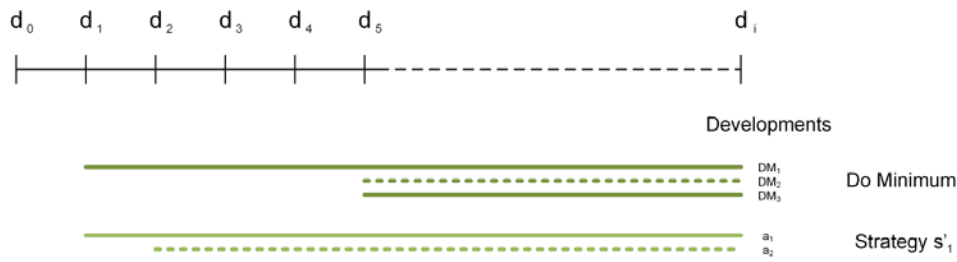
as a matrix of exogenous system state conditions, where:

$$W = [w_{0,t}, w_{1,t}, w_{2,t}, \dots w_{l,t}]$$

and each array $w_{\epsilon,t}$ is a set of conditions under a possible future at a given time 't'. These exogenous system state conditions must be combined with the endogenous model conditions, in our case the baseline development profile. Setting the 'do minimum'¹⁷ strategy against the same implementation policy as our strategy array S' , we can determine the potential 'do minimum' pathway. However, as some of the infrastructure developments within the 'do minimum' strategy will be mutually exclusive to those in the strategies in S' , it is necessary to compare each strategy in S' with the 'do minimum' to determine the actual development context against which it is set. As noted previously, we will refer to this context (the pathway dependant set of infrastructure investments that are implemented in parallel to the development pathway) as the dynamic baseline. The comparison process is shown in Figure 3.9. One strategy is presented with two constituent developments (a_1 and a_2). The 'do minimum' case has three developments (DM_1 , DM_2 and DM_3). The green lines represent the impacts of the developments, with the dashed lines representing developments which are mutually exclusive (DM_2 and a_2 in this case). Where developments are mutually exclusive it is assumed that the latterly implemented development is not implemented. In Figure 3.9, development a_2 will be implemented at delivery point d_2 , therefore, development DM_2 , which should be implemented at d_5 will not go ahead. The strategy in this case will be implemented against a baseline of only DM_1 and DM_3 .

¹⁷ Herein 'do minimum' refers to the time-based counterfactual strategy. It is used to both derive the dynamic baseline and as the comparator case for calculating the net costs and benefits (see Sections 3.4.2 and 3.5).

Figure 3.9 – Comparison of strategies with the ‘do minimum’ to find the strategy’s baseline infrastructure developments (adapted from Young and Hall (2015))



We shall refer to the array of strategies that have been reviewed against both their internal constraints and those of the ‘do minimum’ pathway as S'' ($S'' \subseteq S'$). Each strategy in S'' is specific to an array of exogenous system state conditions $w_{\epsilon,t}$ and will have an associated set of endogenous system conditions associated with the case specific baseline infrastructure developments. We will refer to the combined exogenous and endogenous system conditions as X . There is therefore an array $\{x\}$, where $x_{s''_v, t_\delta w_\epsilon}$ is the combined system state conditions, under strategy s''_v , at time t_δ and under exogenous state conditions w_ϵ . This is shown in Table 3.8 assuming that delivery points are set at 5 time interval periods.

Table 3.8 – Total system state conditions at each delivery point for all fully constrained strategies under exogenous state conditions w_ϵ

Time		t_0	t_1	t_2	t_3	t_4	t_5	...	t_{n-4}	t_{n-3}	t_{n-2}	t_{n-1}	t_n
Future System State $w_{\epsilon,t}$:		$w_{\epsilon,0}$	$w_{\epsilon,1}$	$w_{\epsilon,2}$	$w_{\epsilon,3}$	$w_{\epsilon,4}$	$w_{\epsilon,5}$	...	$w_{\epsilon,n-4}$	$w_{\epsilon,n-3}$	$w_{\epsilon,n-2}$	$w_{\epsilon,n-1}$	$w_{\epsilon,n}$
Delivery Points:		d_0	-	-	-	-	d_1	...	d_i	-	-	-	-
Strategies	s''_0	$x_{0,0}$	$x_{0,1}$	$x_{0,2}$	$x_{0,3}$	$x_{0,4}$	$x_{0,5}$	...	$x_{0,n-4}$	$x_{0,n-3}$	$x_{0,n-2}$	$x_{0,n-1}$	$x_{0,n}$
	s''_1	$x_{1,0}$	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	$x_{1,4}$	$x_{1,5}$	...	$x_{1,n-4}$	$x_{1,n-3}$	$x_{1,n-2}$	$x_{1,n-1}$	$x_{1,n}$
	s''_2	$x_{2,0}$	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	$x_{2,4}$	$x_{2,5}$	...	$x_{2,n-4}$	$x_{2,n-3}$	$x_{2,n-2}$	$x_{2,n-1}$	$x_{2,n}$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	s''_m	$x_{m,0}$	$x_{m,1}$	$x_{m,2}$	$x_{m,3}$	$x_{m,4}$	$x_{m,5}$	...	$x_{m,n-4}$	$x_{m,n-3}$	$x_{m,n-2}$	$x_{m,n-1}$	$x_{m,n}$

3.7.2 Valuation of strategies and potential decision-support criteria

The system states are monetised by the four attribute value functions (each a summation of the component indicator valuation functions), set over the time domain $t_0 - t_n$. The total attribute

value for each strategy s''_{γ} under state conditions w_{ϵ} can therefore be estimated by numerical integration of all attribute indicators over the time domain:

$$v_{attribute}(s''_{\gamma, w_{\epsilon}}) = \sum_{ind=1}^q \sum_{\delta=0}^n (x_{s''_{\gamma} t_{\delta} w_{\epsilon}})$$

where there are q indicators (ind) for the given attribute

The full value (V) of strategy s''_{γ} under state conditions w_{ϵ} can then be assumed to be the array of total attribute values:

$$V(s''_{\gamma, w_{\epsilon}}) = \begin{bmatrix} v_{Environment}(s''_{\gamma, w_{\epsilon}}) \\ v_{Economics}(s''_{\gamma, w_{\epsilon}}) \\ v_{Service}(s''_{\gamma, w_{\epsilon}}) \\ v_{Social}(s''_{\gamma, w_{\epsilon}}) \end{bmatrix} \approx \begin{bmatrix} \sum_{ind_E=1}^6 \sum_{\delta=0}^n (x_{s''_{\gamma} t_{\delta} w_{\epsilon}}) \\ \sum_{ind_M=1}^4 \sum_{\delta=0}^n (x_{s''_{\gamma} t_{\delta} w_{\epsilon}}) \\ \sum_{ind_{Se}=1}^3 \sum_{\delta=0}^n (x_{s''_{\gamma} t_{\delta} w_{\epsilon}}) \\ \sum_{ind_{So}=1}^2 \sum_{\delta=0}^n (x_{s''_{\gamma} t_{\delta} w_{\epsilon}}) \end{bmatrix}$$

If the future was certain, there would be only one system state and the above equation would give four attribute results for each strategy. Assuming that we wish to maintain segregation of the attribute results, we could reduce the decision space to the non-dominated pareto optimal set of strategies ($V(s''_{po})$) by excluding all strategies with attribute results that were all less than those of another strategy (see Equation 3.1).

Equation 3.1 – Pareto optimal set of strategies under certainty

$$\begin{aligned} & V(s''_{po}) \subset V(s'') \\ & \text{such that} \\ & v_{attribute}(s''_{po}) \geq v_{attribute}(s''_{\gamma}) \text{ for } \gamma = 1, \dots, m \\ & \text{and} \\ & v_{attribute}(s''_{po}) > v_{attribute}(s''_{\gamma}) \text{ for } \gamma = 1, \dots, m \text{ for at least one attribute} \end{aligned}$$

The decision maker would then need to further analyse the pareto optimal set to choose the appropriate strategy. A similar result could be obtained under a predictable future. Here, values could be calculated for all possible system states (w_ε : $\varepsilon = 1, 2, \dots, E$), with an expected value calculated for each strategy attribute by multiplying each valuation by its relative probability $P(w_\varepsilon)$ and summing over the decision space of possible futures. The decision maker could again find the pareto optimal set where attribute values were non-dominated when uncertainty was taken into account (see Equation 3.2).

Equation 3.2 – Pareto optimal set of strategies under risk

$$V(s''_{po}) \subset V(s'')$$

such that

$$\sum_{\varepsilon=1}^E v_{attribute}(s''_{po, w_\varepsilon})P(w_\varepsilon) \geq \sum_{\varepsilon=1}^E v_{attribute}(s''_{\gamma, w_\varepsilon})P(w_\varepsilon) \text{ for } \gamma = 1, \dots, m$$

and

$$\sum_{\varepsilon=1}^E v_{attribute}(s''_{po, w_\varepsilon})P(w_\varepsilon) > \sum_{\varepsilon=1}^E v_{attribute}(s''_{\gamma, w_\varepsilon})P(w_\varepsilon) \text{ for } \gamma = 1, \dots, m$$

for at least one attribute

However, under deep uncertainty conditions, no probabilities can be calculated for the system state conditions, therefore we cannot calculate a single value for each strategy attribute. We are left with an array of possible results for each attribute in each strategy, making determination of a pareto optimal set of strategies impossible.

As we noted in Chapter 2, robust decision frameworks (RDF) solve this dilemma, by looking for strategies that offer value over a range of diverse future conditions. Example criteria might be maximin utility (choosing the strategy which maximises the minimum utility), minimax regret (choosing the strategy which minimises the maximum regret) or consider minimum levels of performance/maximum levels of impact and the range of results created (for example the

standard deviation). Equation 3.3 presents the maximin utility decision criteria as an example. However, by considering multiple futures and holding each as equally important, these methods vastly increase the computational requirement of the analysis.

Equation 3.3 – Maximin utility

$$\max \left(\min_{\varepsilon \in E} \left(v_{\text{attribute}}(s''_{w_{\varepsilon}}) \right) \right)$$

3.7.3 Determining pathway flexibility

As we noted in Chapter 2, the alternative approach for improving robustness (taken herein) is to allow for decisions to be actively changed as uncertainty decreases. Such methods concentrate the analysis on preliminary decisions and maintaining flexibility for the long-term, acknowledging that the appraisal results are highly uncertain. By decreasing the importance of the accuracy of the long-term projections, such methods reduce the need for considering arrays of divergent futures and hence the decision space and complexity of the problem.

Taking such an active approach requires a measure of the future value created by an investment. A real options analysis, for example, could use the result of either Equation 3.1 or Equation 3.2 to determine the value of flexibility created by building options into a strategy¹⁸. If we consider how this could be extended to our multi-attribute pathways analysis, while we could still determine the value of flexibility for each attribute in a strategy it would vary depending on the chosen grouping and timing of developments. We therefore need to adapt the methodology to consider the flexibility provided over multiple strategies and implementation routes, referred to herein as the pathway *opportunity* provided.

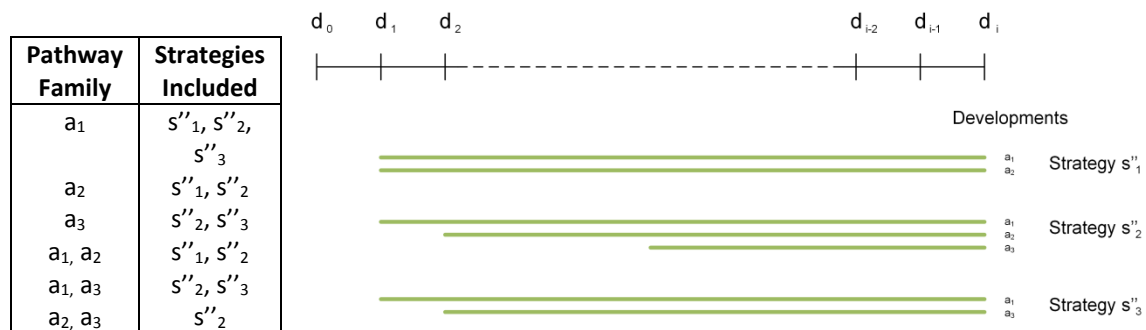
¹⁸ Through comparing the results of a strategy with options to a strategy without options (see Wang and de Neufville (2005)).

We start by defining a ‘pathway family’ as a subset of the total strategies array S'' , which share one or more specified infrastructure developments, examples are shown in Figure 3.10.

The range of attribute values created by the development a_θ pathway family under system state conditions w_ε is therefore given by:

$$(\min(v_{attribute}(s''_{w_\varepsilon}|a_\theta \in s''_{w_\varepsilon})), \max(v_{attribute}(s''_{w_\varepsilon}|a_\theta \in s''_{w_\varepsilon})))$$

Figure 3.10 – Determining pathway families of strategies (adapted from Young and Hall (2015))



We do not attempt to apply a probability distribution to this result, instead maintaining the range as an additional indicator of the uncertainty of the long-term projection¹⁹. Instead, building on the ROA methodology, the attribute range for a pathway family is compared to those without the pathway family’s common development i.e. where an alternative, mutually exclusive development has been chosen, or where the development has simply not been taken forward. The positive and negative opportunity provided by a development for a given attribute is therefore the difference between the maximum and minimum results for its pathway family and those for the family of pathways excluding it:

$$O_{attribute}^+(a_\theta) = \max(v_{attribute}(s''_{w_\varepsilon}|a_\theta \in s''_{w_\varepsilon})) - \max(v_{attribute}(s''_{w_\varepsilon}|a_\theta \notin s''_{w_\varepsilon}))$$

$$O_{attribute}^-(a_\theta) = \min(v_{attribute}(s''_{w_\varepsilon}|a_\theta \in s''_{w_\varepsilon})) - \min(v_{attribute}(s''_{w_\varepsilon}|a_\theta \notin s''_{w_\varepsilon}))$$

¹⁹ This builds on the work of Morel, who found that using reasonable bounds of values for ROA gave relatively consistent results (output changes of only 10 per cent) despite high levels of uncertainty surrounding probability distributions within those bounds (Morel, 2013).

The vast array of possible futures used in RDF are not as necessary under such active robustness approaches. However, we can, and will, explore the effect of uncertainty on our key variables by changing our system state conditions {w} and including these results within our pathway family attribute ranges.

3.7.4 Creating a tool for decision-support

Returning to our active robust decision approach, we can use our two measures of long-term flexibility, alongside any threshold attribute targets we have developed strategically, to determine our preferred pathway family. From this we can derive the preliminary investments necessary to ensure future opportunities remain open. However, given our focus on uncertainty and multi-attribute framing, the methodology will not provide a ranking of options, instead providing information such that a decision maker can choose which opportunities are most valuable. The intention is therefore to provide the results as decision-support graphics for stakeholder discussion. We propose to develop a decision tree of the possible strategies, creating a graphic for each branch division, such that stakeholders can consider the following four decision criteria:

Whether the pathway families offer sufficient threshold results (T^+) for each of the four attributes:

$$\max(v_{attribute}(s''_{w_\varepsilon} | a_\theta \in s''_{w_\varepsilon})) \geq T^+$$

Whether the pathway families exceed threshold impacts (T^-) for any of the four attributes²⁰:

$$\min(v_{attribute}(s''_{w_\varepsilon} | a_\theta \in s''_{w_\varepsilon})) \leq T^-$$

²⁰ These first two threshold decision criteria can be used to apply the financial and impact constraints discussed in Section 3.4.2.

Whether the opportunity provided by a given development provides sufficient benefit in comparison to its alternatives to remove them from the decision space:

$$\begin{aligned} O_{attribute}^{+}(a_{\theta}) &\geq O_{attribute}^{+}(a_{\theta+1}) \\ O_{attribute}^{-}(a_{\theta}) &\geq O_{attribute}^{-}(a_{\theta+1}) \end{aligned}$$

Whether the change in range of opportunity created by a development creates sufficient additional risk in comparison to its alternatives that it should be removed from the decision space:

$$(O_{attribute}^{+}(a_{\theta}), O_{attribute}^{-}(a_{\theta})) \leq (O_{attribute}^{+}(a_{\theta+1}), O_{attribute}^{-}(a_{\theta+1}))$$

Using these decision criteria, the decision space should be reduced as far as possible, leaving only those pathway families that offer sufficient benefit, limited impact, increased flexibility, or reduced risk. The remaining pathways must then be analysed to note:

- The preliminary developments necessary for the remaining pathways;
- The development requirements that should be kept open to allow future developments;
- When future decisions will need to be made;
- What indicators must be tracked in order to enable these decisions to be made; and
- What level of indicator should trigger a review of the current forward plan.

3.8 Application to a case study

The above methodology could be applied to any country context; however a number of additional factors are still required. In particular, the timeframe length, starting date and division must be decided, alongside the discount rate to be used. We will return to these issues after choosing a case study; however, in order to decide whether sufficient data is available for a

given case study, we must first choose a timeframe for the methodology. Given the foci on the long-term and the UK context, we will therefore apply a total time period of one hundred years in accordance with current UK infrastructure systems research through the Infrastructure Transitions Research Consortium.

While this long-term time horizon will provide the opportunity to consider strategic robustness and flexibility, it also presents problems. Projections, must not only predict socio-economic change such as population growth, but also environmental and technological change and whether these will in turn affect behaviour or values. None of these factors can be reliably predicted over this timeframe. While our active approach to robustness counteracts some of these concerns, there is still a strong need to demonstrate the uncertainty of results. We will return to the issues surrounding long-term projections when characterising our case study in Chapter 4. Furthermore, implementation of a sensitivity analysis on the system as a whole (see Chapter 7) will provide useful information about the effects of these factors.

3.9 Conclusions

The aim of this chapter was to fully outline the appraisal methodology set out in Chapter 2 and ensure that it can be used complete the two objectives of this research, namely:

- To develop a common appraisal framework that delivers a more complete valuation of infrastructure developments, capturing the multiple stakeholder perspectives and resources required, but also the cross-sector and systems effects created by the system as a whole; and
- To develop a policy level multi-sector decision-support tool focused on ensuring solutions are robust to future change by considering how future infrastructure

investments are enabled and constrained by the decisions made, the potential total value of the system and the uncertainty of the results.

In Chapter 1 we derived five recommendations to help deliver such an appraisal framework (see Section 3.2). If we return to these recommendations, we can conclude that all have been included in our proposed approach and therefore a more complete valuation of infrastructure from a systems perspective will be produced. Our framework has been designed to be cross-sectoral, with a systems perspective applied at all stages and objectives specifically derived for this purpose. The appraisal analysis continues this perspective ensuring that the same system state conditions, assumptions and fundamental methodology is applied in all cases. It combines assets into cross-sector portfolios to capture systems interdependencies, directly recording resource constraints and using these to reduce the decision space. Furthermore, effects are calculated for the system as a whole and attributed to the pathway family rather than single assets. This includes the emergent system effects caused by interactions, but also the lock-in or opportunity provided by assets for future development. Through the use of pathway family attribute ranges we have conveyed the deep uncertainty of the results, but by comparing different pathway families we still allow for the decision space to be navigated, presenting where assets offer future flexibility and opportunity.

In defining such an analysis, we have, however, introduced some limitations. The scope is strategic and therefore many of the intricacies of the sector specific analysis will not be captured, or will be captured at too higher level for detailed asset planning. Furthermore, we have focused our performance metrics on UK centric objectives. While these could be reconfigured for other countries, the methodology as it stands offers a UK centric policy makers' viewpoint. As outlined in Chapter 1, the framework will therefore sit in a hierarchy between the high level international and sector specific analyses, providing a missing link: a more integrated

assessment of resource constraints, systems effects and opportunities to inform the high level strategies and a way to translate national strategy for regions and infrastructure sectors. However it will not replace either national scale or asset specific appraisals.

3.10 Next steps

As set out in Chapter 1, we intend to investigate infrastructure systems appraisal in five increments applicable to any decision under deep uncertainty:

- Assessment against a single attribute vs multi-attribute valuation;
- Investment in individual projects vs investment in groups of projects;
- A specified single project/portfolio vs consideration of pathway flexibility;
- Single future projection vs valuation under an uncertain future; and
- Isolated predictions of change vs path dependency and feedback (incorporation of the interdependency between the development and the investment landscape).

This will allow us to assess the benefit derived by the additional effort and understand the change in perspective provided by the additional complexity. The first four increments are noted in Figure 3.7 by the 'single asset', 'portfolios', 'pathways' and 'uncertainty' outputs. We will therefore implement the methodology in these increments in Chapters 5 through 7.

However, in order to implement the methodology we must first choose a suitable case study and this will be the focus of our next chapter.

4 Case Study Choice: Cross-Sector Infrastructure Investment in a Mature Economy

4.1 Introduction

In Chapter 3 we defined a framework and methodology capable of more fully appraising infrastructure as a system of systems. As set out in Chapter 1, our intention is to apply this methodology in increments of complexity to understand the information gain provided and the additional effort required. However, first we must find a case study or set of case studies to which the methodology can be applied and which is/are suitable for all proposed increments of complexity. This is the purpose of this chapter. We can therefore derive two aims:

- To review the available literature and data to determine which case study, or set of case studies, will most completely test the methodology from a systems perspective; and
- Having determined the most suitable case study/studies, to define its/their constituent assets, interdependencies and environment such that the methodology can be applied.

We start by reviewing the purpose of case studies and, given the context of this research, the priorities for our case. We split the available case studies into three types: historical projects, current projects and proposals (future projects). We describe their benefits and limitations before reviewing the available examples of each against the identified priorities. Having initially selected the Thames Hub Vision, we provide an outline of its constituent assets and review the benefits and limitations of our choice, determining that it provides sufficient scope as a standalone case study. Finally we provide a sufficient definition of our case study to allow the appraisal methodology to be applied, including assumptions, data, projections and the counterfactual case.

4.2 Choosing an appropriate case study or set of case studies

Siggelkow (2007) suggests there are three purposes for case studies: the development of new lines of enquiry ('motivation'), the development of new theories ('inspiration') and the testing of existing theories ('illustration'). Our research focuses on the last purpose, with the aim of testing the appraisal methodology and framework. We must first, therefore, reflect on the aims of the research to derive the ideal criteria for the case study.

4.2.1 Choice criteria and priorities

Given that the focus of this research is on capturing the interdependencies of infrastructure networks within the appraisal process, the first priority for the case study must be to include as many complexities of infrastructure as a system of systems as possible. We characterised the complexity of the interdependent infrastructure problem in Chapter 1, finding five aspects that must be included with a systems appraisal:

- Valuation against a background of divergent priorities, and impacts which are large, long-term and can be non-marketable, non-marginal and at multiple scales;
- The resource requirements of developments from a whole system perspective;
- Prioritisation across sectors with different functions for the economy;
- The system effects of an investment, including its demand on other sectors, its ability to contribute to emergent effects and its constraint or enablement of future investments;
and
- The robustness of investments over the long-term under conditions of deep uncertainty.

We can generate six facets of infrastructure appraisal complexity from this list:

- The dynamics of the development backdrop (social, technical and environmental change);
- The resources required (number, magnitude, longevity and market value);
- The impacts created (number, magnitude, scale, longevity and market value);
- The inclusion of multiple sectors (functions within the economy/priorities, scale of service delivered, financing and ability to generate wider economic effects);
- Interactions between assets (demands, system effects and enablement or constraint of future developments); and
- The dynamics of each asset (options and flexibility).

If we wish to fully test our proposed methodology, we must aim to include as many of these facets of infrastructure appraisal complexity as possible.

Our first facet suggests we should focus on geographies with a high level of change. Our focus on the UK, not only provides the potential for this facet (with an infrastructure pipeline of £466bn (Infrastructure UK, 2014)), but, as outlined in Chapter 1 presents a mix of ownership methods, a wide variety of infrastructure stakeholders and (in some regions) a high population density. It may therefore also deliver the impact complexity (facet 3) and the opportunity for asset diversity (facet 4). The restriction of case studies to only UK examples would, however, highly constrain the potential pool of examples. UK developments will therefore be *prioritised*, but case studies from other geographies will also be considered if deemed to be suitably similar.

Ensuring that the case study includes a variety of resource and impact types (facets 2 and 3) will require that a number of assets be included within the case study and that these be as varied as possible. Delivering facet 4 (assets from multiple sectors) will help deliver this variety. We will therefore consider the inclusion of multiple assets, originating from different sectors and with

varying characteristics¹ to be a *critical criterion* for the case study. However, given that our methodology has been focused on the regional scale, each asset will need to create a sufficient effect to be identifiable at this level, which may limit the minimum size of assets that can be considered (see Oswald et al. (2011)). Furthermore, should the assets be too different in scale then the effects of one may overwhelm the other assets. Having diversity in size of asset and scale of impacts, will therefore test both the resolution limits of the methodology in recording effects and whether the outputs (decision-support) sufficiently communicates this differentiation between assets.

Facets 5 and 6 again relate to the assets, requiring that they have interdependencies between them and that there is flexibility to change the asset's design or development. Infrastructure interdependencies in mature economies, such as the UK, have developed organically over time, with most assets now reliant on the other networks, particularly energy and ICT (see Table 1.2 in Chapter 1). Therefore, as long as assets from multiple sectors are included within the case study (as stipulated above) it is likely there will be some level of interdependence. Some assets, however, have a stronger cross-sector relationship, producing system effects. As these will further test the methodology, case studies with the potential for such effects will be *prioritised*. Similarly, those assets which offer the potential for significant flexibility and options (that is, those where the flexibility is likely to substantially impact one of the indicators) will also be *prioritised*.

Having defined one critical criterion and three priorities based on the complexity of the case study, our final criterion is one of practicality. Appraisals require large quantities of data both regarding the projected social, economic and technical development of the country or region being considered and more particularly about the infrastructure development itself. While our

¹ Such as resources, impacts, size and financing type.

methodology is designed to be used strategically when elements are still conceptual or in very early stages of design, approximate data on capacities delivered, costs and operational resources will still be required. Furthermore, the development background must be predicted, requiring an understanding of what infrastructure projects would be built in the absence of the development (the counterfactual) and an agreed projection of socio-economic change, such that technological change projections are internally consistent. The availability of data on the infrastructure development and the region will therefore be the second *critical criterion* for the case study.

One way to ensure that projections are internally consistent and that cost data is accurate is to use an ex post case study. However, the more historical the case study, the less relevant the technologies and interdependencies of the assets considered, particularly given the hundred year timeframe of the methodology². In addition, complete data sets, which can be difficult to obtain for recent projects (Weaver et al., 2013) are even less likely to be available over the life of more historical cases. Furthermore, given our pathway approach, the actual development would only represent one of many potential development pathways, with projections and estimations still required for the remaining pathways. Therefore, while ex post case studies provide a single validated dataset that is not available for ex ante examples, this is balanced by their increasing irrelevance to current and future technologies and the difficulty in obtaining a complete dataset. Current projects present a balance between the two extremes with only a small quantity of validated data, but more relevance than the historical cases, while proposals provide the most relevant examples but no validated data. As ex post (historical and current) and ex ante case studies all have merit, we will not prioritise between the three types. However,

² While many infrastructures have decadal lifetimes, technological developments and environmental awareness have changed significantly over the last 100 years. Historical case studies would therefore be unlikely to show high interdependencies on ICT, current behavioural characteristics such as car ownership and usage and may not have collected data on environmental impacts.

as each set presents different benefits and limitations, we will analyse the available examples against these three headings.

We therefore have two critical choice criteria: that sufficient data must be available and that the development should include multiple assets, originating from different sectors and with varying characteristics. Furthermore, we have three priorities: that assets should be as interconnected as possible, offer flexibility likely to have a significant impact on one of the value indicators and that the development should be in the UK or a country/region that could be considered similar from an economic perspective.

Finding all these criteria within a signal case study will be challenging and require a significant effort to undertake the appraisal. There is therefore a trade-off between how many facets of complexity can be included within a single case study and how many case studies can be completed within the research. We next consider this trade off, comparing the benefits of a number of simple case studies against those of a single case study with a high degree of complexity.

4.2.2 Number verses complexity

Stake (1995) notes that case studies can be chosen either for their commonality or for their uniqueness. Common case studies test whether the theory is widely applicable, potentially allowing the derivation of rules that can be applied more broadly. In our context, typical infrastructure assets may only contain a few of the complexities, show less variation between options and/or small scale interdependencies (perhaps a cross-sectoral demand, but limited potential for creating system effects). Many authors criticise this type of case study as being

susceptible to bias and a researcher's preconceived ideas (Flyvbjerg, 2006)³. Therefore care must be taken in the choice of case study and its commonality critically considered or tested with other case studies before applying conclusions more widely. In contrast, unique case studies test the range under which existing theories hold, pushing their application to an extreme. Specific conclusions drawn from such case studies are unlikely to be widely applicable; however, they present the opportunity for falsification⁴, or to better understand the limits of theories. Furthermore, Flyvbjerg (2011) suggests that unique cases can provide greater amounts of information, due to their higher levels of complexity and therefore their illustration of factors that can be overlooked (or not present) in typical cases. His proposition that the main strength of a case study lies in its depth, suggests that detailed reviews of unique cases provide the greatest test for a methodology and the maximum information regarding its use.

Given that 'maximising learning' is Stake's (1995) first criterion for selection of a case study, it appears that we should choose the highly detailed unique case studies. However, as we accept more complexity within the case studies, we must also limit their number. In order to appraise the most complex infrastructure examples, we may, therefore, have to limit our consideration to a single case study.

The use of single case studies to draw conclusions is often criticised, with authors suggesting that results are context-dependent and generalisations cannot be drawn (Flyvbjerg, 2006). Stake (1995) argues that while this may be true for common case studies, which are reliant on representing the whole, a feat unlikely to be achieved from a small sample, the same is not true of the unique case study, where we are instead focused on the additional information provided by extreme cases and whether theories still hold under these conditions. Flyvbjerg (2006; 2011)

³ Flyvbjerg notes this trend, but personally disputes the conclusion, finding case study research to be more frequently targeted towards falsification than verification (Flyvbjerg, 2006).

⁴ Evidence that a theory does not hold in all cases, see Popper (1959).

particularly recommends two types of extreme unique case for testing the limitations of existing theories: the 'deviant case' (one which is particularly problematic or especially good) and the 'critical case' (the most likely or least likely alternative)⁵.

From the above discussion, we can conclude that the greater the complexity captured within a single case study, the greater the information it can give. Furthermore, such case studies are more testing for theories and methodologies. While these advantages come at the expense of commonality, if the limitations of generality are accepted, this also removes the need for the multiple cases that would be required for a statistically valid sample. We will therefore prioritise case studies with as many types and sectors of infrastructure as possible and with multiple interdependencies and options. The computational burden created by this complexity will be solved by limiting the number of case studies. Indeed, if a case study can be found that fits all criteria and priorities, it will be acceptable to only consider a single case. However, given the limited commonality of a unique case study, it will be important that, should a single case study be taken, it fully reflects the focus of the research. In particular, the use of a non-UK based case study may need to be even more carefully considered if we wish to draw conclusions regarding the methodology's applicability to the UK regional context.

4.3 Candidate case studies

Case studies have been taken from the literature reviews of Chapter 1 (infrastructure complexity and the UK context), Chapter 2 (infrastructure appraisal and decision making under deep uncertainty) and Chapter 3 (performance measurement in existing academic and industry literature). Drawing on Section 4.2.1, we split the potential case studies by their implementation

⁵ Note the two types are not mutually exclusive, indeed the deviant (best and worst case) results may well be the least likely, or from a decision making perspective, the best case may be that most likely to be chosen.

date. Historical projects are those already implemented, therefore have accurate costing and implementation data for a single pathway; however, the technologies included may now be redundant. Current projects (those in construction or implemented for less than ten years) have accurate costing data and use current technologies; however, the long-term effects must be projected for all pathways. Finally, proposals are conceptual projects without approval, those still being designed, or those with some support but that have not started construction. These examples most strongly reflect those for which the methodology is planned to be used; however, they have no validated data, relying on previous projects and statistical inaccuracy analyses⁶.

Over the next three sections, we briefly review each case study against our two critical choice criteria (that data must be available and that the development should include multiple varied assets) and three priorities (that assets should be interdependent, offer flexibility, and be in a mature economy, preferably the UK), drawing conclusions for each group, before making an initial choice of case study.

4.3.1 Historic examples

Examples of potential historic case studies are shown in Table 4.1, costs are quoted in 2010 prices unless otherwise stated.

⁶ Such as reference class forecasting (see Flyvbjerg and COWI (2004), for an example methodology).

Table 4.1 – Potential case studies (historical)

Development	Description
Tennessee Valley Authority (TVA), US (see Kline and Moretti (2014))	The TVA was a federally owned corporation, created in 1933 to invest in the Tennessee Valley ⁷ . Approximately US \$20bn ⁸ of federal funds were invested between 1934 and 2000 (73 per cent of this investment occurred between 1940 and 1958). The aim of the development was to enable rapid modernisation of a historically agricultural region to attract the manufacturing industry and generate wider economic benefits. The investments entailed large-scale lifeline and social infrastructure assets including electricity generation through dams, the creation of a new road network, a 650 mile navigation canal and development of flood control systems.
Chek Lap Kok International Airport and Airport Rail Link, Hong Kong (see Dimitou et al. (2013); Omega Centre (2014a); and Langmead and Garnaut (2001))	Completed in 1998 at a cost of approximately US \$8.6bn. The project entailed the parallel development of a new two runway International Airport and the first railway built primarily as an express service between an airport and its city centre. The railway includes a commuter service (Tung Chung Line) which opened with six stations, expanding to eight over the period to 2003. The project required extensive land reclamation (extending the existing Chek Lap Kok island to four times its original size) and dredging in Rambler Channel and Victoria Harbour. It therefore has some interdependencies with the water sector. It was also associated with major property development works (including a new town in Lantau) as part of a regional development plan.
Heathrow Express, UK (see Heathrow Express (2014) and Le Blond (1999)).	Completed in 1998, the project cost approximately £620 million and delivered a direct rail link between Heathrow airport and London St. Pancras Station. The project included some interdependencies with other sectors, requiring electrification of the existing Great Western main line to the 25kV AC catenary system, and the building of replacement ponds for wildlife. It also made active use of ICT, being the first train company to launch an e-ticketing service with validation by an emailed barcode and providing both flight information and remote check-in facilities at London Paddington station. Most of the active interactions, however, are intra-transport, operationally between the rail and the airport and competitively against the existing Piccadilly Line rail and road network connections to Heathrow.
Jubilee Line Extension (JLE), UK (see Dimitou et al. (2013); and Omega Centre (2014b))	Completed in 1999 and costing approximately £3.5bn, the JLE project was a 16km extension of one of the existing London Underground lines. The line runs from Westminster in central London to Stratford in east London and included the development of six new stations. Interactions with other infrastructure sectors were limited. For example, although energy and ICT represented 4 and 11 per cent of the project spend respectively, in the former case this represented only transmission equipment and in the latter case was mainly project specific standalone communication equipment (signals etc). Within the transport sector, there were some interdependencies with one of the project benefits being road decongestion. Regeneration was also a focus.

⁷ The Tennessee Valley included 163 counties from Tennessee, Georgia, Alabama and Mississippi.

⁸ Year of price valuation not specified.

Development	Description
Tagus River Bridge, Portugal (see Gesner and Jardim (1998))	Originally completed in 1966 at a cost of approximately US \$220 million, upgrades finished in 1999 costing an additional US \$305 million. The upgrades took advantage of designed in flexibility, to add a railway deck and an additional road lane to the existing Tagus River suspension bridge ⁹ , while allowing the bridge to remain fully operational. Aims included reduction in road congestion and the need for ferry crossings, along with enabling greater commuter rail and long-distance rail freight.
TGV Méditerranée Valence-Marseille, France (see Dimitou et al. (2013); and Omega Centre(2014c))	Completed in 2001, at a cost of approximately US\$6.8bn, the project provided a high speed rail service from Paris to the south of France, with travel times from Paris to Marseille of under 3 hours. The work included the construction of three new stations (Valence, Avignon and Aix-en-Provence) and the refurbishment of six more, as well as upgrades to the Paris-Lyon line to allow speeds of up to 300km/hr. Interdependencies with the other transport sectors were a strong consideration, with three of the new stations designed to be multi-modal transport hubs (interchange for taxis, hire cars, buses and regional rail) and design speeds derived to compete with air travel. The project also created the foundation for high speed rail connections to Italy and Spain. Interdependencies with other sectors were mainly limited to spatial interactions, with the line crossing 138km of floodplains and passing near a nuclear power station.
M6 Toll Road, UK (see Dimitou et al. (2013); and Omega Centre (2014d))	Completed in 2003, costing approximately £0.9bn, the project built a tolled 43km dual three-lane motorway to provide a congestion free alternative to the M6 motorway in the West Midlands. Transport interdependencies were mainly spatial with three rail over bridges, two rail underbridges and seven junctions with other roads. ICT was also part of the project, with 200,000m of communications cables laid and infrastructure installed to allow use of the remote TAG toll payment system. Interdependencies with the water sector included the diversion of 9.5km of watercourses, the creation of twenty ponds, the retention and modification of a further eleven to minimise ecological impact and, in one case, to provide commercial fishing. Drainage was a significant concern with twenty eight balancing ponds built to limit or attenuate drainage discharge, each with oil inceptors to limit water pollution. Furthermore, a 12m deep, 12m diameter wet well was built with four 1,100 litre/second capacity pumps to allow for a 1:50 year storm. Wider economic priorities include Improved accessibility to and from Cannock, Lichfield and Tamworth and the stimulation of development in the nearby industrial land.

⁹ The bridge was initially reconfigured in 1990, removing the centre barrier to allow five rather than four lanes of traffic.

Development	Description
Airtrain: JFK Airport to New York City, US (see Dimitou et al. (2013); and Omega Centre (2014e))	Completed in 2003 at a cost of approximately US \$2.2bn, the Airtrain was a 2.9km rail loop linking the separate terminals in JFK airport with each other and surface access modes including car rental and long-term parking, but also rail, subway and bus services to promote these as alternatives to car access. Travel times to the airport were becoming increasingly long and unreliable by road and the project was seen as an opportunity to ease congestion in light of growing demand for air travel. Some future flexibility was considered, particularly the extension of the line into central New York, with trains developed to run on existing rail and subway tracks and with power systems designed to be compatible with the existing networks. The provision of check-in facilities at Jamaica station was also considered, but was not implemented, although flight information is displayed. The project also sought to support economic redevelopment of Jamaica, Queens.

Most of the potential case studies centre on transportation assets. The Tennessee Valley Authority (TVA) provides the exception with inclusion of electricity, water and transport infrastructure; however, no fundamental interdependencies between the assets are noted in the literature. The other cases do highlight some interdependencies with other sectors through their demands (for example, electricity and ICT for the rail developments), their resilience to flooding in the case of the M6 toll road and TGV Méditerranée, and their location (reclamation in the case of the Hong Kong airport rail link and Chek Lap Kok International Airport, or environmental protection in the case of M6 toll). However, these interdependencies are limited both in number and their potential for wider system impacts. Indeed, in the case of the Jubilee Line extension, the communications equipment was specifically designed to be standalone. Interdependencies within the transportation sector are more prominent, indeed many of the business cases rely on these interdependencies. For example, both road and rail developments are designed to alleviate road congestion and the airport rail links facilitate airport accessibility and communication¹⁰. Furthermore the transport assets compete with each other. For example, the Tagus River Bridge reduced the need for ferries and the TGV Méditerranée speeds were defined to compete with air travel.

¹⁰ Flight details are provided at stations in London and New York.

Flexibility is particularly well illustrated by the Tagus River Bridge project. In real options terminology, this project provides a case study on the 'option to expand', allowing evaluation of the benefits achieved by strengthening the bridge to allow future additions without disruption. While some of the other examples demonstrate phased design, most do not show forward planning for flexibility, simply adding infrastructure to existing services that gave no forethought to, or provisioning for, such extensions. An exception is the New York Airtrain project which has ensured that trains and power distribution systems are compatible with existing rail and subway systems to allow for future expansion.

As with any appraisal, each of these historical cases necessitates the development of a suitable counterfactual in order to calculate the value derived from the development. Kline and Moretti (2014) give this subject considerable thought, outlining their difficulties in producing a counterfactual for the TVA. In particular they note how easily this counterfactual could become biased. For example, they review other US counties with similar economic and social features¹¹ to estimate the counterfactual case for the TVA; however, they note that the local (and even more remote) regions considered could have been affected directly or indirectly by the development, enabling or constraining their growth. Furthermore, the considered region (the TVA) could have experienced "unique unobserved shocks" (Kline and Moretti, 2014, p297) not reflected by the social and economic features considered, meaning that the counterfactual counties selected were inappropriate. Their solution was to use three sets of comparison counterfactual groups¹² and only draw conclusions that were robust across all three, significantly increasing the computational expense of the appraisal.

¹¹ Population, total employment, housing units, average manufacturing wage, manufacturing share, agricultural share and average agricultural land value.

¹² The United States as a whole, 'the South' and a smaller set of authorities that most closely reflect the socio-economic factors of the TVA.

The TVA is also the oldest case study, with Kline and Moretti's (2014) review considering the 66 year period of the scheme's operation and the 34 years prior. It therefore presents the problems with collection of data for the 100 year period required by our proposed methodology, particularly from a historical context. Data for the TVA was gathered from multiple sources, but the consistency, completeness and precision with which it was recorded was found to vary between these sources and over time. For example, while the authors note substantial changes in population growth rates and land values, they state that "the estimates are very imprecise and preclude definitive conclusions" (Kline and Moretti, 2014, p303). We also do not know how much of this information could have been projected at the programme's conception. It may not be appropriate to test the methodology using ex post data, when it is intended to be applied ex ante. Furthermore, the context is socially and technologically different to the modern day UK. Socially, the region was highly agricultural, with low urbanisation and almost no foreign immigrants. Technologically, many of the population did not even own a radio due to low wages and a lack of electricity. Projections developed for demand, usage and behavioural change are therefore unlikely to be reusable or relevant to the UK case. Furthermore, modern day environmental concerns such as carbon dioxide emissions, were not recognised in 1930 and would not have been recorded.

With the exception of the TVA (age and cross-sectoral assets) and the Tagus River Bridge (flexibility), international examples appear to offer few advantages over the UK cases. The Heathrow Express strongly reflects the qualities of the Hong Kong and New York airport rail services. It is also of a similar age to the Hong Kong line, suggesting equivalent amounts of data are available, although the Hong Kong line has potentially greater environmental effects being built on reclaimed land. Similarly, the Jubilee Line extension already reflects interdependencies between rail, ICT and energy, so presents a similar case to the TGV high speed rail, although the transportation interdependencies are fewer as it does not compete with air travel. Similar intra-

transport interdependencies are, however, included as part of ‘current’ projects such as CTRL, which was completed only six years after the TGV (see Section 4.3.2). Information on UK public infrastructure developments is also often provided freely and openly, therefore is more likely to be readily available than some of the international cases.

The historical case studies have therefore tended towards single assets, with limited cross-sector interdependencies and in some cases a purposeful reduction in the potential for system interactions. While the older case studies suggest a greater wealth of information to draw on, much of the data available is found to be inconsistent or incomplete (see Kline and Moretti (2014)), or has been gathered with a single purpose (Tagus River Bridge). Furthermore, the oldest case study (the TVA) represents a very different economic, environmental and technological climate. Its use is therefore likely to be inappropriate for drawing conclusions on modern UK infrastructure developments. The older studies also make it difficult to know what level of information was available at the beginning of the project, although a number of the newer studies have tracked inaccuracies in regard to costing. However, the cases do present a number of opportunities in regards to UK infrastructure, one example of multiple cross-sector asset investment (TVA) and one example of prior consideration of flexibility (Tagus River Bridge).

4.3.2 Current examples

The second set of projects presents examples that are currently being constructed or have been implemented in the last ten years (see Table 4.2)¹³. They overcome four of the issues of historical cases:

- Irrelevance technologically, environmentally, socially and economically;

¹³ Costs are quoted in 2010 prices unless otherwise stated.

- Lack of knowledge of information available at the concept stage;
- Lack of knowledge of behaviour without the project, for development of the counterfactual case; and
- Lack of data on current priorities such as carbon dioxide emissions.

Some information is provided for validation of the appraisal; however, unlike some of the ‘historical’ case studies, even the implemented pathway will require most of the data to be generated through projections and estimations. As previously noted, pathways not implemented will have to be generated in all types of case study.

Table 4.2 – Potential case studies (current)

Development	Description
Shinkansen High Speed Rail Link: Kagoshima-Chuo to Hakata, Japan (see Dimitou et al. (2013); and Omega Centre (2014f))	The project consists of a 257km railway line connecting Hakata Station to Nishi-Kagoshima Station, including five new stations. The Shin-Yatsushiro to Kagoshima-Chou section was finished in 2004 with the Hakata to Kagoshima-Chuo section finished in 2011 at a total cost of approximately US \$7.5bn. The aim of the project was to encourage population decentralisation and economic growth through regional industrialisation. While not stated as a priority for the project, the travel time between Hakata and Kagoshima by Shinkansen train is approximately ten minutes less than by air, which has led to the development stealing modal share from air transport.
Channel Tunnel Rail Link (CTRL) ¹⁴ and Interconnector, UK/France (see Dimitou et al. (2013), Omega Centre (2014g), Frontier Economics (2012) and Infrastructure UK (2011))	Finished in 2007, at a cost of approximately £5.8bn, the project provides a high speed rail service connecting central London to the Channel Tunnel and, through this, to the mainland Europe high speed rail network. The development included upgrades to London St Pancras station and the construction of three intermediate stations at Stratford, Ebbsfleet and Ashford. Interdependencies with the transport sector are mainly spatial with 60 rail bridges, 62 road bridges and 30 foot bridges. The project did, however, aim to transfer freight from road to rail to aid road decongestion and while airlines are the main competitors for the service, British Airways was appointed as one of the joint operators. Outside of transport, interdependencies were initially limited with London Electricity as a shareholder of LCR (appointed to design, build, finance and operate the CTRL) and water interconnections due to environmental protection (seven ponds and two wetlands created). However, the interconnector project (currently under construction) seeks to include a 75km 500MW capacity cross-channel electricity connection through the Channel Tunnel at a cost of approximately £205m.

¹⁴ Often now referred to as High Speed 1 (HS1).

Development	Description
Frog Island Mechanical and Biological waste Treatment (MBT) plant, UK (see Engineering and Interdependency Expert Group (2011))	Completed in 2007 at a cost of approximately £49m ¹⁵ , the Frog Island MBT plant provides an interconnection between the waste and energy sectors, treating up to 180,000 tonnes of household rubbish and recovering solid fuel by shredding and drying materials. The plant is dependent on transport and waste collection for resources, as well as energy and ICT for the operation/control of the plant.
Heathrow Terminals 5 and 2, UK (see Brady and Davies (2014), Infrastructure UK (2013a))	The project includes two phased upgrades to Heathrow airport: Terminal 5 was completed in 2008 at a cost of approximately £4.4bn, with Terminal 2 completed in 2014 at a cost of £5.0bn. The development included extension of the existing Heathrow Express and Piccadilly Line (London Underground) rail connections and an integrated IT system across all buildings as well as rail and air assets.
Isle of Grain Combined Heat and Power (CHP) plant, UK (see Engineering and Interdependency Expert Group (2011) and E.ON (2010))	Completed in 2010 at a cost of approximately £500m, the Isle of Grain CHP plant is one of the most efficient power plants in the UK. It produces 1,275MW of electricity and provides 340MW of waste heat to the Isle of Grain Liquefied Natural Gas (LNG) plant, allowing the LNG plant to reduce its carbon dioxide emissions by an estimated 350,000 tonnes per year. However, the two plants, have also been designed to allow independent operation. The CHP plant is reliant on electricity and water ¹⁶ infrastructure for operation, but transport interdependencies are also an issue with the one road to the Grain peninsula (essential for deliveries and staff access) recognised as a single point of failure. It is difficult to record the exact efficiency of the plant as demand for waste heat is constantly fluctuating.
West East Link Main (WELM) pipeline, UK (see Frontier Economics (2012))	Completed in 2012 at a cost of approximately £125 million, the project built a 55km pipeline capable of transporting 100 million litres of water a day between the Prescot and Woodgate Hill reservoirs in North West England. The development has strong interactions with the water supply system, aiming to reduce risks from climate change and increasingly strict water abstraction limitations, as well as providing redundancy for other supply assets. The pipeline also has spatial interdependencies with the transport and water sectors, crossing three motorways, six railways, trunk roads, canals and 28 watercourses. While it is reliant on energy and ICT for operation, only essential transmission assets were built as part of the project, with no additional assets allowed for as part of the design.
London Olympics, UK (see Engineering and Interdependency Expert Group (2011) and Brady and Davies (2014))	Completed in 2012, the LOCOG (London Organising Committee of the Olympic and paralympic Games) had a budget of £2.0bn and the ODA (Olympic Delivery Authority) had a budget of £9.8bn ¹⁷ . Most of this budget was for development of the site; however, £0.8bn of the funding was spent stimulating or accelerating transport infrastructure developments to improve accessibility. Provision of energy, ICT, water and waste for Olympians (in residence and competing) and visitors was provided by the construction of new transmission assets. Time, quality and cost were the primary foci of the project, but it had secondary objectives in relation to the long-term social and economic impacts of the games, including safety, accessibility, equality, employment and sustainability. A one day travelcard for London's public transport system was included in the ticket price to encourage use of sustainable transport.

¹⁵ 45m cost assumed to be in 2007 prices.

¹⁶ Draws directly from the river Medway, therefore reliant on water quality of the river.

¹⁷ Cost year of reference not stated in literature.

Development	Description
DP World London Gateway, UK (see Infrastructure UK (2013a) and Grace and Pearson (2013))	Completed in 2013, at a cost of approximately £1.3bn, the DP World 'London Gateway' container port and logistics centre was the largest privately-funded infrastructure project in the UK. It presents clear interdependencies between the water and transport sectors, including coordinated upgrades to nearby road and rail networks and extensive environmental work (dredging, flood risk mitigation and the creation of a 30ha compensatory wetlands habitat). The port is sited on the north bank of the Thames Estuary, with additional reclaimed land formed from the dredged material. As an area of international environmental significance, an extensive data collection and monitoring scheme has been created to assess the project's impacts.
Commonwealth Games, UK (see Audit Scotland (2015) and Commonwealth Games Federation (2014))	Completed in 2014, the Games cost £475 million. The development included transmission of existing infrastructure for the athlete's village and sports venues, preparation of Strathclyde Loch for the triathlon, energy generation through photovoltaics and a CHP plant, and multiple transport investments (upgrades and enhancements of four existing rail stations, refreshed subway stations and installation of smart ticketing, additional park and ride facilities, a cycle hire scheme, and 13.6km of new or refurbished walking and cycling routes). Furthermore, a number of transport developments were linked to the development including the M74 extension, the Clyde Gateway and refurbishment of Dalmarnock Station, Cathedral Street Bridge and Bell's Bridge.
Panama Canal, Panama (see CH2M HILL (2014a))	A US \$4.9bn expansion of the 50-mile waterway created in 1914, planned for completion in 2016. The project presents fundamental interdependencies between water and transport infrastructures. Work includes a new set of locks to allow an additional lane of traffic, doubling the canal's capacity and allowing much longer, wider ships to use the waterway.
Greater Manchester Smart Motorway, UK (see Butcher (2015) and Highways Agency (2014))	A £180m scheme to upgrade 17 miles of motorway between junction 8 of the M60 and junction 20 of the M62, one of the most congested motorways in the UK. The project follows test cases on the M42, M6 and M40 motorways, making use of ICT to ease and manage transport congestion. CCTV cameras will provide real-time traffic monitoring and over 200 overhead message signs will be used to inform drivers of travel times and lane closures. Furthermore, the signs will allow dynamic control of the roads to ease congestion (through variable speed limits and use of the hard shoulder) or aid emergency operations (lane closures). Construction commenced in 2014 and is aimed to complete in 2017.
Crossrail, UK (see Infrastructure UK (2011; 2013a; 2014) and Crossrail Ltd (2014))	Crossrail is a new 118km rail line running from Maidenhead and Heathrow Airport, through central London to Shenfield and Abbey Wood in east London. Construction commenced in 2009 with completion planned for 2019 and a total funding envelope of approximately £13bn. The project will increase rail transport capacity in London by almost 10 per cent, with a total of 40 stations (including 10 new stations) and 26 miles of tunnels. The 4.5 million tonnes of excavated material will be used to create a new 1,500 acre nature reserve in Essex.

Development	Description
Ebbsfleet, UK (see Infrastructure UK (2014) and Lewis (2015))	The development of a new garden city at Ebbsfleet, Kent. The development has been supported by a commitment of approximately £250m from the UK Government; with £80m to start development and stimulate further investment in the site in 2014 and a further £170m for infrastructure funding in 2015. The development will include 15,000 new homes and supporting infrastructure, with a planned review of transport provision (including HS1, Crossrail and existing local rail lines) and development of the A2 Ebbsfleet Junction. Plans are currently highly conceptual.
King's Cross Central, UK (see Mayor of London (2006), Engineering and Interdependency Expert Group (2011) and Frontier Economics (2012))	This mixed use development is currently under construction, aiming to be completed in 2020 at a cost of approximately £1.8bn. The development covers a 67 acre site in central London and is mainly focused on the development of residential, commercial and academic buildings as well as public spaces. However, it also includes the installation of entirely new energy, water, waste and ICT infrastructure. Most of the assets only transmit from the main grid systems; however, plans also include embedded photovoltaics and a CHP plant connected to a district heating system. Delivery of utilities (energy, water and sewage) will be coordinated through a single group of companies. Due to the site location, there are also spatial interdependencies with significant transportation developments including CTRL and upgrade works to King's Cross underground station.
Thames Estuary Asset Management (TEAM) 2100, UK (see CH2M HILL (2014b))	Awarded in 2014, TEAM 2100 is a £260 million 10 year flood defence programme representing the first decade of the 100 year Thames Estuary 2100 (TE2100) plan. It is one of the world's largest flood risk management programmes, requiring the maintenance, refurbishment and replacement of over 3500 assets along a 170km length of the Thames Estuary.

Some of the examples still relate to single sector assets. In line with the historic examples, these often show limited cross-sector interdependencies. The Shinkansen and CTRL lines, for example, do show interdependencies, but these are mostly limited to the transport sector (road decongestion benefits analogous to the historic airport rail links and competition with air transport like the TGV). However, many of the case studies in Table 4.2 show a much greater understanding of interdependency. Four of the examples are specifically designed to be multifunction site developments (the London Olympics, the Commonwealth Games, King's Cross Central and Ebbsfleet), requiring the development of assets from different sectors as part of the same project¹⁸. In all cases most of the assets were for transmission, connecting into the

¹⁸ Much larger multifunction site developments have been delivered in the Middle East; however, these require vast areas of land (for example, 5.2 million km² in the case of Al Raha Beach) that would be

existing UK national networks; however, the King's Cross Central and Commonwealth Games projects also include energy generation assets (photovoltaics and CHP plant), with King's Cross Central also planning for a coordinated approach to utility delivery.

Smaller developments also consider interdependency and in some cases actively seek to take advantage of it, through efficiencies (such as the Greater Manchester Smart Motorway), industrial symbiosis (such as the Isle of Grain CHP plant), or through new options enabled by the developments (such as the CTRL Interconnector¹⁹). The Isle of Grain CHP plant also shows that failure interdependencies have been considered, with the project noting the single access route to the site and the necessity of transport access for operation.

Phased integration of complexity (like the addition of the Interconnector to CTRL) is also more common than in the historic projects, with similar phasing or extension plans for the Shinkansen rail line and Heathrow terminals. However, in line with the extensions shown in the historic case studies, these extensions do not reflect additional flexibility, being either fully predetermined (in the case the Shinkansen route), or conceived after the initial project has been finished (in the case of Heathrow or the Channel Tunnel Interconnector). While these did not present future flexibility in reality, they present options which could have been prepared for. They could therefore be considered from this perspective within the proposed appraisal framework. In contrast, the TEAM 2100 project represents the first decade of the TE2100 100 year flood management plan for London. The pathways approach taken for TE2100 does provide flexibility and while only two pathways have been selected, the full list of options proposed could be explored from a multi-sector perspective with the proposed appraisal methodology.

unfeasible in the UK context. Such developments are therefore not considered as suitable case studies for this research.

¹⁹ It has been estimated that creation of a similar interconnector under the sea would cost in the region of £280-420 million (Infrastructure UK, 2011).

Modern social and environmental concerns are more prevalent in the case studies with one of the key benefits of the Isle of Grain CHP plant being the reduction in carbon dioxide emissions and most of the 'secondary priorities'²⁰ for the Olympics being based on its long-term social and economic legacy. These concerns also provoke greater data capture, with more innovative or controversial examples like the Frog Island MBT plant or DP World London Gateway subject to additional ongoing monitoring and analysis. Furthermore, the examples demonstrate a greater wish to fully understand the assets, with comments, for example, on the difficulty of recording exact data in the case of the Isle of Grain CHP plant. This greater wish for data and monitoring alongside more aligned environmental and social priorities suggests that the current cases will have more complete or precise data than the historic examples.

Our final criterion is a prioritisation for UK projects. The Shinkansen line is the only non-UK project in Table 4.2 and, alongside the 'historical' TGV project, strongly mirrors the CTRL, suggesting that it would not provide additional value. Given that the use of a Japanese case study would be an abstraction from the UK focus of the research, the Shinkansen will not be taken forward as a potential case study. However, the comparison highlights a difficulty of high speed rail as a possible case study. While the Shinkansen line is limited to Japan, the travel is across regions and therefore the project is a national (rather than a regional) investment. CTRL goes further, providing greater accessibility and connectivity to mainland Europe. It therefore provides international benefits. As the proposed appraisal framework, takes a regional perspective, should such a nationally or internationally important project be taken forward, the implications for the value estimation will need to be carefully considered.

Considering the analysis above, many of the current case studies provide examples of interdependency and potential flexibility through later additions to the project. Their effects are

²⁰ Primary priorities were time, quality and cost.

also more aligned to current environmental and social concerns, with some specifically noting that such impacts are being recorded and monitored. Furthermore, all but one is in the UK. As a group the current case studies therefore appear to more closely reflect our criteria. However, only CTRL, the London Olympics, DB World 'London Gateway', the Commonwealth Games, Ebbsfleet and Kings Cross Central show investment in cross-sector assets and, in each case, the number of infrastructure sectors and interactions is limited. More than one case study would need to be taken forward to more fully sample the possible interactions between the different sectors.

4.3.3 Proposals

The final set of potential case studies are projects for which construction has not yet started (see Table 4.3)²¹. They therefore range from conceptual ideas which may never be implemented, to agreed projects. This group most closely reflects the stage at which the proposed appraisal methodology is designed for, allowing strategic decisions to be made prior to construction of assets. Project data is therefore that which would be available to a decision maker when applying the framework, providing the opportunity to consider whether the proposed appraisal methodology is feasible. Furthermore, contrary to the historic case studies, the environment prior to construction is fully understood and as the newest projects, they should most closely reflect current technology and environmental, social and economic concerns. However, as they have not been implemented, all benefit and impact pathways must be projected. It will also not be possible to validate costing data; however, the probable uncertainty of estimates can be assessed by comparison to other projects, using methods such as reference class forecasting (see Flyvbjerg and COWI (2004)).

²¹ Costs are quoted in 2010 prices, where the base year for costing is not stated, it has been assumed that costs are priced for the year of publishing.

Table 4.3 – Potential case studies (proposals)

Development	Description
High Speed 2 (HS2), UK (see Frontier Economics (2012), Rosenberg and Carhart (2014), and Infrastructure UK (2011; 2012; 2013b))	Construction of a high speed rail service, initially from London to Birmingham (phase 1) with extensions to Manchester and Leeds (phase 2). Passive interconnections to CTRL and Heathrow Airport will also be included. The construction is planned to start in 2017, with completion in 2033. A maximum funding envelope has been set at £40.5bn for construction and £7.1bn for the rolling stock ²² . Options for extending the project were identified by Rosenberg and Carhart (2014) and included use the rail corridor for utility lines (electricity, ICT or water) or for additional flood protection. The development is highly reliant on the electricity ²³ and ICT networks, but there are no current plans to develop further generation assets.
Thames Tideway Tunnel, UK (see Infrastructure UK (2011; 2012))	A 25km interception, storage and transfer sewer under central London to ensure that untreated sewage no longer escapes into the River Thames after heavy rainfall. Main construction is planned to start in 2016, with completion in 2023, costing approximately £3.8bn.
Lower Thames Crossing, UK (see Carhart (2014), Infrastructure UK (2011; 2014) and Highways England (2015))	Governmental commitment to build a new road crossing across the Thames was given in 2011 in light of growing congestion on the Dartford Crossing. Public consultation on the final option is planned for 2016, with construction starting in 2021 to allow implementation in 2025 (assuming public funding is granted). Estimated Benefit Cost Ratios (BCR) for the scheme are low, with the project promoted based on aiding regeneration and connectivity. Options for extending the project were identified by Carhart (2014) and included using the crossing to generate electricity or transmit utilities, combining it with flood defences and sharing construction resources with other parallel projects. Estimates for cost range from £1.2bn to £3.4bn depending on the option chosen.
Northern Line extension, UK (see Ward (2014))	The extension of the current London Underground Northern Line from Battersea to Kennington and the development of two new stations at Nine Elms and Battersea. The project will cost approximately £890m and is aimed for completion in 2020. The development will create spatial interdependencies with the Vauxhall, Nine Elms, Battersea (VNEB) Opportunity Area (OA), which currently includes proposals for a range of transport improvements, provision of new infrastructure transmission assets, development of a low carbon district heating network and improved flood mitigation measures. Options for extending the project were identified by Ward (2014) and included delivering utilities through an integrated provider, sharing the rail tunnel with other infrastructure transmission assets and co-location of assets with the VNEB OA.
Heathrow expansion, UK (see Heathrow Airport Limited (2013))	Proposal submitted to the Airports Commission in 2013 suggesting three alternatives for delivering a third runway at Heathrow. No rail or road upgrades are included within the £14-18bn budget, although plans for Crossrail to service the airport are noted. While asset development is limited to the (air) transport sector, the sustainability of the proposal has been considered, with aims to minimise energy and water demand and avoid waste where possible. The 'South-West option' would involve building over land which is currently used for water storage (reservoirs), therefore, this option has stronger interdependencies with the water sector than the alternatives.

²² Trains.

²³ Would represent approximately 0.5 per cent of the UK's electricity demand.

Development	Description
Severn Barrage, UK (see Department of Energy and Climate Change (2010))	A proposal to build a tidal barrage across the Severn Estuary. The barrage could potentially provide 5 per cent of the UK's current electricity capacity; however, the development would be likely to cause significant environment damage on a site that is internationally protected for nature conservation. Furthermore, the development would be likely to necessitate additional flood protection measures if current flood risk levels are to be maintained. Five possible schemes were reviewed in 2010 by the UK Government, costing between £5.1bn and £34.3bn and generating 1.2-15.6TWh/y.
Wave powered desalination plant, Australia (see Clifford (2013) and Water Technology (2014))	The world's first wave powered desalination plant. Interaction between waves and submerged buoys generate the energy for drive pumps which are used to pressurise water. This can then either be used to drive hydroelectric turbines to generate the energy, or used directly for reverse osmosis desalination. An initial pilot project was supported by a US \$1m federal grant and was completed in 2014. Costs for the full plant have not yet been estimated.
Temple Quarter Enterprise Zone, UK (see CH2M HILL (2013) and Bristol Temple Quarter Enterprise Zone (2013))	Approved by HM Treasury in 2013, the proposal is for the development of a 70 hectare site in Bristol. The development includes a number of infrastructure investments centring on improving access to the site. These include: £19m to improve vehicle, cycling and pedestrian access to the area; £180m for a new citywide MetroBus scheme; and a new multi-lane bridge costing approximately £10m. ICT developments are also planned with a £10m project to provide superfast broadband for businesses. Parallel developments will see electrification of the London to Bristol rail line and redevelopment of Temple Meads railway station.
Thames Hub Vision, UK (see Foster+Partners et al. (2011a; 2011b))	Formally proposed in 2011, the Thames Hub Vision is a £50bn proposal for a multi-sector infrastructure hub, centred around a new hub airport in the Thames Estuary. Additional transport assets include road upgrades and a high speed and commuter rail orbital connecting HS1 and HS2 while circumventing London, aiming to reduce road congestion by encouraging a modal shift of travellers and road freight to rail. Air travellers will be strongly encouraged to make use of the rail system to travel to the airport, with an active traffic management policy limiting onsite parking and providing long-term park and ride facilities at orbital stations. The project also includes a new Thames flood barrier, integrated with road and rail crossings and tidal energy generation sufficient to support the airport. Significant land reclamation would be required, firstly for the airport site itself and secondly for compensatory wildlife habitat for that lost during construction.

Some of the 'proposal' case studies are strongly analogous to historical or current cases, except for technological improvements that have occurred in the intervening period. For example, the Northern Line extension to Battersea is akin to the historical Jubilee Line extension, HS2 can be compared to CTRL, the TGV or Shinkansen, and the third runway extension to Heathrow is an extension of the Terminal 2 and 5 upgrades. In these cases a choice must be made between the additional information provided by the older cases and the more current framing of the

proposals technologically, environmentally and socially. However, there are also some revolutionary ideas, including those driven out of necessity (for example the Thames Tideway sewer), the pursuit of a low carbon future (for example the Severn Barrage), or both (for example the wave powered desalination plant). While some of these proposals may never be implemented, they have the potential to consider much greater complexity and therefore more fully test the proposed appraisal methodology.

Three of the proposals include cross sector asset investment²⁴, with the Thames Hub Vision being specifically derived out of a wish to consider infrastructure assets as a system of systems, aiming to recognise interdependencies and maximise beneficial systems effects (Foster+Partners et al., 2011a). However, even where the project assets belong to only one sector, the complexity introduced by cross-sector interdependencies is more widely recognised than in the historical and current examples. Indeed, three of the projects have reviewed the opportunities for increasing the complexity and interdependency of the initial designs for greater benefit (see Carhart (2014), Rosenberg and Carhart (2014) and Ward (2014) for the Lower Thames Crossing, HS2 and Northern Line extension respectively). These interdependencies build on the lessons learned from other projects, particularly the opportunity to make use of the space in and around infrastructure assets. The inclusion of utility lines in rail corridors, for example, was implemented as part of the CTRL Interconnector and has been now proposed as part of HS2, while the inclusion of energy generation assets has been proposed as part of the Lower Thames Crossing. However, many of these opportunities are simple additions and have no, or very little, interaction with the fundamental proposal. The HS2 project has not investigated how system benefits can be derived from the utility line and the Lower Thames Crossing has little power requirement. Unless the additional infrastructure assets derive significant benefits for the

²⁴ The Thames Hub Vision, the wave powered desalination plant and the Temple Quarter development.

proposals, it is unlikely that stakeholders will be invested in their delivery and they may be lost over time under the constraints of delivery deadlines and budget.

Designed interdependencies aimed at realising system benefits within the proposals are rarer, limited to the wave powered desalination plant (making use of the pressurised water for reverse osmosis directly) and the Thames Hub Vision (for example integrating a rail crossing into a flood barrier to allow a rail orbital and actively managing road access to the airport to encourage rail uptake). In these cases the delivery of the 'additional' infrastructure assets is integral to the success of the proposal and therefore must be prioritised throughout design and implementation. Both proposals also generate renewable energy and attach this capacity to the assets demanding it. They therefore promote greater understanding of the demands of the assets on other sectors and pass on some responsibility for managing this demand, limiting operational costs if the demand can be kept to that supplied directly.

None of the projects consider flexibility specifically. However, potential flexibility could be derived from considering some of the assets or developments within the proposals as optional. It could therefore be considered for the proposals where more than one infrastructure asset is included (Thames Hub Vision, wave powered desalination plant and Temple Quarter development), where options have been proposed by interdependency studies (HS2, Lower Thames Crossing and Northern Line extension), or where the developments are phased. The Heathrow extensions present an interesting case of the latter, with two upgrades completed as part of the 'current' case studies (Terminals 2 and 5) and a proposal for the development of a third runway. It could therefore be used to consider whether the terminal upgrades enabled the runway development and whether more flexible design could have provided greater benefit in light of this further expansion.

Again, our review has focused on UK case studies with only one proposal in Table 4.3 from outside the UK. The wave powered desalination plant is a proposal for Australia, which, while a British colony and a mature economy, has many differences to the UK. Water scarcity is a particular concern, therefore the benefits of a desalination plant in Australia may be very different to a similar project in the UK. As our review has highlighted other multi-asset investments with system benefits (the Isle of Grain CHP plant current case study and the Thames Hub Vision proposal), it is unlikely this case will offer substantial additional benefit and therefore it shall be discounted as a potential case study. While the remainder of the proposals are UK based, three have national or international impact (HS2, Heathrow expansion and the Thames Hub Vision); therefore, their appropriateness for a regional assessment will need to be carefully considered if taken further.

Finally, while the proposals have no validated information, they offer significant benefits for the counterfactual case. Each proposal has been made against the dynamic background defined by the previously agreed proposals and those current projects already under construction. Indeed many of the proposals mention the other projects, noting interdependencies and constraints (for example between HS2 and CTRL (HS2 Limited, 2013), or between Crossrail and the Heathrow expansion (Heathrow Airport Limited, 2013)). Therefore both the single 'do minimum' case (in the absence of the case study) and the dynamic baseline (as the case study is implemented, see Chapter 3) will be easier to define.

In conclusion, the proposals offer similar benefits to the current case studies, being relevant to current technologies and priorities. However, in most cases they provide a greater consideration of interdependencies, both internally, to improve the proposals themselves, and externally, with other prior developments. They also provide the potential for revolutionary proposals which, while they may never be implemented, could provide more extreme cases to

test our methodology. As noted in Section 4.2.2, the more complex the case studies, the more information provided, but the fewer that can be considered. Use of such a complex proposal may therefore limit the number of case studies that can be appraised.

4.3.4 Conclusions and initial choice

Returning to our two critical choice criteria, there are fourteen potential case studies with multiple asset investments (see Table 4.4). Of these, the Tagus River Bridge, Heathrow Terminal upgrades and TEAM 2100 project only contain single sector investments, suggesting the remaining eleven show greater diversity in the assets included. Data is available for all the projects, indeed, for two of the current case studies (Frog Island MBT and DP World London Gateway), additional monitoring is being conducted to ensure their environmental performance; however, not all studies show the same level or detail of analysis. The historical studies are particularly problematic with current priorities (such as carbon dioxide emissions) not recorded and in the case of our oldest potential case study (the TVA), data found to be inconsistent, with some missing or poorly recorded. Furthermore, Kline and Moretti's (2014) study of the TVA demonstrated how difficult it was to project a counterfactual for a historical case. The TVA therefore presents a weaker case study than similar current or proposed UK regional developments (the London Olympics, King's Cross Central and Thames Hub Vision), which will be more applicable given the focus of this research.

Table 4.4 – Case studies with multiple infrastructure asset investments (non-UK highlighted)

Development	Multiple Assets	Interdependencies	UK	Notes
TVA	Energy and transport (road and canal)	Limited	No	Data found to be inconsistent, incompleteness and imprecise; counterfactual difficult to determine
Tagus River Bridge	Transport (road and rail)	Rail and road (decongestion)	No	Planned flexibility

Development	Multiple Assets	Interdependencies	UK	Notes
CTRL and Interconnector	Transport (rail) and energy	Airport (competition, ownership), energy (ownership) and spatial interdependencies with road and environmental water concerns	Yes	N/A
Heathrow Terminals 5 and 2	Transport (airport and rail)	Rail (surface access) with integrated IT across airport and rail	Yes	Phasing could be used to investigate flexibility
London Olympics	Mainly transport (access), but also energy, ICT, water and waste transmission assets	Transport, energy and ICT critical for facilitation of games	Yes	N/A
DP World London Gateway	Transport(port, some road and rail) and water (habitat)	Transport/water interface, water (operations and environmental), road and rail (freight)	Yes	Additional environmental data recording
Commonwealth Games	Transport and energy, also ICT, water and waste transmission assets	Transport, energy and ICT critical for facilitation of games	Yes	N/A
Ebbfleet	Mainly transport (access), but also energy, ICT, water and waste transmission assets	Significant spatial interdependencies with transport	Yes	Plans highly conceptual
King's Cross Central	Energy (generation), water, waste and ICT transmission assets	Significant spatial interdependencies with transport	Yes	Delivery of utilities through a single group of companies
Wave powered desalination plant	Energy (generation) and water (desalination)	Energy/water interface	No	Systems benefits
HS2	Mainly transport, other assets currently being considered	Airport (competition), road (decongestion), potential spatial interdependency with utility lines/flood protection	Yes	Phasing could be used to investigate flexibility
Lower Thames Crossing	Mainly transport, other assets currently being considered	Potential for spatial interdependency with water (flooding), energy (tidal generation) or utilities transmission	Yes	N/A
Northern Line extension	Mainly transport, other assets currently being considered	Spatial interdependencies with the VNEB OA infrastructure developments (transport, utilities, district heating and flood mitigation measures)	Yes	N/A

Development	Multiple Assets	Interdependencies	UK	Notes
Thames Hub Vision	Energy, transport (air, rail and road) and water (flood)	Road (decongestion and access), rail (access), tidal energy for airport operations, water (environmental and reclamation)	Yes	Systems benefits, potential to consider how assets enable other developments

Considering the remaining cases against our three priorities, only two are from outside the UK.

The wave powered desalination plant, was dismissed when compared to other proposals and the Tagus River Bridge has already been noted to only contain single sector assets. While the Tagus River Bridge was highlighted as a unique historical case, offering the potential to consider the value of flexibility, when compared to the proposal case studies, both the Lower Thames Crossing and Thames Hub Vision present similar opportunities and do so within the UK context. We can therefore limit examples to UK cases.

Of the UK case studies in Table 4.4, all include some level of interdependency, although in many cases this is indirect, through spatially sharing land, or competing with other assets. In some cases this separation between sectors may be intentional, possibly to avoid cascade failures. Indeed, the JLE specifically chose to ensure communication equipment was standalone (Omega Centre, 2014b). If we wish to maximise interdependencies, we must focus on those projects that seek complementary assets and system effects rather than straightforward additions with limited impact on the proposal design. This could be present in three ways:

- Recognition of cross-sector demands, such as the surface access developments included within the DP World 'London Gateway', Heathrow expansions and Thames Hub Vision;
- Industrial symbiosis or system effects, such as the Isle of Grain CHP plant heat and active airport traffic management to promote the Thames Hub Vision rail orbital; or

- Understanding of how one asset enables future development, such as use of a Thames River road crossing to provide future rail crossings, a flood barrier, or energy generation, as proposed by both the Lower Thames Crossing and the Thames Hub Vision proposals, or potentially the phasing of the Heathrow expansions.

This last facet of the interdependencies also presents an opportunity to understand the flexibility of a development and to calculate the value inherent in such designs to adapt to future change.

From the perspective of our five criteria/priorities and particularly our analysis of interdependencies, the project which most fully captures the facets of infrastructure appraisal complexity is the Thames Hub Vision. In addition, it presents a regional perspective and significant data has been put together as part of the proposal documentation, therefore is available for the study. Furthermore, the high population density of London is likely to amplify impacts, testing each of the 15 performance indicators identified in Chapter 3.

Given the complexity of the Thames Hub Vision and the scope of this research, if chosen, the proposal would likely need to be the only case study considered. While it fulfils our preliminary criteria and priorities for the case study, in the next section we consider the proposal more carefully, particularly whether it provides sufficient information to be the standalone case study for the research.

4.4 The Thames Hub Vision

4.4.1 Overview of the proposal

The Thames Hub Vision is a proposal for a £50 billion multi-sectoral infrastructure hub developed by Foster+Partners, Halcrow and Volterra (Foster+Partners et al., 2011a), most commonly portrayed through the artist's impression in Figure 4.1.

Figure 4.1 – Artist's impression of the Thames Hub Vision (Foster+Partners et al., 2011a)



The development is centred to the east of London in the Thames Estuary (see Figure 4.2) and includes:

- A new four runway 150 million passenger per annum (mppa) hub airport, built on a platform of reclaimed land 7 metres above sea level off the Hoo Peninsula in the Thames Estuary. The airport could potentially be built by 2028 and would provide capacity for an additional 64mppa over Heathrow, the UK's current hub airport (Department for

Transport, 2011b). Furthermore, with the prevailing winds in the area, it is approximated that 70 per cent of landings could be from the east, with departures to the west (Foster+Partners et al., 2011b), significantly reducing flights over central London and thereby both noise and security risk.

- A new Thames flood barrier near Tilbury, with integrated road and rail crossings (see Figure 4.3), increasing connectivity between north and south London and protecting 2.5 times the land area protected by the current Greenwich Thames Barrier.
- A high speed and commuter/freight rail orbital, connecting CTRL (HS1) to HS2 (see Table 4.2 and Table 4.3 respectively) and four of the radial mainline rail routes²⁵. The orbital provides the opportunity to circumvent London, freeing up capacity on the central London rail and tube routes. Furthermore, through the radial mainlines, it can interconnect with the London ports²⁶, increasing rail freight and decreasing road congestion. The line will consist of two high speed and two commuter/freight lines, capable of running a service of 40 trains per hour. It will have six interchange stations with park and ride facilities (see Figure 4.4) which, alongside restricted airport parking, are designed to substantially increase modal use of rail for the airport²⁷. The line will follow the route of the M25 motorway to reduce the noise impact of the development.
- Improved road connections to support the airport and connect the new road crossing to the south London motorways, which, alongside the rail connections, substantially increase accessibility to and from the Hoo Peninsula²⁸.

²⁵ West Coast, Midland Main line, East Coast and East Anglia lines.

²⁶ Over 50 per cent of container traffic in the UK arrives within 50 miles of the Thames Estuary and this is set to rise now that the DB World London Gateway is able to receive the world's largest container ships. Over 80 per cent of the onward transport of these containers is conducted by road (Foster+Partners et al., 2011b).

²⁷ The aim is for a 60 per cent share by rail.

²⁸ The Isle of Grain currently has no rail line and is only accessible via a single 'A' road.

- Tidal energy generation, either through generators integrated into the new flood barrier and crossing or through an installation of hydropower arrays, providing approximately 525GWh of electricity, sufficient to support the demands of the airport.
- The redevelopment of Heathrow to provide more residential and commercial space for London, making use of its existing rail, underground and road transport connections.

Figure 4.2 – Thames Hub Vision infrastructure elements (adapted from Young and Hall (2015))

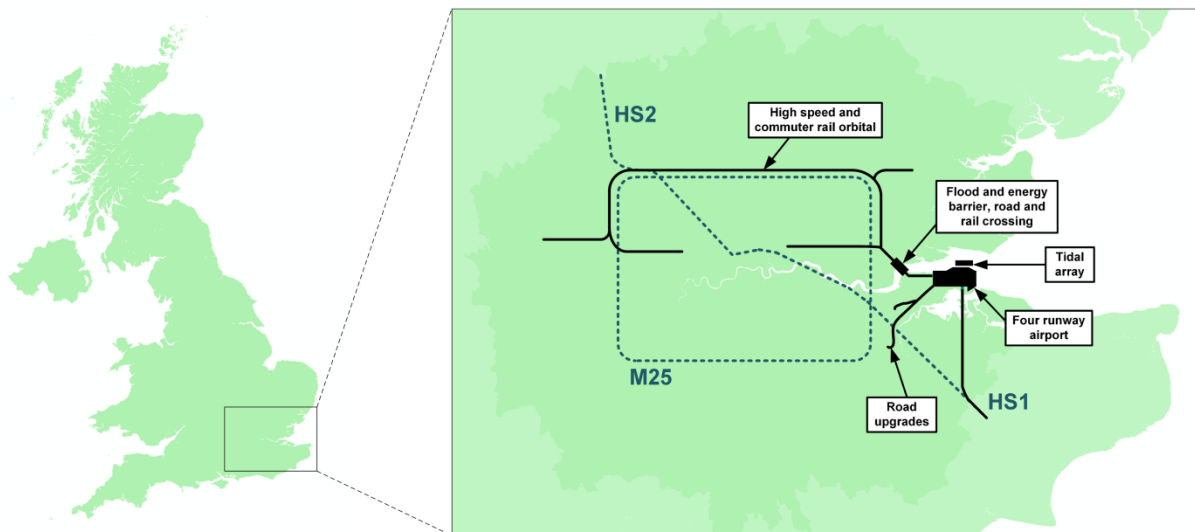


Figure 4.3 – Artist's impression of the barrier and transport crossings (Foster+Partners et al., 2011a)

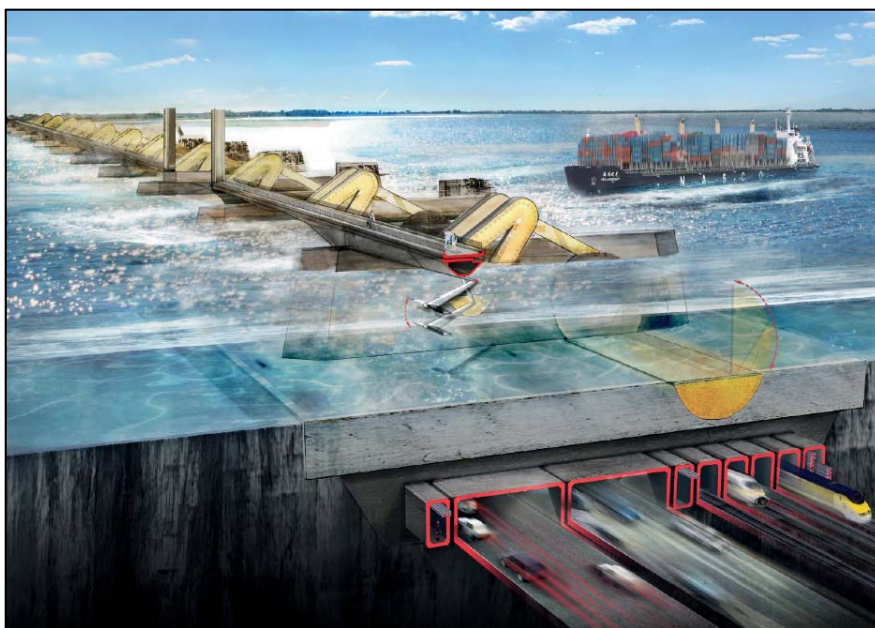
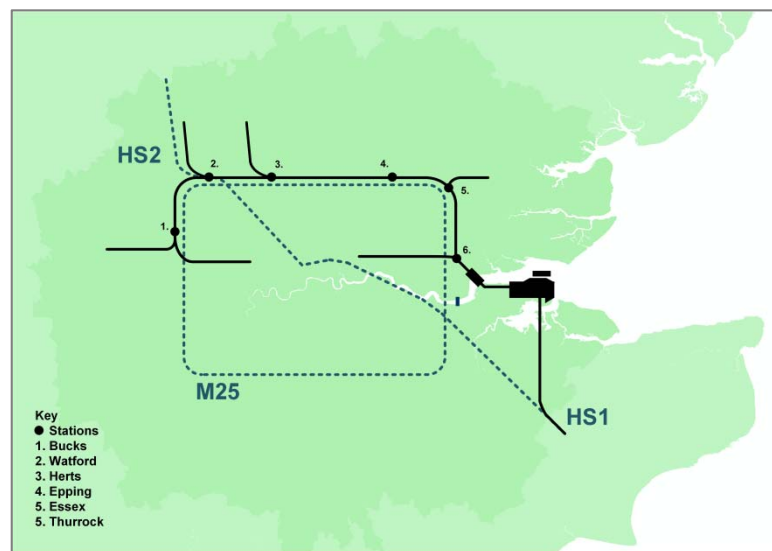


Figure 4.4 – Rail orbital stations and radial mainline interconnections



The proposal was developed in response to the UK's aging and increasingly capacity constrained infrastructure, particularly London's airports, rail and road networks, which form a bottleneck to efficient national (and international) passenger and freight transport. Therefore, while all the developments are located within the London region, there are wider economic impacts for other regions and the nation as a whole.

Taking air travel as an example, Heathrow, is already perceived to be at capacity, operating at runway utilisations of approximately 98 per cent, with many of the other London airports nearing capacity²⁹. At Heathrow, this has constrained growth in long haul destinations. Airlines focus on the most popular and profitable routes (Airports Commission, 2013), with no spare capacity for experimental services to emerging markets. Frontier Economics (2011), estimated that the cost of this specialisation on the UK economy as approximately £1.2bn a year.

Furthermore, similar restrictions on domestic routes³⁰ undermine the airport's ability to function

²⁹ Gatwick, City Airport and Luton are predicted to reach full capacity by 2030 and Stanstead in 2041 (Airports Commission, 2013). International guidance (followed by the three other main European hubs) recommends runway utilisations of only 70-75 percent (Transport for London, 2014).

³⁰ See Airports Commission (2013).

as an efficient hub (Transport for London, 2014) and threaten the economies of UK regions (Transport for London, 2014) which rely on Heathrow to export high value manufacturing products (Airports Commission, 2013).

Alternatives to the Thames Hub Vision airport have been proposed, one of which was considered as part of the case study review process (Heathrow third runway expansion, see Table 4.3). This was noted as presenting the opportunity to consider phasing and flexibility by combining with the earlier Heathrow Terminal 2 and 5 expansions (see Section 4.3.3). However, in line with the other proposals for expansion of London airports, interdependencies between the airport and other transport assets or other sectors were largely ignored, with no other assets included. The case was therefore not taken forward.

The Thames Hub Vision was found to be unique among the proposed case studies in its system scale consideration of integrated infrastructure requirements and benefits, being the only case to provide all critical choice criteria and priorities identified. However, its scale, location and breadth of consideration create additional complexities that must also be included within its appraisal. It therefore provides a more challenging test case for appraisals. Indeed the proposal documents specifically noted the shortcomings of existing appraisal methods for such a project, stating that: “The incremental nature of current modelling and appraisal tools are not suitable for estimating benefits of such a large, transformational and integrated project” (Foster+Partners et al., 2011b). Over the next two sections, we consider these additional complexities, in the context of regional infrastructure appraisal and whether these are sufficient for the Thames Hub Vision to be the only case study considered by this thesis.

It should be noted that, while this case study is drawn from the original Thames Hub Vision design, a revised proposal, focusing on just the airport element was submitted to the Airports

Commission as part of their review into increasing the UK's airport capacity (Foster+Partners, 2013). The proposal was reviewed alongside 51 other long-term plans, including seven for a new hub in or alongside the Thames Estuary. The commission's interim report (Airports Commission, 2013) concluded that there would be a need for an additional runway's worth of capacity in South East England by 2030 and, analysing the proposals against this target, shortlisted two existing airports (Heathrow and Gatwick) at which to undertake further analysis of possible expansion plans. In addition, they proposed to undertake a feasibility study into building a new airport on the Isle of Grain, assessing whether such a proposal was sufficiently credible to be considered against the shortlisted expansion proposals. The conclusions of this feasibility study (Airports Commission, 2014c) were that the obstacles in delivering an inner Thames Estuary airport were significant and alongside potentially high costs and uncertain benefits, such proposals should not be considered further. The Thames Hub Vision airport proposal was therefore dismissed alongside the other inner Thames Estuary proposals at this point. The Commission's final report (Airports Commission, 2015) concluded that the optimal solution would be to create an additional North West runway at Heathrow.

4.4.2 Benefits of the proposal as a case study for the appraisal methodology

As noted in Section 4.3.4, the Thames Hub Vision inherently meets the case study choice criteria, being a UK case study with multiple varied, complex and interdependent infrastructures and with the proposal team putting together significant information prior to release. This data has been made fully available for use in this thesis through the proposal partner Halcrow, who are partially funding this research. However, in addition to these criteria, the proposal offers a number of benefits, both in the variety of the assets and in the complexity and size of the outputs.

Three sectors (energy, water and transport) are represented along with three different modes of transport. Each asset is a significant investment in its own right and is dependent on at least one of the other assets, as shown in Figure 4.5. The assets also show a mix of financing types, with the proposal documents suggesting that the barrier, road and rail developments be publically funded and the airport be privately funded. The case study therefore tests whether the appraisal methodology can capture the performance of multiple different sector assets, of the system as a whole and against the context of both private and public funding. Furthermore the specific assets of the case study recognise different types of service and timings of service delivery. The barrier provides safety and asset protection, but only on occurrence of an extreme weather event, while the energy and transport assets provide additional capacity and/or reliability on a daily basis.

Figure 4.5 – Map of Thames Hub Vision interdependencies

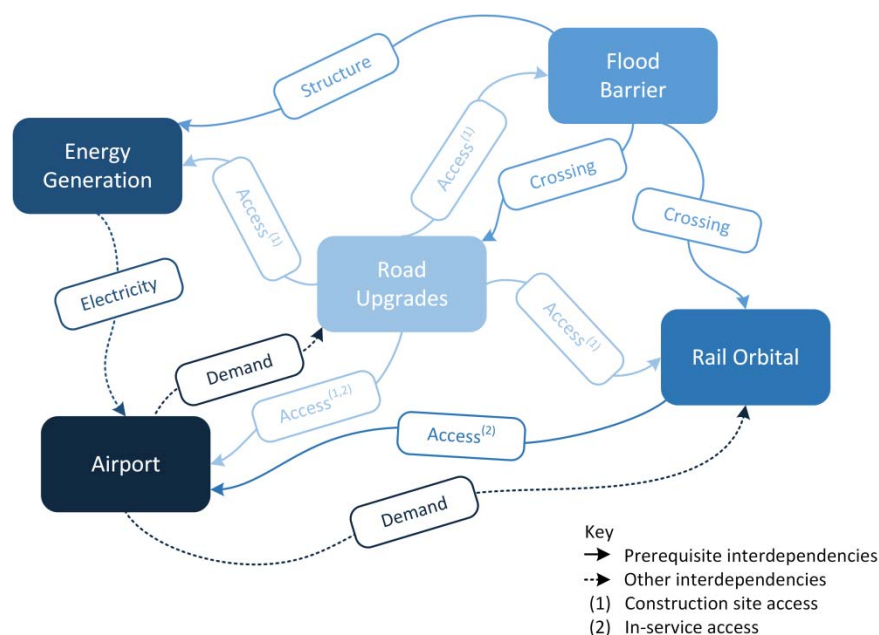


Figure 4.5 also shows that some of the assets are enabled by the other investments, with the road providing site access for construction, the barrier providing one alternative for energy generation and a means for the road and rail developments to cross the River Thames, and the road and rail developments facilitating access to the airport. The developments therefore have

prerequisite conditions in the form of the other infrastructure assets. Combining these prerequisite conditions we can develop potential development pathways, exploring the value of initial investments as enablers of future investments. The interdependencies in Figure 4.5, will therefore allow us to undertake both the portfolio and pathways analysis stages of the appraisal methodology.

The social and environmental impacts of the developments are also significant and will be magnified due to the high population density of London. For example, the airport would require the loss of approximately 12km² of internationally protected waterbird habitat and interrupt the open marsh landscape, reducing the visual amenity of the area. However, by reducing flights over London, it will also greatly reduce the number of people currently exposed to noise nuisance³¹. As noted in Chapter 2, such impacts must be valued using shadow pricing techniques, which are far more uncertain than market valuations. The case study therefore provides the opportunity to compare the uncertainty of the different impacts of the development and whether this is suitably captured and segregated by the attributes within the appraisal methodology.

Finally the cross-regional and national impacts of the rail and airport infrastructure provide the potential for wider economic impacts. The proposal therefore provides the potential to examine the spatial effects of the developments and how these factors can be brought into the appraisal process. This reflects the last of our five increments of complexity: the feedbacks between infrastructure developments and the investment landscape.

The case study therefore provides the potential to test all stages of the methodology and all five increments of complexity. Furthermore, it includes all six facets of complexity identified in

³¹ Currently 766,000 people are exposed to noise in excess of 55dB Lden (Transport for London, 2014).

Section 4.2.1 as intrinsic to infrastructure appraisal, with multiple resource types, impacts, sectors, interactions and dynamics. In addition, the variance between the assets will test the resolution of the methodology for different scales and types of infrastructure investments. The links between the proposal and current debates regarding airport expansion will also ensure the research is relevant to current thinking and technologies. Finally, considering the developments in Table 4.2 and Table 4.3, a number are in the same region as the Thames Hub Vision (see Table 4.5). We therefore have information on which investments are likely to be occurring in the absence of the case study and/or in parallel to it, allowing us to derive our ‘do minimum’ case and the dynamic baseline.

Table 4.5 – Current and future projects in the London region

London Projects	Impact on Thames Hub Vision Elements
Heathrow Terminals 5 and 2	Already completed, no impact
Isle of Grain CHP plant	Already completed, no impact
Thames Tideway	Parallel project, no impact
Northern Line extension	Parallel project, no impact
London Olympics	Already completed, possible indirect impact through changing population distribution of London
King’s Cross Central	Parallel project, possible indirect impact through changing population distribution of London
Crossrail	Parallel project, provides greater links to Heathrow in counterfactual case
DP World London Gateway	Already completed, creates rail/road freight demands
CTRL and Interconnector	Already completed, link to rail orbital, connection into mainland Europe
HS2	Parallel project, link to rail orbital, connection to Northern England
Lower Thames Crossing	Parallel project, provides additional Thames River road crossing, limiting demand for Thames Hub Vision road crossing
TEAM 2100	Parallel project, counterfactual case for flood demand
Heathrow expansion	Proposed project, provides a counterfactual case for airport expansion

4.4.3 Limitations of the proposal as a case study for the appraisal methodology

In Section 4.2.1 we justified the lack of prioritisation between ex ante or ex post cases, noting that each had benefits and limitations. The main limitation of an ex ante choice was the lack of validated data. However, given that multiple pathways are to be explored by the methodology,

a single validated development pathway (as given in the ex post case) provides little advantage. In addition, the conceptual nature of the proposal, while appropriate to the type of projects we wish to assess with the methodology, inherently means that the design is not fixed. For example, it would be expected that the development of the orbital stations would promote local commercial and residential development; however, these were not directly discussed in the initial proposal and therefore have not been included within our case study³². These limitations must be remembered and analysed as part of the appraisal, considering additional options on the developments, the sources of the data being used and their likely uncertainty.

As previously noted, past developments can be used to provide statistical information on the uncertainty of cost estimations at various stages of the design process. Such 'reference class forecasting' is already undertaken within transport sector appraisals in the UK (see Flyvbjerg and COWI) and will be included as part of the appraisal methodology. However, the available statistical data focuses on costs and demand revenues. It will therefore be necessary to assess any bias that may be attached to other factors of the scheme.

In the UK, future socio-economic and technical projections have been created by Government Departments and Agencies. Not only do these provide some consistency between estimates, each being based on the Office of National Statistics (ONS) population projections, but they remove any biases specific to the promoter. In addition, the data is freely available, regularly updated and projected over the long-term. This current and ongoing availability is particularly important if it is to form the basis of a methodology that is to be used and reviewed over the long-term.

³² The potential for such developments to make locations more attractive as places to live is, however, considered in Chapter 8.

Two Government provided data sources are of a particularly strong pedigree and have been used by multiple studies. The first of these are the population projections provided by the ONS. These are derived and validated against the decadal census also undertaken by the ONS, the most complete review of the UK's population. Multiple projections are provided, with each being updated regularly to reflect to new findings. As noted above, these projections form the basis for many of the other departmental projections, and have been applied in similar infrastructure research projects, such as the Infrastructure Transitions Research Consortium fast track analysis (Hall et al., 2012a) and the Land Use Transport Interaction (LUTI) models discussed in Chapter 8. The second dataset is that provided by the Department for Transport for their WebTAG appraisal process. The data and methodology is based on research commissioned by the department for this purpose (Headicar, 2009)³³ and is considered to be one of the most comprehensive transport appraisal methodologies in the world (Sumner, 2011). It has been widely used and is cited by many studies including other integrated infrastructure appraisals, such as INTRA-SIM (Hickman et al., 2012)), and infrastructure land use change studies, such as the Tyndall Cities project (Dawson et al., 2011).

We will therefore use Government projections (particularly the ONS and WebTAG datasets) wherever possible, limiting our reliance on the proposal documentation to costing data (which will be assessed against historical inaccuracies), engineering specifications of the development (spatial footprint and maximum capacity) and operational resources which cannot be derived from existing assets³⁴. Demand, for example, while estimated within the proposal documentation, can (and will) instead be estimated based on Government projections, current usage and academic studies into long-term usage. Where it cannot be estimated by

³³ See, for example, Nellthorp et al. (2007) for derivation of the costs of noise nuisance.

³⁴ For the Thames Hub Vision this is limited to the energy and staffing demands of the airport, which cannot be estimated from Heathrow due to new technologies in the former case and the size and impacts of integration with sea and rail freight in the latter case.

Government projections or past information, such as for the inherent demand created by a new service, it will be explored from an uncertainty perspective, but not included within the benefits of the appraisal. The effect of uncertainty from promoter biases will therefore be limited to data that cannot be drawn from other sources and would need to be used in any appraisal methodology.

The complexity of the Thames Hub Vision will require significant computational effort to analyse and therefore will limit the opportunity to consider other case studies. As we have noted above, the Thames Hub Vision includes all complexities we wish to consider and in Section 4.2.2 we concluded that a detailed review of such a case would provide the greatest information on the methodology. However, it also limits the generality of the conclusions. This is particularly true of the Thames Hub Vision, which is exceptional in its size, level of investment and focus on system benefits. Siggelkow (2007) notes that while one must be cautious about drawing conclusions from such special cases, it is possible to infer information about more normal cases, from the insights of the special case. Therefore, while we will be aware of this limitation, we will not dismiss the Thames Hub Vision as a potential case study.

Finally, these large integrated investments could in turn provide the potential for wider economic effects, which are less likely to be present in the smaller, more common developments, particularly in the context of a mature economy (Banister and Berechman, 2003). Indeed, of the £150 billion of benefits anticipated by the Thames Hub Vision proposal, £75bn were due to economic growth (induced employment)³⁵. These wider economic benefits will, in part, be delivered to the London region and, in such cases, may come at the expense of another region. However, the airport and rail orbital aim to improve connectivity and accessibility

³⁵ The remaining benefits were £35 billion in user benefits from the road and high speed rail lines (drawn mainly from time savings for rail users), £35 billion corresponding to removing flight capacity constraints (additional air fares) and £2 billion in environmental benefits from noise reduction and habitat creation.

nationally and internationally, providing benefits outside of the regional focus of the appraisal methodology. As the methodology focuses on micro-economic rather than macro-economic change, these factors will not be captured apart from benefits derived by direct employment. However, the impacts of the case study spatially on the investment landscape will be considered in Chapter 8. Indeed, the wider economic impacts will provide a beneficial additional test of the methodology.

4.4.4 Conclusions

From the above discussion it is clear that the Thames Hub Vision provides the single extreme case we sought in Section 4.2.2. While we must take care in drawing generalisations from the insights of such a case study, its complexity will provide the most complete test the methodology, both from the perspective of the six facets of infrastructure appraisal complexity derived in Section 4.2.1 and the five methodological increments we wish to apply (as outlined in Chapter 1).

Having completed the first aim of this chapter and determined the Thames Hub Vision to be the case study that will most completely test the methodology, we will now provide a definition of its elements and assumptions alongside those for the 'do minimum' and dynamic baseline.

4.5 Characterisation of the case study

4.5.1 Costs and design requirements for the Thames Hub Vision

Our case study will capture the Thames Hub Vision according to the technical annex prepared for the original proposal (Foster+Partners et al., 2011b). It will therefore include the elements as described in Section 4.4.1. A number of barriers to the development were also identified within

the proposal, with the resulting relocation/remediation requirements (people, habitats, wildlife and cultural heritage buildings) estimated (see Table 4.6). It will be assumed that none of the barriers are sufficient to invalidate the proposal, but those with estimated costs will be included as construction costs of the airport asset.

Table 4.6 – Barriers to implementation

Group 1 (Not quantified within the proposal)	Group 2 (Quantified within the proposal)
• Work to assess and remedy any hydrodynamic effects of the scheme (increase erosion, water levels or currents)Relocation of Isle of Grain Liquid Natural Gas plant	• Displacement of people (3,000 permanently and 16,000 adversely affected) • Necessity to relocate cultural heritage buildings • Works to remove or ensure integrity of the wreck of the SS Richard Montgomery • Necessity to destroy and replace internationally protected wildlife habitats

As noted in Section 4.4.3, proposal documentation estimates are highly uncertain, particularly the costs and projected demands. These estimates will therefore only be used to estimate the factors that cannot be estimated through other means. This includes:

- The engineering specifications of the infrastructure assets (the spatial and capacity design requirements);
- Impacts or benefits that cannot be estimated through other existing assets (particularly relevant for the new airport due to its size); and
- The construction costs, which will be compared to previous infrastructure investments using reference class forecasting.

These estimations are shown in Table 4.7.

Table 4.7 – Data taken from proposal documentation (Foster+Partners et al., 2011b)

Infrastructure Asset	Proposal Estimates	
Road	Cost (2010 prices)	£2bn: £1.4bn for link improvements and £575m for major interchange improvements
	Spatial Footprint	1,250ha (non-designated land)
	Capacity	Not estimated
	Other	1,460,000 lorries of freight per year converted to rail
Flood barrier	Cost (2010 prices)	£1bn
	Spatial Footprint	100ha (non-designated land)
	Capacity	Protection from 1/1000 year event
	Other	N/A
Tidal energy generation ³⁶	Cost (2010 prices)	£1bn
	Spatial Footprint	270ha (non-designated land)
	Capacity	525GWh/year
	Other	N/A
Rail orbital	Cost (2010 prices)	£20bn (construction) £0.7bn (operating NPV) Cost of rolling stock (trains) excluded
	Spatial Footprint	5,200ha (non-designated land)
	Capacity	Sufficient to carry 60% of airport travellers and 4000 lorries per day of freight
Airport	Cost (2010 prices)	£19.1bn
	Spatial Footprint	1,700ha (internationally designated habitat) 2,300ha (non-designated land)
	Capacity	150mppa
	Other	100,000 direct employees 525GWh/yr electricity requirement Regulatory Asset Base model funding proposal (including £14bn proceeds from the sale of redevelopment of Heathrow and enterprise zone)

Comparing the Thames Hub Vision elements to existing infrastructure assets, it seems reasonable that all but one could still be viable at 2110 with appropriate maintenance. The exception is the tidal energy asset, which is assumed to have a service life of 25 years (see Li and Florig (2006))³⁷. In the absence of appropriate refurbishment costs for this asset, the full construction costs will be applied at 25 year intervals to estimate the renewal costs of the asset.

³⁶ Cost and capacity assumed to be the same for both the tidal turbine arrays in the water or integrated into the new flood barrier. Where unqualified, figures are for either arrays or generators within the barrier.

³⁷ While Li and Florig note that tidal turbines in the UK have design lifetimes of 20-30 years, there is evidence that their true operational lives may be significantly longer. The service life used herein is therefore likely to be conservative.

Other maintenance and operational costs have, where possible, been taken from existing sources and scaled as appropriate by the capacity of the infrastructure assets (see Table 4.8).

Table 4.8 – Additional maintenance and renewal costs

Infrastructure Asset	Data and Source	
Road	None assumed	N/A
Flood barrier	Employees	Assumed to be the same as the current Thames Hub barrier, therefore no net change in employment
	Maintenance	Assumed to be in line with TE2100 project Tilbury barrier cost assessment (Environment Agency, 2009)
Tidal energy generation	Construction (if array)	Based on La Rance tidal power plant (de Laleu, 2009)
	Employees	Based on that for Siemens tidal array (Shankleman, 2013)
Rail orbital	Employees	Based on that for HS2 (RAC Foundation, 2013)
	Energy Consumption	Based on existing high speed and conventional rolling stock (Network Rail, 2009)
	Electricity costs	Based on current costs (Department of Energy and Climate Change, 2011)
Airport	Flight Movements	Based on Heathrow (AMEC, 2014a)
	Reliability	Based on Heathrow and average London delay (Civil Aviation Authority, 2013)
	Electricity costs	Based on current costs (Department of Energy and Climate Change, 2011)
	'Other' revenues from airport	Based on Heathrow (Civil Aviation Authority, 2008)

4.5.2 Demand for the Thames Hub Vision elements

There is significant uncertainty in all future predictions over the time period considered herein.

This is particularly true for demand, which requires not only estimating population, but also how behaviour may be affected by socio-technological change. Our proposed approach therefore focuses on active robustness (through pathways) and sensitivity analysis of key variables. This will provide some resilience to the uncertainty. Furthermore, as was shown in Chapter 2, the discount rate will significantly reduce the impact of the future on the appraisal. Even at the minimum projection timeline of 20 years, taking a 3 per cent discount rate, the value would have dropped by almost 60 per cent on a similar cost or benefit at the outset. Therefore, as the

uncertainty increases, the effects on the appraisal are reduced. The impacts of the discount rate and the long timeframe will be considered further through the sensitivity analysis in Chapter 7.

Demand is known to be poorly estimated by proposal documentation, therefore we will instead rely on UK Government projections, academic sources and historic trends, limited by the design constraints of the proposal (see Table 4.7). Most UK Government Department or Agency projections build on the population projections developed by the ONS (2011) and historical precedent, there is therefore some consistency between estimates. Furthermore, the Departments and Agencies draw on each other's expertise; for example, the carbon cost figures quoted in the Department for Transport's WebTAG methodology were developed by the Department for Energy and Climate Change. However, the length of time projected by each department varies significantly, from approximately 20 years for electric vehicle uptake to approximately 70 years for the population projections. Where projections are less than the 100 years required for this assessment, we will simply hold figures constant from the final projection date point onwards. This will create inaccuracies in the projections; however, as noted our active approach to robustness and application of discounting will provide some resilience to these inaccuracies.

For airport demand we use the central projection created by the Department of Transport (2011c) in the same year as the population projections, assuming that the hub maintains its current percentage of the total UK demand³⁸. Road and rail passenger demand will be derived purely from the surface access requirements of these projections³⁹ with no latent demand assumed⁴⁰. This will allow the assessment to focus on the system aspects of the assets, but will

³⁸ 32 per cent (Civil Aviation Authority, 2012).

³⁹ That is, passenger travel to and from the airport.

⁴⁰ The potential effects of latent demand on the results will, however, be discussed as part of the uncertainty analysis in Chapter 5 and the spatial analysis in Chapter 8.

present a conservative estimate as, historically, the introduction of new transport connections has generated additional usage. The significant road and rail investments being undertaken in the region (see Table 4.5), will reduce the impact of this model simplification.

To allow estimation of the surface access demands of the airport, historical passenger origin data has been obtained from the Civil Aviation Authority (2003). It has been assumed that the number of interliners⁴¹ remains constant at 38 per cent, therefore, that 62 per cent of passengers travel to and from the airport. As the traffic management approach defined in the proposal documentation is reliant on a number of the infrastructure elements, the method of transport used to access the airport will be dynamically assessed based on the assets available. Where the rail and road assets are available, the strict reduction of parking spaces and planned availability of park and ride at the orbital stations will be assumed, making rail options attractive to passengers travelling to the airport from directly connected regional rail services. Furthermore, those using rail to access the airport will switch from central London trains/Underground lines to the orbital if this presents a shorter route to the airport. Where this alleviates capacity on central London trains/Underground, the capacity will be assumed to be fully utilised by new demand, reflecting the population growth and existing capacity constraints of the service.

Similarly, the electricity generated by the tidal barrage will be assumed to be fully utilised. As the Thames Hub Vision airport is estimated to use less energy than the 'do minimum' case, the difference in electricity demand will also be assumed to be fully utilised. This recognises the growing constraints of UK energy generation capacity as legacy power plants are decommissioned (Infrastructure UK, 2011).

⁴¹ Passengers who are connecting to other flights, therefore travel to and from the airport by aircraft.

‘Demand’ for a flood barrier is not straightforward to calculate, with ‘utilisation’ of its services being restricted to extreme weather events whose frequency and severity cannot be predicted simply. However, the location of the Thames Hub Vision flood barrier is similar to the Tilbury barrier reviewed by the TE2100 programme (Environment Agency, 2009). We can therefore draw on the results of the expert estimation process used within TE2100 when estimating the damage avoidance and safety benefits of the Thames Hub Vision barrier. The assessment includes estimations for sea level rise (climate change thermal expansion), polar ice melt, sea surges (including the effects of climate change), future peaks in fresh water flows and 1/1000 year events. It therefore estimates most of the situations likely to induce a flood event.

4.5.3 The counterfactual case

As we have previously noted, the counterfactual case is not straightforward to calculate. Indeed this was one of the most significant barriers for the historical case studies. The counterfactual is not simply the ‘world without’ the case study. Infrastructure development will still take place, with some assets implemented in parallel and some implemented in place of those proposed. In Chapter 3 we therefore split the counterfactual into two: a single ‘do minimum’ pathway, against which the development pathways will be compared; and a dynamic baseline of potential projects, delivered in the absence of conflicting investments within the development pathway.

Our analysis of case studies provided a list of current and future projects in the London region (see Table 4.5). Four projects were deemed to have no impact on the Thames Hub Vision (Heathrow Terminals 5 and 2, Isle of Grain CHP plant, Thames Tideway and the Northern Line extension). To minimise the additional complexity of the case studies, these will not be included. The London Olympics and King’s Cross Central were assessed to create only indirect impacts on the proposal through changes in population distribution. As the population

projections were calculated in 2011 when both of these projects would have been approved, it will be assumed that any changes are already incorporated within these projections. Other effects from these two projects will be excluded from the appraisal to minimise additional complexity.

The DP World London Gateway and CTRL are already constructed and therefore can provide or accept requirements from the Thames Hub Vision or counterfactual case. The former provides additional freight which could be transported by rail (as in the case of the Thames Hub Vision) or must otherwise be transported by road. The latter creates a connection from central London to mainland Europe and which could be further connected to the national rail networks. There are no current plans to change these assets or further connect them, they therefore provide a static resource/demand for the counterfactual and Thames Hub cases.

HS2, the Lower Thames Crossing and Crossrail will all be built in parallel to the Thames Hub Vision. The Lower Thames Crossing directly competes with the Thames Hub Vision road crossing for congestion relief benefits. Furthermore, it is likely to be built before the Thames Hub Vision crossing can be designed and approved. It will therefore be assumed that the Lower Thames Crossing relieves the current road congestion on the other Thames road crossings and there is no additional benefit (for road congestion) created by the Thames Hub Vision road crossing. This is clearly a conservative estimate and, as noted previously, will be explored further when the appraisal is conducted. As the potential for including provision for a rail crossing as part of the Lower Thames Crossing has been rejected (Carhart, 2014), no new rail crossing will be included within the 'do minimum' or dynamic baseline.

HS2, in contrast, provides additional benefits to the Thames Hub Vision. Through interconnection of the orbital and HS2, the airport is more accessible by the north of England,

providing support for the active traffic management process. No other rail connections propose to interconnect directly with HS2, therefore this benefit is limited to the Thames Hub Vision and assets that locate close to its terminus at London Paddington. The Heathrow Express also interconnects into London Paddington, but as an interchange will still be required, this provides little additional benefit over the increased accessibility and connectivity of HS2 generally.

Crossrail similarly provides greater connectivity and accessibility, but also necessary relief for the congested central London rail services. Furthermore there is a plan to interconnect it to Heathrow, slightly increasing accessibility by rail. However, as Heathrow is already served by the London Underground and the Heathrow Express from London Paddington, it will be assumed that Crossrail simply provides sufficient additional capacity to allow the current surface access distributions to be maintained as airport passenger numbers increase.

The remaining projects are planned and proposed alternatives to two of the Thames Hub Vision assets. Firstly, the TEAM 2100 project presents the first ten years of the TE2100 programme, which undertook to plan the necessary flood protection investment in the Thames Estuary until 2170 (Environment Agency, 2009). The preferred route requires maintenance of existing assets and has the option of a new barrier at Long Reach, to be commissioned in 2070; however, the Thames Hub Vision barrier could already be implemented by this time, protecting a larger area and invalidating many of the benefits of the existing assets and barrier. The two projects are therefore deemed to be mutually exclusive, with the TE2100 programme presenting the counterfactual case that the Environment Agency intend to implement. It will therefore be present in both the 'do minimum' and the dynamic baseline. Should the Thames Hub Vision barrier be built, the baseline will not include the TE2100 barrier. If no Thames Hub Vision barrier is built, the baseline will remain that according to the TE2100 project. In both cases, data from TE2100 will be used to estimate the costs and benefits ensuring the alternatives are internally consistent. Although the TE2100 maintains two alternatives (one with and one without the Long

Reach barrier), to simplify the model, it will be assumed that the intention is to build the Long Reach barrier in 2070.

Secondly, the Heathrow expansion proposal provides a possible alternative to the Thames Hub Vision airport. To allow for the expected increases in airport passengers, in the absence of the Thames Hub Vision airport, it will be assumed that Heathrow will be expanded to three runways. The proposal submitted to the Airports Commission (Heathrow Airport Limited, 2013) will be used to estimate the design requirements of this expansion, assuming that the preferred 'North West Option' is taken forward.

The Thames Hub Vision elements, parallel projects and counterfactual case defined in this section are presented in Figure 4.6, with data sources for the additional 'do minimum' assets noted in Table 4.9.

Figure 4.6 – Thames Hub Vision infrastructure elements and 'do minimum' counterfactual developments (adapted from Young and Hall (2015))

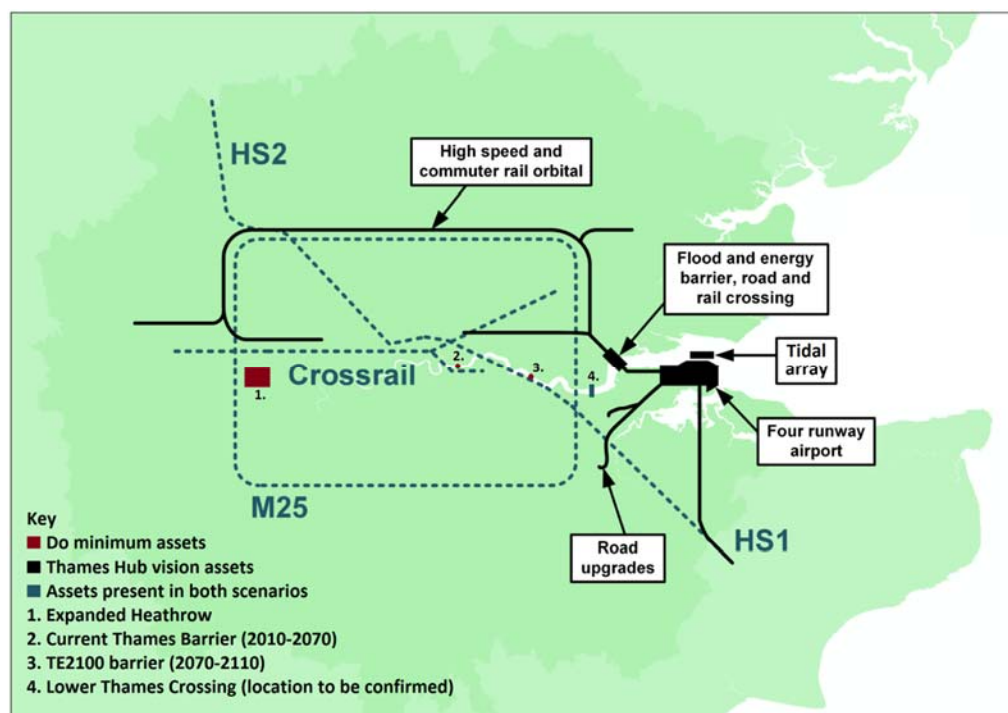


Table 4.9 – Data for ‘do minimum’ assets

Infrastructure Asset	Proposal Estimates	
Thames Barrier and TE2100 barrier ⁴²	Cost (2010 prices)	£1.4bn
	Spatial Footprint	Unspecified, assumed zero
	Capacity	Protection from 1/1000 year event
	Other	£3.2bn additional flood protection measures
Expanded Heathrow Airport	Cost (2010 prices)	£16bn (Foster+Partners et al., 2011b)
	Spatial Footprint	Unspecified, assumed zero
	Capacity	130mppa (Heathrow Airport Limited, 2013)
	Other	72,000 direct employees 815GWh/yr electricity requirement (Foster+Partners et al., 2011b; Heathrow Airport Limited, 2012)

4.5.4 Additional projections and data

In order to quantify all fifteen indicators identified in Chapter 3, more information is necessary regarding the current and future social, economic and technological context of the region. To ensure internal consistency between the remaining datasets, most will be sourced from the Department for Transport’s WebTAG appraisal data (Department for Transport, 2011a), using that available at the time the aviation and population forecasts were made. General system data taken from this source is listed below:

- GDP growth rates⁴³
- Indirect tax rates
- Household size
- Values of working and leisure time⁴⁴
- Value of carbon (calculated based on Department of Energy and Climate Change guidance)⁴⁵

⁴² All data taken from Environment Agency (2009).

⁴³ Held constant after 2061.

⁴⁴ Projected using GDP growth rates from (Department for Transport, 2011a).

⁴⁵ Held constant after 2101.

- Uptake of transport technology (uptake of electric vehicles, and effects of the Renewable Transport Fuel Obligations Order (UK Government, 2007) requiring biofuels to be blended into transport fuel, making them less efficient)⁴⁶

The remaining data will be sourced, where possible, from similar projections from the Department of Transport (not within the WebTAG guidance) and other Government Departments, to ensure its consistency and long-term availability. Where not available through Government Department datasets, either current values will be used, or historical record will be consulted. These remaining system definition datasets are listed below:

- Population projections (Office for National Statistics, 2011), as regionally disassociated by Hall et al. (2012)⁴⁷
- Sea level rise (Department for Environment Food and Rural Affairs, 2006)
- Current pollution levels (Department for Environment Food and Rural Affairs, 2012b)
- Current noise levels (Department for Environment Food and Rural Affairs, 2012c)
- Average salaries (Reed, 2012)³⁶
- Income tax and national insurance percentage rates (HM Revenue and Customs, 2013)
- Unemployment benefits (UK Government, 2014)³⁶

These datasets will be used for the Thames Hub Vision pathways, the 'do minimum' and the dynamic baseline to ensure consistency. Further datasets will be necessary to quantify and monetise the fifteen performance indicators (see Chapter 5). These will follow the same

⁴⁶ Held constant after 2030 (electric vehicle uptake) and 2035 (fuel efficiency), while this will provide a level of balance between the introduction of biofuels and increasing efficiency, it may underestimate electric vehicle usage over the long-term.

⁴⁷ Held constant after 2080.

sourcing priorities as used here, applying WebTAG and other Government Department datasets where possible.

4.6 Conclusions

The aims of this chapter were:

- To review the available literature and data to determine which case study, or set of case studies, will most completely test the methodology from a systems perspective; and
- Having determined the most suitable case study, to define its constituent assets, interdependencies and environment such that the methodology can be applied.

Through review of 32 potential case studies, we have determined that only the Thames Hub Vision has the potential to test all the facets of infrastructure appraisal complexity identified in Section 4.2.1, meeting all of our critical choice criteria and priorities. As a proposal, it is the most relevant type of case technologically, socially, economically and environmentally and exhibits the information that is likely to be available at the strategic/conceptual design stage for which the methodology has been designed. Furthermore, it presents a regional perspective, in a high population density location that will amplify impacts, testing the proposed performance indicators. It is therefore the case most able to completely test the limits of our appraisal methodology and framework.

The Thames Hub Vision will be complex case study; however, it allows consideration of all five increments of the appraisal methodology to be completed and therefore provides sufficient scope to be a standalone case. This can be set against a known baseline of projects and tested against a known 'do minimum', each derived from the parallel London based projects, identified

by our review. Having defined the case study characteristics we can now implement the proposed methodology.

5 A Multi-Attribute Cost Benefit Approach to Valuing Infrastructure Impacts

5.1 Introduction

The aim of this research is to provide a more complete appraisal of infrastructure developments through a greater appreciation of the interactions of the set of systems as a whole. In Chapter 3 we outlined the framework devised to undertake this research and derived fifteen infrastructure performance indicators from an industrial and academic literature review. In Chapter 4 we introduced our case study, the Thames Hub Vision, discussed the rationale for our choice and derived an appropriate counterfactual development pathway ('do minimum') against which the impacts will be compared. This chapter describes the work undertaken as the first stage in applying the appraisal framework to this case study, reviewing how the fifteen indicators can first be quantified and then monetised, before applying the methodology to each of the case study elements. The work builds on current appraisal methodologies, capturing cross-sector strategic and key sector specific indicators within a single appraisal methodology. It thereby provides the foundational building blocks necessary to undertake the systems appraisal and pathway uncertainty analyses in Chapters 6 and 7.

The main objective of this chapter is therefore to progress the framework developed in Chapter 3, by creating a common, long-term, multi-sector and multi-attribute methodology for infrastructure appraisal, then test this methodology against the Thames Hub Vision case study, to determine whether:

- The fifteen variables identified in Chapter 3 provide a complete valuation of impacts and whether aggregation of these into four attributes sufficiently highlights the diverse nature of costs and benefits, without obscuring necessary detail;
- The monetisation methods used are sufficiently robust that conclusions can be drawn despite the inherent uncertainty of the timeframe and valuation process;
- The commonality of the methodology allows comparison and prioritisation of projects across sectors, enabling future development of cross sector portfolios; and
- The methodology proposed is sufficiently robust to provide a basis for the more complex systematic appraisal of infrastructure interdependencies to be developed in Chapters 6 and 7.

We start by reviewing the impacts associated with our case study, relating these to the fifteen performance indicators identified in Chapter 3. We consider the methods available to quantify these impacts, concentrating initially on market valuation and our four monetary indicators. For the remaining indicators, we consider non-market valuation methodologies and the additional uncertainties¹ and biases these introduce, before systematically considering each indicator and methodology in the context of long-term multi-sectoral appraisal. As each indicator relates to a substantial body of literature in its own right, we cannot, and do not try to, cover each within this chapter. Instead, we aim to provide an introduction to the quantification and monetisation methods available for each indicator and the uncertainties generated by their use. We restrict the analysis to those methods most suitable for the limited data available at the strategic appraisal stage and the most recent, complete and applicable methods for the framework and London case study. We apply the derived set of valuation methods to the case study, appraising each element as a standalone ('single asset') investment. The results do not, therefore consider

¹ Market valuation uncertainties discussed in Section 5.3.

interactions between the assets, but rather provide a baseline against which the future analyses can be compared, allowing us to consider the uncertainty of the results and our ability to derive useful information. Finally we draw conclusions on the methodology, reviewing its limitations and strengths at this stage and as a foundation for the more complex systemic appraisal analyses.

5.2 The benefits and impacts of infrastructure

Having introduced our case study in Chapter 4, we must first consider whether the fifteen performance indicators are sufficient to capture the main benefits and impacts of the Thames Hub Vision. We therefore consider each of the infrastructure elements of our case study against the four attributes identified in Chapter 3.

5.2.1 Benefits and impacts of the Thames Hub Vision

Starting with service benefits, the energy and transport elements of the case study provide services through a capacity increase. While benefits may initially only manifest through increased reliability (for example, less congestion on the rail network), as demand grows, for example through population growth, service benefit is realised through utilisation of the additional capacity. In contrast, the service provided by the flood barrier is an increased physical protection from extreme events, with no direct, tangible benefit realised unless an extreme event occurs. This is therefore temporally different to the utilisation and reliability benefits and requires forecasting the probability of future events. It is also different in that those receiving the benefits are not ‘users’ in the same respect as the other assets, but rather the local population.

The restriction of service benefit from the barrier to extreme events also presents a different investment perspective to the transport and energy infrastructures, which can generate a regular income by charging for use. Therefore, while the energy generation and transport investments present the opportunity for at least partial private funding, it is likely the barrier would need to be publically funded². Other economic benefits are generated by increased employment (airport and energy generation) and increased tax benefits to the Treasury. Here it is useful to note the circular nature of the impacts, with employment being felt as a cost to the investor, but as a benefit to those employed and the Treasury who receive additional income tax and pay less unemployment benefits. While there is a movement in funds, the majority of these effects sum to zero and therefore it is important to note where the benefit is felt as well as the total.

The creation and operation of the infrastructures also generates a number of environmental externalities. Given the proposed site for the airport is protected wetlands and reclaimed land, its large spatial footprint will destroy habitats and will significantly decrease the visual amenity of the area. Furthermore the barrier and chemicals used on roads and runways could impact water quality in the River Thames or in ground water. Transport infrastructures are known for generating substantial noise and air pollution; however, the reduction in flights over London (through the transfer from Heathrow to the Thames Hub Vision airport) will reduce noise impacts in central London. Yet, while the lower population density of the Hoo Peninsula, will mean that the number of people for whom the noise is increased is relatively few, for these few, there will be a dramatic increase in noise levels. Finally, the reliance of the transport infrastructures on fossil fuels (either directly, or through electricity generation), will increase carbon dioxide emissions³. The generation of renewable energy by the barrier may, however, go

² Private finance initiative models for flood defence have been tried, but were not based on user charging.

³ Unless the infrastructure is replacing a less energy efficient asset as in the case of the airport's electricity usage.

some way to negate this impact. By capturing effects on a common scale we can compare beneficial effects such as the noise reduction of the airport or the carbon dioxide emissions avoided by the tidal energy generation against the detrimental effects of the other infrastructure assets.

Finally, the service effects of the infrastructure assets can also generate social externalities, changing the risk experienced by users and employees or the security felt by the general population. The airport, for example, will increase usage of the surrounding roads, increasing the number of accidents, whereas, the rail asset may reduce road demand, moving travellers to a statistically safer means of transport (Department for Transport, 2013) and hence reducing accidents. Airport workers are also at a higher risk of injury than a statistically average profession (Health and Safety Executive, 2012) and therefore by increasing employment in this field, additional injuries are likely to be generated. Finally, the safety provision of the barrier and the reduction of flights over London, increases the security felt by those living in the protected area and under the flight path.

A qualitative mapping of the effects identified above against the fifteen performance indicators derived in Chapter 3 is shown in Figure 5.1. All effects can be seen to map to an indicator. However, two assets (the rail orbital and airport) are noted to place significant additional demand on other infrastructure services (both require electricity to operate and the airport requires additional surface access transport). They will therefore have secondary effects through their demand on other assets. These indirect effects will need to be captured within the single asset appraisals.

Figure 5.1 – Qualitative impacts and benefits of the elements of the Thames Hub Vision

	Cost	Revenue	Tax	Employment	Capacity	Reliability	Protection	Air Quality	CO ₂ Emissions	Habitat	Landscape	Noise	Water Quality	Safety	Security
Road	↘	—	↗	—	↗	↗	—	↘	↘	↘	↘	↘	—	↘	—
Barrier	↘	—	—	—	—	—	↗	—	—	↘	↘	—	↘	—	↗
Barrage	↘	↗	↗	↗	↗	↗	—	↗	↗	↘	↘	—	—	—	—
Rail	↘	↗	↗	↗	↗	↗	—	—	—	↘	↘	—	—	↗	—
- Electricity	—	—	—	—	↘	↘	—	↘	↘	—	—	—	—	—	—
Airport	↘	↗	↗	↗	↗	↗	—	↘	↘	↘	↘	↗	↘	↗	—
- Electricity	—	—	—	—	↗	↗	—	↗	↗	—	—	—	—	—	—
- Road	—	—	↗	—	↘	↘	—	↘	↘	—	—	↘	—	↘	—

Key

↗ Situation improves

↘ Situation worsens

— Limited impact

Given that we have not identified any significant impacts in addition to our indicators, and having confirmed the relevance of all fifteen to our case study, we can continue with the appraisal as outlined in Chapter 3. In the next sections we therefore present a critical evaluation of the methodologies available to capture the fifteen performance indicators and our proposals for their quantification and monetisation within a standardised cost benefit appraisal.

5.3 Market indicators

Four of the performance indicators naturally appear in monetary terms and can be determined directly from market prices (these are grouped within the 'monetary' attribute). Market prices present a straightforward measure of the current willingness to pay (WTP) for commodities that are traded (Ergas, 2009). But while such values are simple to gather, reduce the need for subjective judgements and are easily understood by stakeholders (Salzman, 1997), they assume perfect market conditions (including perfect competition, independence, and an absence of missing markets (Frischmann, 2012)). Furthermore, with the long-term nature of infrastructure, market prices must be projected past foreseeable socio-economic, technological and

environmental change. For example, new materials, processes or environmental restrictions may change the capital cost of projects, new methods (such as automation) may affect operational costs and/or employment, and new technologies may affect the price people are willing to pay for infrastructure services. There is therefore intrinsic uncertainty attached to even market valuations. In addition, the demand for the traded commodity is also necessary and this must be estimated through models or historic trends. In the case of rail and road transport, demand projections have been seen to be inaccurate, with a study by Flyvbjerg (2007) showing average inaccuracies of -51 per cent and +9 per cent respectively. We will therefore need to consider the effects of all these inaccuracies on our results.

Before discussing the four monetary performance indicators, we briefly outline how the values will be presented to ensure consistency, along with the additional uncertainties that this implies.

5.3.1 Constant value representation

To ensure that values can be compared they must be captured in a consistent manner, including whether inflation and tax are included and whether benefits are captured per stakeholder group or in totality. In Europe, little consistency is shown between which values are used (Bickel et al., 2006); however, as both the developed and base case are affected equally, the net value is unaffected. In this thesis, we present results as real term, market prices, as is common for UK appraisal, thereby allowing comparison with other studies⁴. We also choose to record the movement of costs and benefits between stakeholder groups rather than just the net change ('WTP approach' rather than 'social cost approach'). As noted in Section 5.2.1, employment is a cost to the infrastructure owner, a benefit to those employed (local population)

⁴ Conversion of values to include inflation or to factor costs (including indirect tax) can be calculated by multiplication of the yearly results, by the rate of inflation or the reciprocal of the indirect tax correction factor ($1 + \text{average rate of indirect taxation in the economy}$) as required.

and a benefit to the national economy (greater income tax and national insurance and lower unemployment benefits paid out), but the only net product is the reduction in unemployment benefit. By capturing these individual changes in value, we gain a greater understanding of who is benefiting and can therefore consider the viewpoints of the stakeholders and the equity of the proposal, the lack of which is a common criticism of Cost Benefit Analysis (CBA)⁵.

Intrinsic to any valuation approach is the incorporation of time preference. This is perhaps the most controversial aspect of valuation, particularly for infrastructure investments, where costs or benefits will be felt by future generations and where there are duty of care and ethical considerations to those impacts (Ackerman, 2007; Ackerman, 2008). Proposed discount rates show significant variation and can be sufficient to completely change the results of an analysis (see full discussion of discounting in Chapter 2). Our final choice is therefore what discount rate should be applied. We choose to apply the discount rate recommended by HM Treasury, to provide consistency with sector specific infrastructure appraisals and thereby allow comparison of the results. This requires use of a 3.5 per cent discount rate, descending to 2.5 per cent over the 100 year time horizon to make some allowance for inter-generational equity (HM Treasury, 2003). However, while the rate gives a greater precedence to long-term impacts than rates based on cost of capital (between 5 and 12 per cent (Pearce and Turner, 1990)), it is still sufficient to cause large reductions to future effects⁶. The uncertainty created by our choice of discount rate is therefore an important factor of the appraisal; however, we delay analysis of its impact until Chapter 7, where it is considered for the system of systems as a whole.

⁵ See, for example, Stanton and Ackerman's critique of the Heathrow Airport expansion economic case (Stanton and Ackerman, 2008).

⁶ For example, by 2060 (half way through the time horizon), the value of a given impact is one fifth that of the same impact occurring in 2010.

5.3.2 Monetary attribute indicators

Having provided a consistent basis for the presentation of our values, we can now return to consideration of the four monetary indicators themselves. Our four monetary indicators are cost, revenue, employment and tax. As noted in Section 5.2.1, all investments will have a cost and all but the barrier will have the opportunity to generate revenue directly from service demand (although this opportunity may not be exercised). The airport, rail and energy generation infrastructures will create additional long-term employment, which will have implications on tax, as will the use of surface access transport (through petrol duty and electricity taxation). Our indicators are therefore quantified either by demand profiles (revenue and tax from transport) or approximations of construction and operational costs (cost, employment and employment taxes).

Cost

Construction costs were derived as part of the case study and ‘do minimum’ characterisation in Chapter 4. These costs will be felt by the developers and operators of the infrastructure, who may be private, public or a mixture of the two. Estimated costings for infrastructure have an historically consistent inaccuracy (‘optimism bias’), which can strongly affect the results of an appraisal process (see Table 5.1)⁷. It is possible to reduce this bias through the use of ‘reference class forecasting’, a sensitivity analysis based on information gathered from previous infrastructure projects (Flyvbjerg and COWI, 2004).

Table 5.1 – Inaccuracy of transport project cost estimates (Flyvbjerg, 2009)

Project Type	Cases Reviewed	Average Cost Overrun (%)	Standard Deviation
Rail	58	44.7	38.4
Bridges and tunnels	33	33.8	62.4
Road	167	20.4	29.9

⁷ Flyvbjerg notes that while his research has centred on the transport industry, comparative work has shown similar problems, causes, and cures in the energy, water and ICT sectors (Flyvbjerg, 2007).

The data gathered by Flyvbjerg included many infrastructure projects outside of the UK and few of the size of our case study⁸. However, as the largest study of infrastructure cost uncertainty, it provides the most appropriate approximation for a cross-infrastructure appraisal framework. Indeed this approach is recommended in the UK by HM Treasury and has already been applied to the appraisal of major infrastructure projects (Flyvbjerg, 2009). Therefore, where costs are estimated based on the investments suggested within the Thames Hub Vision proposal (Foster+Partners et al., 2011b), the sensitivity of results will be considered against the optimism bias uncertainty noted in Table 5.1.

While the inclusion of construction costs is common for all infrastructure sector appraisals, the consideration of residual value⁹ varies. For example, in the UK, it is not considered for transport projects, despite many assets enduring long past the 30 year appraisal period, but was for the Thames Estuary 2100 flood protection project, where a 170 year appraisal period was considered. The indefinite nature of infrastructure lifetimes and the dependence on maintenance regimes makes estimation of residual value challenging and given that no data is available for the majority of the assets within the case study, residual value will not be considered as part of this analysis. However, given the extended appraisal period (100 years), the residual value will be much smaller than for the current sector appraisal methodologies. Indeed, the operational life of some of the assets is known to be shorter than this appraisal period, for example the tidal energy barrage (Li and Florig, 2006). As noted in Chapter 4, additional maintenance/renovation costs will be included to allow assets to function for the entire appraisal period.

⁸ The OMEGA project found that mega transport projects (those costing more than US \$1bn, such as the rail orbital and airport) had lower cost overruns than the average produced by Flyvbjerg, with an average of 22 per cent (Dimitriou et al., 2013).

⁹ The amount the infrastructure asset is worth at the end of the appraisal period (for example, the amount it could be sold for).

Employment

Employment will occur in both the construction and operation of the asset; however, those employed during construction may not be UK citizens, depending on the skills required. In such cases it will not benefit the Treasury through a reduction in unemployment benefit and will have different tax implications depending on the residency status and nationality of the employee. We will therefore only consider the longer-term operational employment within the appraisal, with construction employment simply captured as part of the cost to the developer.

As noted in Section 5.3.1, the social cost of employment is quite small, as most of the value is simply transferred between stakeholder groups. By noting how this value is transferred, the small net change (the economic benefit to HM Treasury) is overshadowed by the (gross) benefit to the local population (through wages). Furthermore, we capture the perspective of the operator, as the net zero transfer of value from them to their employees disguises a reduction in their revenues that may affect their profitability.

Employment costs and benefits will therefore be estimated based on average UK salaries (Reed, 2012), estimated airport employee numbers from the Thames Hub Vision proposal (Foster+Partners et al., 2011b) and current employment levels for the energy generation and rail assets (Shankleman, 2013; RAC Foundation, 2013). No long-term employment benefit is assumed for the road developments and while the barrier will require employees, these are likely to be similar in number to the current Thames Barrier and future 'do minimum' Thames Estuary 2100 barrier, therefore no net benefit to employment will be felt. Tax and unemployment benefits will be based on current UK levels (UK Government, 2014).

Revenue

Revenue will be felt as a benefit to the infrastructure owner or operator, therefore may be a private investor or the Treasury. Average demand inaccuracies have been recorded by Flyvbjerg (2007) for road and rail infrastructures, with road found to be routinely underestimated by almost 10 per cent and rail overestimated by over 50 per cent. Proposal demand projections must therefore be considered as highly uncertain. Revenue generated directly by the airport and energy generation assets are perhaps more certain. The airport owner is one-step removed from the fluctuations in passenger numbers, which affect airline profitability rather than the number of flights directly. Of course, should passenger numbers be significantly in error, airlines may reduce the number of flight slots taken, but they may also experiment with new routes¹⁰. Given the UK's climate change obligations and current trends for rapidly increasing energy demand (Tran et al., 2014), it seems reasonable to assume that all renewable energy generated by the tidal barrier will be bought by the National Grid, or used directly at the airport.

As discussed in our system characterisation in Chapter 4, we recognise the inaccuracy of the proposal demand profiles, instead using UK Government demand projections limited by the proposal and 'do minimum' design capacity constraints. Energy and rail charges and tickets will be assumed to be in line with current market prices (Department of Energy and Climate Change, 2011; Transport for London, 2013) and grow in accordance with predicted GDP growth rates (Department for Transport, 2011a). Landing fees will be in accordance with current CAA restrictions and Thames Hub Vision proposals thereafter (Foster+Partners et al., 2011b).

¹⁰ Heathrow's limited connection to emerging markets and limited slot space for such routes has been noted as a potential issue for the UK economy; should capacity not be limited, airlines may be able to open the new routes that had previously proved impossible (Frontier Economics, 2011).

Tax

Tax changes will be felt in two main areas: employment (as described above) and through the changing use of transport modes (petrol duty and traded/non-traded electricity usage). The increased capacity of the Thames Hub airport compared to the base case (expanded Heathrow, see Chapter 3), will allow passenger growth and therefore increase surface access demand. Furthermore, the location of the Thames Hub airport will require longer journeys for most travellers. There will therefore be more passengers, each travelling for longer on average in the Thames Hub Vision case. This will increase petrol use and hence the petrol duty paid by air passengers travelling to/from the airport by car. In addition, should this increase in road use generate congestion, as would be expected given road transport projections in the South East of England (Tran et al., 2014), this will further increase the petrol used by motorists. In the full Thames Hub Vision proposal, active traffic management is used to increase the modal share of rail use from 23 per cent to 60 per cent, reducing petrol usage and replacing it with non-traded electricity (hence reducing the tax benefit). However, this change in surface access is a system effect and while it will be considered in Chapter 6, it will not be present in the single asset case explored within this chapter.

The tax changes for transport will be estimated using the Department for Transport (DfT) WebTAG projections (costs and fleet constitution) and estimations of petrol usage for congestion (Department for Transport, 2011a). Income tax and national insurance will be estimated based on current levels (20 per cent and 12 per cent respectively).

5.4 Non-market framework indicators

5.4.1 Valuing non-market impact

The remaining eleven performance indicators are not marketable commodities and therefore require a different method of quantification and valuation. Some of these effects are produced by the construction of new infrastructure assets (landscape and habitat loss/creation), while others are produced as by-products of its operation (pollution, time wasted, additional accidents). Others still only provide benefit under certain future conditions that may never occur (physical protection/ safety of the barrier and security from terrorist attacks by the airport), requiring estimations of probability and severity of future events. While some of these benefits may have some market values (for example, property protection from a flood), they all have aspects that are not market commodities (environment, life and lifestyle impacts) and therefore need different methods to assess their value.

We discussed the types, strengths and limitations of the ‘shadow pricing’ techniques¹¹ available for quantifying such non-market impacts in Chapter 2. These are summarised in Table 5.2. In this section we will consider the applicability of these techniques and the availability of data for each of the remaining eleven indicators. As we noted in Section 5.1, each indicator relates to a substantial body of literature, which cannot be fully reviewed herein. We therefore focus our review on those methods which are most relevant to early stage strategic appraisal in the UK context. Given the focus of our methodology, we will further prioritise valuation data that will be readily available to policy makers, already considers the long-term, is consistent with our projection data (see Chapter 4) and is applicable to multiple infrastructures.

¹¹ Methods which estimate value by asking individuals directly (stated preference methods) or derive value from current behaviour (revealed preference methods).

Table 5.2 – Shadow pricing techniques (adapted from Navrud (2000))

Shadow Pricing Method	Examples	Benefits and Limitations
Revealed Preference Methods (RPMs) ¹²	Individual Based Methods: - Hedonic pricing¹³ - Household production function (e.g. travel cost method) Expert Based Methods: - Production function methods (e.g. damage cost avoided) - Implicit evaluation	- Can only quantify existing values (Hanley and Barbier, 2009); however individual methods reflect demonstrated behaviour - Only one response per respondent - Relies on individuals being well informed and consistent - Relies on behaviour reflecting a single variable¹⁴ - Expert methods may not reflect values of the general public and are abstracted from actual behaviour (Navrud, 2000) - Relies on ability to pay for benefits therefore can devalue benefits to the poor
Stated Preference Methods (SPMs)	Individual Based Methods: - Contingent valuation (e.g. choice experiments) Expert Based Methods: - Delphi technique	- Able to quantify non-use values¹⁵ and behaviour change, but reliant of suitably realistic hypothetical situations being created and conveyed - Multiple responses per respondent possible - Rely on individuals being truthful¹⁶, well informed and consistent - Normally substantially more expensive than RPMs - Expert methods may not reflect values of the general public and in the case of the Delphi technique, results may not be repeatable (Powell et al., 1997)
Derived methods	- Combined SPM-RPM approaches - Benefits Transfer	- Grounds the SPM¹⁷, providing a validity check on the results (actual behaviour from RPMs) - Allows extension of RPMs into non-use and hypothetical scenarios (Hanley and Barbier, 2009) - Requires two sets of information therefore more expensive than either RPM or SPM individually - Cheaper and faster than new SPM or RPM - Significantly increases error margins; however generally accepted to provide useful advice on magnitude of environmental costs (Entec, 2004) - Requires care in application (Navrud, 2000) - Transfer of data between countries should be avoided (Ready et al., 2004)

¹² Also referred to as 'surrogate market pricing'.

¹³ Use of the variations in market price to estimate an element of the purchase, for example comparison of house prices in quieter and more noisy neighbourhoods to value the avoidance of noise.

¹⁴ See omitted variable bias in Chapter 2.

¹⁵ Such as 'altruistic', 'bequest' and 'existence' values.

¹⁶ Contingent valuation methods in particular are known to suffer from 'strategic bias'/protest voting (see, Hanley (1991) for example), with the method used for dealing with such answers significantly affecting the results (Navrud, 2000).

¹⁷ Englin and Cameron (1996), for example, show that this combination of real and hypothetical behaviour can improve the precision of consumer surplus estimates.

We will consider the indicators in the three aggregated attribute groups already discussed: the service characteristics traditionally considered as the primary benefit of infrastructure investment and whose benefits will be felt by current and new users; environmental externalities whose impact will mostly be felt by the local population; and the social impacts inherent to the design and developed through behaviour change, experienced by both the users and the local population.

5.4.2 Service indicators

Our three service indicators represent the traditional economic benefit received by users of the new infrastructure in the form of new capacity (road, rail, airport and energy generation) or increased levels of protection in the case of the barrier (termed 'physical protection' in this research). Additional capacity can either provide benefit by being utilised directly by new users, or by improving service quality for current users through increased reliability of service. New infrastructures can also have system effects on the service of existing infrastructures.

While considered separately, the two capacity factors form an equilibrium (reliability is effected by demand levels and demand is partially determined by the reliability of service provided).

When capacity is increased by an investment, the initial reliability improvement experienced by users is eventually eroded by increasing demand until a new equilibrium is reached. User behaviour and value derived from these factors is therefore, in reality, an iterative relationship, although this is rarely if ever recognised by appraisal frameworks.

Capacity Utilised

Developing additional capacity is intrinsic to almost all infrastructure developments. For our case study, this includes energy generated by the barrier and additional capacity for road, rail

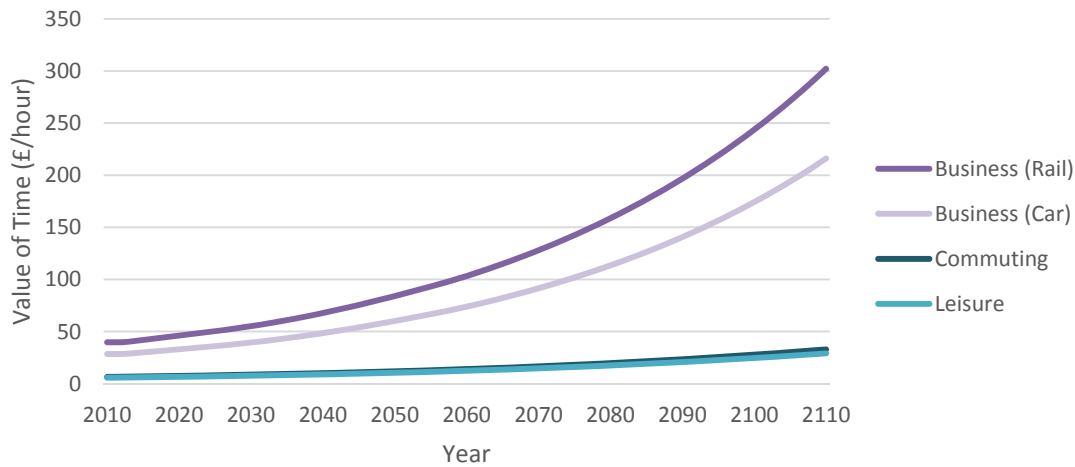
and air transport. However, only some of this capacity will be utilised directly. Quantification of the capacity produced by a new infrastructure is relatively straightforward, being determined by the design; however understanding how much of the capacity created will be utilised is more difficult. Indeed estimations of road and rail demand in the UK have been found to be significantly inaccurate, with average inaccuracies of +9.5 per cent and -51.4 per cent respectively (Flyvbjerg, 2009).

Once demand has been estimated, the benefits of utilised capacity have traditionally been valued through the change in consumer surplus (the value attributed over that paid). Capacity improvements are assumed to either marginally reduce financial cost or reduce travel time (or both), therefore, the perceived cost to users reduces and their consumer surplus increases. Transport appraisals have concentrated on the travel time savings, which, in Europe, are invariably disaggregated into work and non-work time, with the 'value of time' calculated through market prices for the former and contingent valuation for the latter (Bickel et al., 2006). For example, the values of time given for use in the DfT WebTAG methodology are shown in Figure 5.2. This valuation approach significantly favours benefits to business travel¹⁸ (Mackie, 2010) and further, it prioritises improvements to modes used by those with higher wages. More recently, questions over whether the time saved is 'useful' and whether additional time is truly 'lost', have eroded belief in this approach, particularly for rail improvements (see Lyons et al's (2007))¹⁹.

¹⁸ Approximately one-sixth of total traffic in the UK.

¹⁹ The public have also lost faith in this approach as highlighted by the rejection of the economic case for the UK High Speed 2 rail line; the BBC reported: "...in the last four business cases, the government's been ridiculed for assuming people don't get much work done on trains. Plainly unrealistic in the world of mobile phones and laptops." (Westcott, 2013).

Figure 5.2 – Value of time for commuters and leisure travellers (Department for Transport, 2011a)



At the strategic appraisal stage, a detailed origin destination model for local demand will not be available. Furthermore, for our system case in Chapter 6, active traffic management will be included to move passengers from road travel, where time can be assumed to be unproductive, to rail or park and ride, where the productivity of the time is under question. Therefore, as the time savings and their relative productivity cannot easily be estimated, we will instead concentrate on the derived surface access demand and the perceived costs of this travel. This demand will be quantified from DfT demand projections (Department for Transport, 2011b), historical origin-destination data for Heathrow (Civil Aviation Authority, 2003) and, in the system case, the active traffic management plan for the Thames Hub Vision (Foster+Partners et al., 2011b). Any additional mileage required to travel to the airport developments will be subtracted from the utilisation benefits as a cost to users. Given the high levels of energy demand growth in the UK and rail demand through central London (Tran et al., 2014), capacity created by the barrier and relieved by the orbital will be assumed to be fully utilised.

Valuation of the new services presents a problem. The services were not available before the development and the only knowledge we have of the value attributed by the user after the development is the price paid. Given the limited data available for consumer surplus in such

cases a pragmatic approach has been taken, transferring a 50 per cent share of the revenue benefit. It must therefore be remembered that revenue figures indicated within the monetary attribute only reflect half the fares paid for services.

Reliability

Where developed capacity is not utilised it may still be useful if it improves the reliability of service for existing users. Similarly, as the proposed development will interact with the existing system of systems, it can affect the reliability of existing infrastructure services, thereby changing their value to users. As the energy from the barrier only represents a small proportion of the national grid capacity it is unlikely to affect either the reliability of its own sector or the other sectors. Our reliability estimates for the case study will therefore concentrate on the transport infrastructure.

Most notably, transport infrastructure reliability creates time savings, such values are normally captured using value of time estimates (see capacity utilised critique). However, congestion also causes less reliable travel times, use of additional fuel, frustration, discomfort and a number of other economic and social costs (Frischmann, 2012). These externalities, have historically been considered as less important²⁰ and therefore have largely been ignored in the US (Delucchi and McCubbin, 2011). In Europe, such valuations have been undertaken, but only for road projects (OECD, 2011), using a mixture of contingent valuation and RPMs²¹ to value the additional risk of

²⁰ More recent studies have suggested that the value of reliability could be comparable to the journey travel time (Bates et al., 2001; Small et al., 2005).

²¹ While there are examples of RPMs being used to value more reliable services without stated preference method studies, it is difficult to disassociate value, as it is often linked to other factors. For example, fast train services have less stops, so can reach higher speeds and have less opportunity for delays to be incurred at stations, hence offer both shorter travel times and more reliable services. Equally, higher reliability broadband service providers are likely to be those with greater capacity margin (ie those with the fastest service speeds), such that small drops in service provision are unnoticed by the user. Without SPMs it is difficult to differentiate between the value attributed to the service time saving and that for the reliability increase.

accidents, noise, infrastructure damage, local air quality and carbon dioxide (see safety, noise, air quality and carbon critiques). In the UK these valuations were combined with the DfT's multimodal National Transport Model to estimate the marginal external cost of car traffic for a number of different road types (see Sansom et al. (2001)).

Reliability information is also available in the form of average delay for each of the London airports. The necessity of operating close to capacity at Heathrow has caused its delay to be longer than the average London airport. To investigate the effect of this delay, it will be assumed that when not at the current high level of utilisation, both the Thames Hub Vision and expanded Heathrow airports will instead function at the average London airport reliability rates. Any time savings will be estimated based on leisure time WTP values.

Reliability will therefore be quantified using Sansom et al.'s (2001)²² mixed contingent valuation, damage cost avoidance, hedonic pricing and statistical value of life methodology for road travel and contingent valuation for waiting time at airports.

Physical Protection

Our final service indicator represents the physical protection provided by the barrier under extreme weather events. Flooding can have a number of impacts. It initially damages property and causes physical injury and emotional stress to those affected. These can then cause further economic costs in the form of lower productivity and amenity during repairs, which can be of significant duration (particularly where infrastructure has been damaged or left unusable by the event). Depending on the environment, shipping, agriculture and habitats can be affected and polluted floodwater can cause longer term health concerns. The extent of these impacts will be

²² As value is not projected it will be held constant over the appraisal period.

dependent on the specific event and therefore it is necessary to quantify both the frequency and severity of future events before effects can be monetised.

With detailed knowledge of a location's natural terrain, flood defence measures (and reliability), developments and climatic conditions, the extent of a given pluvial or fluvial flooding event can be modelled²³. However, appraisals built on such models are simplifications, often focusing on the direct damage costs alone and estimating these based on probable inundation levels.

Furthermore, they require the modeller to predict the frequency of such events. Given the limited occurrence of 'extreme' events and the non-stationarity of climatic conditions (see Milly (2008)), a high degree of uncertainty must be attached to these predictions. This, along with the scale of the less tangible indirect impacts of such events, has led to a tendency towards monetisation through risk models and value-based judgement by experts. Such methods will be specific to the location and therefore a generalised quantification and valuation approach is unlikely to be suitable.

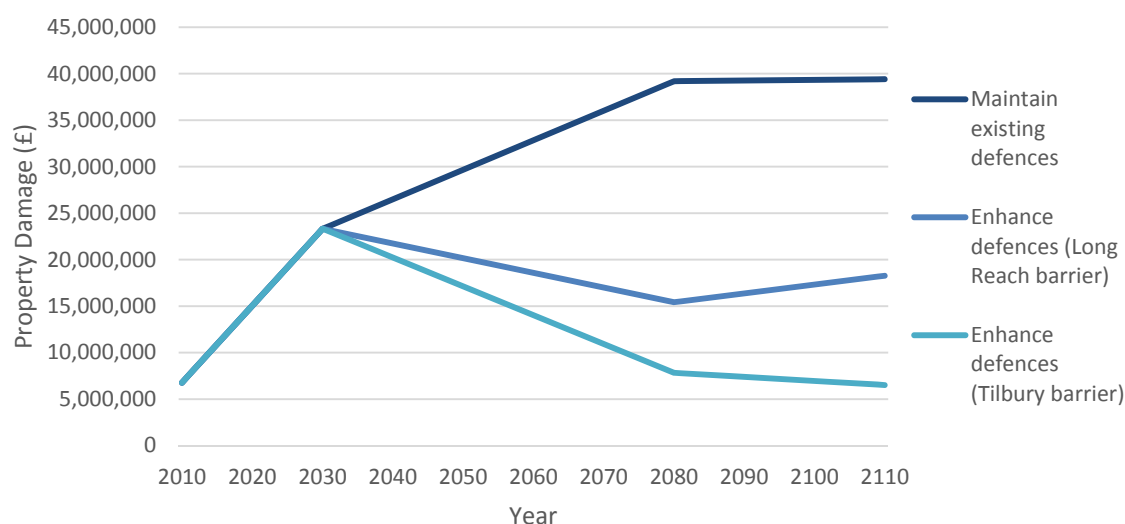
In the UK, flood risk management is a topic of intense research, particularly around the Thames River catchment. Therefore, while a generic approach is not available, it is possible to draw on the results of previous location specific studies. One study, the Thames Estuary 2100 project (TE2100), is in particular alignment with this research, taking a long-term options based approach. Estimates of damage are provided up to 2170, with two barrier locations considered, one of which is near the proposed location of the Thames Hub barrier ('Tilbury barrier'). The study was commissioned by the Environment Agency and is the primary source informing their future flood management plans in the area, providing the basis for our 'do minimum' flood risk

²³ In the UK, a large body of data has been collected on both the historic climate, its impacts on sea level and the extent of previous flood incidents, which can be used to estimate the severity of events should they occur again.

management case. The TE2100 damage cost avoided data will therefore form the basis of our physical protection valuation.

Drawing on costings from the 2007 floods in England, physical damage impacts account for the majority of costs²⁴. For our assessment, we will therefore concentrate on the physical damage estimates made by the TE2100 project (see Figure 5.3), using the Tilbury barrier as an equivalent to the Thames Hub Vision barrier and the ‘maintain existing defences’ (until 2070) and Long Reach barrier (after 2070) for the ‘do minimum’. Human costs (injuries and fatalities) will also be captured, but grouped with the social indicators (see security indicator). While these have formed the majority of costs in previous events, it is recognised that the impact estimate produced will be a lower bound estimate.

Figure 5.3 – Estimated property damage for three of the TE2100 options (Environment Agency, 2009)



²⁴ In the Environment Agency’s assessment of the costs of the 2007 floods, physical damage to households, vehicles, infrastructure/communications and utilities makes up approximately 80 per cent of the impacts quantified (Environment Agency, 2007).

5.4.3 Environmental indicators

The environmental indicators are unique, affecting those who may not be benefiting in any way from the infrastructure investments. They occur from the initial construction and operation of the infrastructure and are predominantly negative given that infrastructure services are typically large structures and net polluters. The case study offers some interesting counterpoints. Tidal energy generation will reduce carbon dioxide emissions, although this is a national benefit and may not sway local stakeholder opinion; whereas, the reduction of aircraft noise over London could provide a direct benefit thousands of non-users. Local residents will still be negatively impacted by a large increase in noise, but given the relatively low population density on the Hoo Peninsula, the airport could have a beneficial environmental impact on London residents.

Noise

Noise is an externality particularly associated with transport infrastructure developments. It affects the local population causing stress and annoyance, disrupted sleep and/or distraction from work (Delucchi and McCubbin, 2011). It is usually measured on a logarithmic scale (decibels); therefore effects cannot be calculated by simple addition, with the perceived change in noise levels being dependant on the background levels of noise and attenuation due to the profile of the environment. In addition, both the change and total noise effects are relevant, as some health effects are only produced once a given noise threshold has been reached (de Kluizenaar et al., 2001).

Given these factors, full quantification of noise levels is challenging, requiring modelling of the background noise, the 3D profile of the area and detailed service data (Friedrich and Quinet, 2011). It therefore requires information and a resource commitment greater than would normally be available at the strategic appraisal stage. If noise is to be included in the appraisal process a much simpler method is required. In the UK, average noise mapping is freely available

through the Department for Food and Rural Affairs (2012c). This does not represent the complicated noise creation and attenuation processes, nor does it provide information on maximum noise levels. However, it can be used to provide a first pass estimate of current levels of noise within a locality and average levels of noise dissipation from similar infrastructure developments. While further modelling will be necessary as part of the individual sector assessments, this method will allow the early stage strategic appraisal that forms the focus of this research.

Valuation of the effect of noise is also not straightforward, requiring the consideration of both short-term (annoyance) and long-term (stress) effects. While the long-term effects are more easily associated with statistical values of life or years of life saved (see Safety indicator), WTP research suggests that the long-term health impacts are of minor importance compared to annoyance (Friedrich and Quinet, 2011). Valuation according to the long-term health impacts is therefore unlikely to represent individual WTP values. Instead, in both America and Europe, noise values are estimated through use of hedonic pricing²⁵ (Bickel et al., 2006; Delucchi and McCubbin, 2011). While consistently applied, this method may undervalue WTP, ignoring non-use values and consumers unwilling to consider properties due to the noise level experienced (see Chapter 2). Indeed, Schipper's (2004) comparison of hedonic prices for aircraft noise against those derived by contingent valuation showed the former to be 464-1700 per cent lower.

In alignment with current practice, we will apply hedonic pricing in our appraisal, using the data made available as part of the DfT's WebTAG methodology (Department for Transport, 2011a). Based on road daily average equivalent constant noise, this data will over-estimate both rail

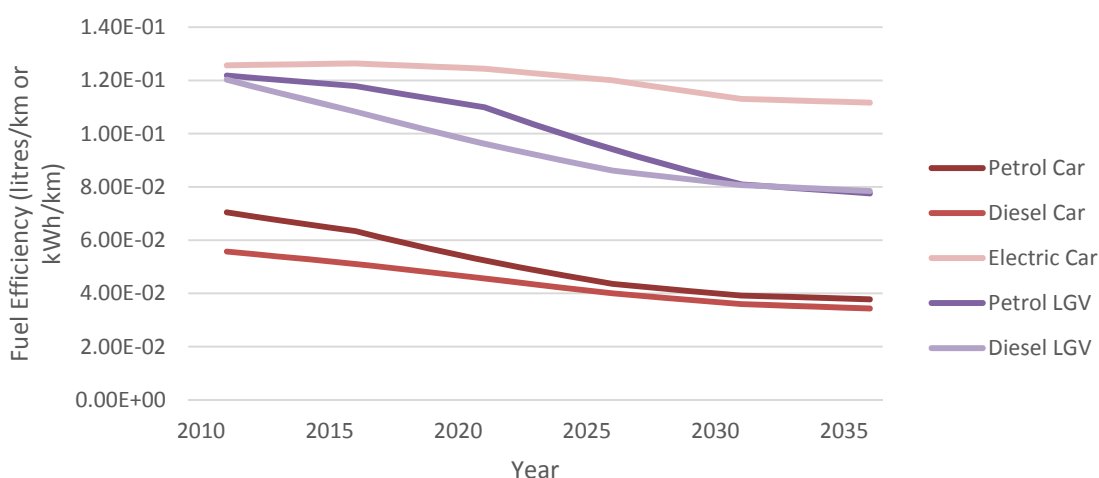
²⁵ The HEATCO project only found one European country that did not apply this method (Bickel et al., 2006).

noise (regarded as less intrusive (see Frost (2007)) and aircraft noise (recorded according to 16 hour daytime average). The WebTAG guidance also provides information on GDP growth such that valuations can be increased over time (as recommended by the UNITE project (Bickel et al., 2006)). While produced by a government agency (therefore available for the long-term and relevant to the UK), the data was created by benefit transfer from another region of the UK (see Bateman et al., 2004), so will be subject to additional inaccuracies (see Section 5.4) alongside those associated with hedonic pricing directly and with the uncertainties of quantification. These will therefore need to be considered as part of our analysis.

Air Quality (NO_x, PM₁₀)

Air pollution impacts the health of humans, wildlife and plants, it damages materials (causing, for example, building degradation) and reduces visibility (Delucchi and McCubbin, 2011). For infrastructure assets, it is mainly produced by the combustion of hydrocarbons as fuel and is therefore generated directly by many forms of transport infrastructure and some forms of energy generation. Secondary generation can therefore be assumed by almost all other forms of infrastructure, through their use of electricity. In the UK, areas of low air quality are termed Air Quality Management Areas (AQMAs) by the Department for Environment Food and Rural Affairs. In most cases the main reason for the poor air quality is attributed to emissions of NO₂ and PM₁₀, with transport emissions being the main cause for 97 per cent of the AQMAs declared for NO₂ (AMEC, 2014a). Emissions can therefore be estimated based on the changes in road, rail and airline traffic (Department for Transport, 2011a; AMEC, 2014a) and the projected fuel efficiencies of these modes (see Figure 5.4).

Figure 5.4 – Projected increase in fuel efficiency for cars and goods vehicles (Department for Transport, 2011a)



While these emission estimates are relatively accurate in the short-term (Delucchi and McCubbin, 2011), estimation of how this will change over the long-term introduces uncertainties, particularly regarding the uptake of electric vehicles²⁶ and renewable energy generation, which introduce further interdependencies for both air quality and carbon dioxide emissions (see carbon dioxide emissions critique). Yet the greatest uncertainties surround the impacts of the air pollution, a factor complicated by the number of potential effects, the environment exposed²⁷ and the complex relationship between exposure and effect, both chemically in the air (Friedrich and Quinet, 2011) and within living organisms (particularly the probability of effect and the delay experienced before its manifestation).

While hedonic pricing has been used to value air quality (see Smith and Huang (1993) for a review of US models), in European policy analysis a (marginal) damage cost avoidance approach

²⁶ As noted in Chapter 4, uptake of electronic vehicles and other transport technologies will be assumed to be in line with WebTAG projections (Department for Transport, 2011a).

²⁷ Both meteorological/chemical conditions such as the composition of the atmosphere and height of release as well as the types of life/material and the density of populations within the exposure range (Friedrich and Quinet, 2011).

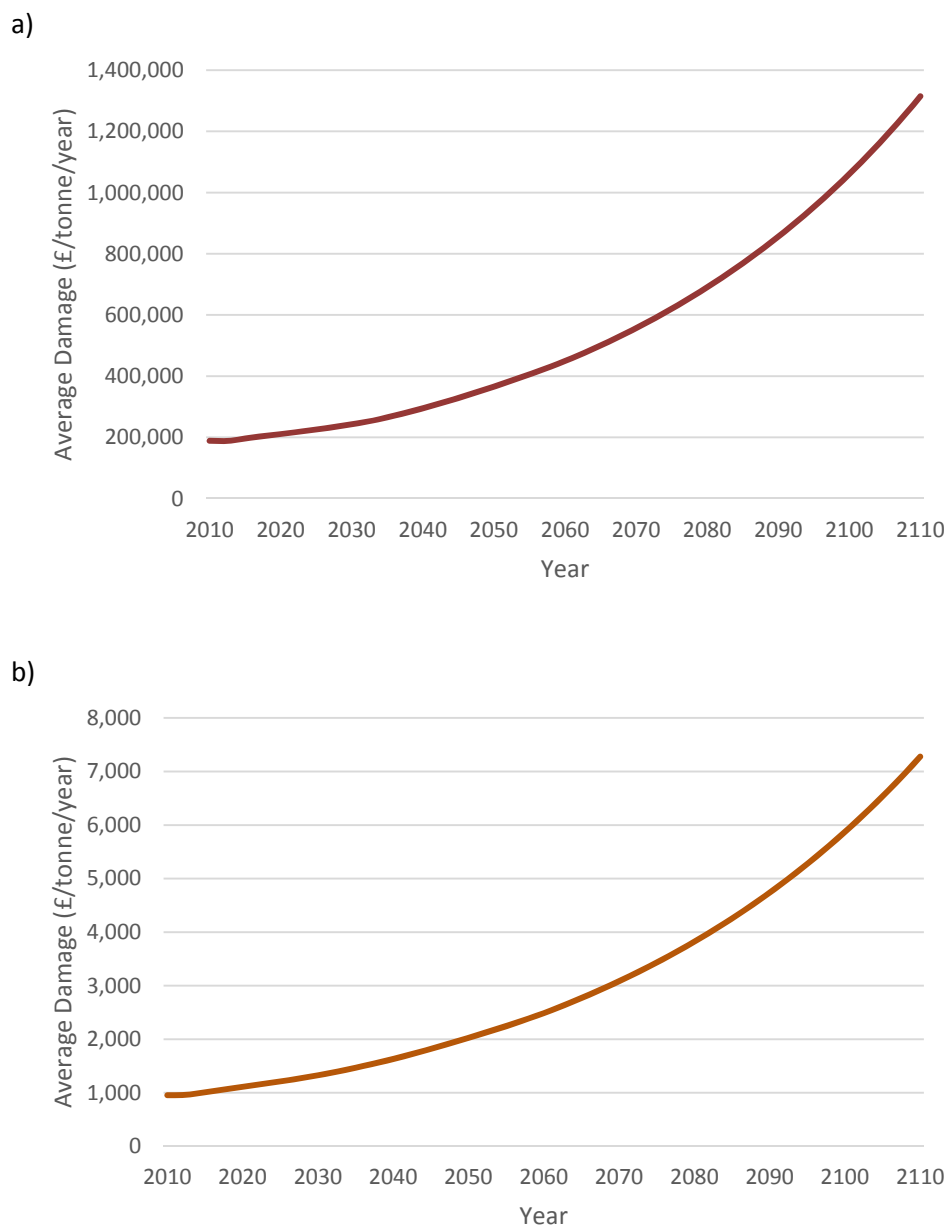
is normally taken (see AEA (2005) for a listing of values for the EU25 member states). In the UK, these values are drawn from research by the Inter Departmental Group on Costs and Benefits (Air Quality) (IGCB(AQ)) as part of the 2006 Air Quality Strategy Review (see Figure 5.5). The values focus on health and health infrastructure impacts²⁸, which are thought to substantially outweigh all other effects (Delucchi and McCubbin, 2011), and allow for uncertainty in response times through provision of high, central and low estimations (0-40 years). However, the approach in general disguises the difference in spatial impacts²⁹. Furthermore, the valuation of PM₁₀ is an average of the coarse PM₁₀ and smaller particles i.e. PM_{2.5}, the latter of which have been shown to be significantly more damaging per gram (McCubbin and Delucchi, 1999). While this includes the effects of the smaller particles, it may become less accurate if the mix of particulate emissions changes over time. Finally, it should be noted that if air quality impacts are greater than £50m, the UK Department of the Environment, Food and Rural Affairs (Defra) recommends a more detailed spatial analysis ('impact pathway' approach) be conducted (Interdepartmental Group on Costs and Benefits, Air Quality Subject Group, 2013).

The IGCB(AQ) data is the most comprehensive and appropriate data-set available to use for the calculations. However, given the Defra guidance, the chosen method may need to be reviewed if the magnitude of this impact is found to be greater than £50m. Furthermore, air quality is likely to be of greater concern in areas that already have high levels of pollution, particularly where the development may affect compliance with legal limits. Therefore, given the case study, analysis could also consider the proximity of the intended development to existing AQMAs and the London Emission Zone (LEZ).

²⁸ Although they also include damage to buildings and impacts on materials in some cases.

²⁹ For example, over 99.9 per cent of the change in PM₁₀ concentration occurs within 200m of the source (Department for Transport, 2011a).

Figure 5.5 – Medium projection damage costs for a) PM₁₀ and b) NO_x in London (Interdepartmental Group on Costs and Benefits, Air Quality Subject Group, 2013)



Carbon Dioxide (CO₂) Emissions

The impact of CO₂ is global, long-term and highly uncertain, potentially creating large climate changes that may be catastrophic and/or irreversible. It is generated by combustion of fossil fuels and therefore is as intrinsic to (current) infrastructure developments as air pollutants.

However, movement to renewable energy generation and conversion from fossil fuels to electricity could significantly reduce current generation patterns.

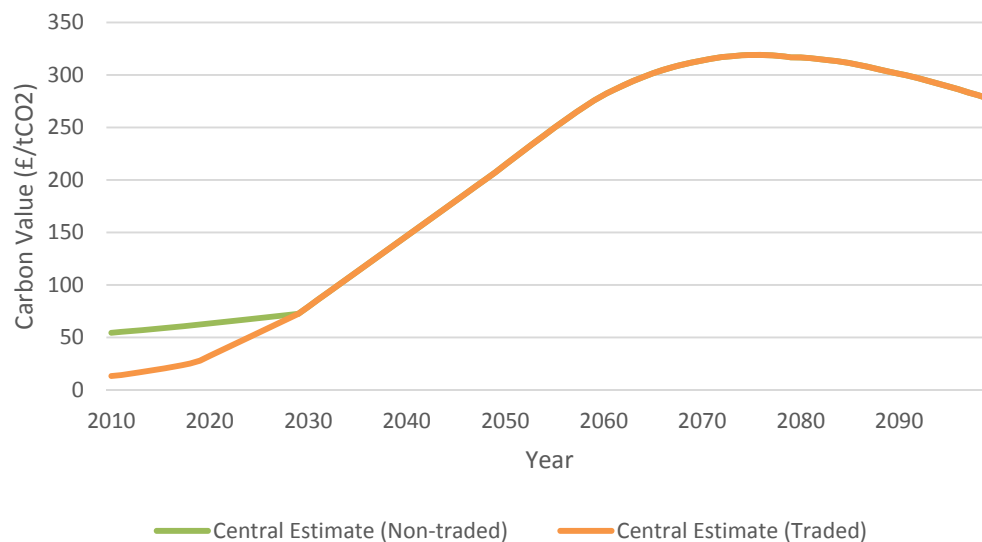
CO₂ emissions can be measured in the short-term and modelled in the long-term in a similar manner to air pollutants (see Department for Transport (2011a) and AMEC (2014b)). However, here even recorded emissions can vary widely, particularly from transport (Beuthe, 2002), and future levels are highly dependent on the assumed decisions regarding modal change in transport and energy generation.

In addition to quantification uncertainties, the uncertainty of climate change impacts along with varying opinions on discounting and aggregation of damages across countries has led to an extensive debate on the 'social cost' of CO₂ (Kuik et al., 2007). This has led to a wide range of values being proposed. For example, a review of European carbon values have shown variations of +/-95 per cent (Marcial Echenique and Partners Ltd, 2001) and two orders of magnitude for American values (Delucchi and McCubbin, 2011) depending on the assumptions made and method of derivation. Looking at current guidance, the European Union favours an avoided abatement cost approach, which would give a carbon price of €77/tonne in 2050³⁰, while the UK, given their stricter emission targets has developed artificial emission trading prices in the range of £104-£311/tonne for the same period (central estimate shown in Figure 5.6). This latter figure is more in line with that estimated by the European CASES project as necessary to meet the 2°C Kyoto limit (circa €200/tonne), suggesting that the European Union figure would be too low to meet this target (Friedrich and Quinet, 2011). As the higher UK prices reflect their commitment to carbon dioxide emission reduction, we will apply these figures; however, given

³⁰ Friedrich and Quinet (2011) calculate this starting from the 12-15 Euros/tonne Kyoto certificate prices, assuming abatement cost increases are kept in line with an annual discount rate of 3 per cent by policy measures and inflating to allow for sectors not involved in carbon trading.

the high levels of uncertainty, it will be necessary to evaluate the sensitivity of the results to this factor.

Figure 5.6 – Traded and non-traded carbon values (Department for Transport, 2011a)



Water Quality

A number of our case study elements are either in, over or next to the River Thames and therefore have the potential to pollute river water through runoff, degradation of materials, or in the case of the barrier, by affecting the hydrological dynamics of the river. Such pollution will affect the local population and wildlife habitats, but value of this change will differ according to the individual's location, wealth and use of the river³¹ (see, for example Birol et al.'s (2008) analysis of the benefits of water quality measures in Poland).

Quantification of water quality impact from infrastructure developments requires either a deep understanding of the operation of the asset and the hydrology of the river, or data on a similar

³¹ Uses may include commercial fisheries, abstraction, amenity, heritage, landscape and recreation; non-use values may relate to conservation or biodiversity (Environment Agency, 2003).

asset. However, detailed information on the proposed development is unlikely to be available at the strategic assessment stage; historical developments in the same location are unlikely to be similar technologically due to the long life of the assets; and similar developments elsewhere are likely to have different hydrological environments. Indeed, the Thames Estuary 2100 project (TE2100) noted water quality as one of the key uncertainties in their analysis, relying on qualified expert statements rather than computer based modelling (Environment Agency, 2009).

In addition to the change in quality we must quantify the population affected. A recent development in this field is to apply a distance-decay to the benefits generated (see Bateman et al (2006)), which has been found to apply to both use and non-use values (see, for example, Hanley et al.'s (2003) study on the River Mimram (2003)). There are, however, concerns that the decay profiles may be unique to the river considered, depending on the recreational/ environmental benefits created, making them of limited use to further studies (Hanley and Barbier, 2009).

Monetisation of water quality impacts of infrastructure developments has become more of a focus in Europe since the implementation of the Water Framework Directive in 2000 (Hanley and Barbier, 2009). While academically RPM have been applied to specific recreational activities and risks associated with water quality (see, for example, Train (1998) and Dwight et al. (2005)), most studies have concentrated on SPM. In UK, for example, the Environment Agency (EA) recommends the use of Georgiou et al.'s (2000) study of the River Tame in Birmingham (see Table 5.3)³².

³² Contingent Valuation methods were also applied, but a significant number of protest votes and null responses were received giving lower overall values.

Table 5.3 – Contingent Ranking results from Georgiou et al.’s (2000) study on River Tame in Birmingham³³

Water Quality Level	WTP £/household	Dissolved Oxygen %	BOD mg/l	Distance Decay (WTP = 0) km
Large Improvement	23.78	80.00	2.50	57.73
Medium Improvement	15.84	65.00	5.00	39.83
Small Improvement	9.97	50.00	8.00	26.63
Current Situation	0.00	20.00	15.00	N/A

The results are recommended for non-use valuation; however, responses in the study included those wishing to improve the river for future generations, recreation, fishing, public health and to protect the environment, therefore the study presents a useful estimate of WTP for a broad range of purposes. Georgiou also notes the ‘distance decay’ revealed by the results (as shown in Table 5.3).

Although the Georgiou data is likely to provide only a rough estimate of impacts and will be impacted by the need for benefits transfer, it will be used for the initial assessment of water quality impacts of the developments³⁴, to give an idea of scale such that developers can understand whether this issue is likely to be significant compared to the other impacts and therefore whether it warrants a more detailed assessment.

Habitat Loss/Creation

Given the large spatial footprint of infrastructure, its construction necessitates the clearance of a significant plot of land; furthermore, its presence, once developed can segregate the land that remains. It therefore has the potential to destroy plant life and habitats even in highly urban areas. While similar habitats could be created elsewhere, our limited understanding of the species within them and the relationships between them means that such undertakings have no

³³ Converted from 2000 prices to 2010 prices using the composite price index from the Office for National Statistics.

³⁴ Assuming that quality deteriorates from medium to low.

guarantee of success. We therefore risk the loss of habitats and the species reliant on them when we build new infrastructure.

Quantifying the footprint of the infrastructure is straightforward; it is an integral part of the engineering design. However, understanding the resultant effect on habitats and wildlife is challenging. Even if a full audit of all species were possible, wildlife may be transient or hidden and would therefore be missed; furthermore, the changes in habitat may not have a linear effect on the species remaining. Valuation is also difficult as although habitats provide a number of directly used benefits, for example ecological services, marketable products and tourism, they also provide non-use value, particularly conservation for future generations.

Historically, valuation studies concentrated on nature-based tourism and recreation, applying SPM and travel cost RPM to determine the WTP value (Hanley and Barbier, 2009; Pearce et al., 1989). However, having recognised the diversity of benefits, economists are now increasingly using a mixture of methods to calculate the combinatorial value (Hanley and Barbier, 2009). A key example of this in the UK is the UK National Ecosystems Assessment (NEA). Taking our case study as an example, the main habitat affected will be wetlands, which are known to provide a number of goods and services including flood control, nutrient removal, fish products and recreational opportunities (Van Den Bergh et al., 2001). For their estimation of value the NEA therefore used hedonic pricing (amenity value), SPM (amenity, biodiversity and water quality) and market price cost savings (flood protection and water quality), producing a total value of £1,231/ha/year.

An alternative is to combine the historic values with Geographical Information Systems (GIS) and benefit transfer methods to provide bounding WTP estimates for new locations (for example Bateman et al.'s (2003) meta-analysis on SPM valuations in the UK), or to improve estimations of

changing preferences over time (such as Zandersen et al.'s (2007) twenty year analysis of WTP for the conservation of forests in Denmark). These more simplistic analyses can be applied when far less data is available regarding the type of habitat present and is the method used by the UK Water Companies as part of their Water Resource Management Plans. Here, a more general WTP for the continued conservation of Sites of Strategic Scientific Interest (SSSI) of £5603/ha/year (2010 prices)³⁵ (taken from Willis' (1989) contingent valuation analysis of three SSSIs in north England), is multiplied by a factor dependant on the area's designation (see Table 5.4).

Table 5.4 – Water Company multipliers and resulting values for habitats

Habitat Designation	Multiplier	Value £/ha/year (2010 prices)
Internationally Designated	2	11,206
Nationally Designated	1	5,603
Local Nature Reserve	0.5	2,802
Non-Designated	0.1	560

Given the limited understanding of habitats and species present (and indeed the exact construction site) likely at the strategic appraisal stage, we will apply Willis' (1989) contingent valuation with the UK Water Company multiplication factors. However, it is recognised that this is over four times the value of that calculated for wetlands in the UK NEA and therefore its uncertainty will be considered.

Landscape and Visual Amenity

In addition to habitat loss, the size of infrastructure facilities also disrupts the landscape; the structures are normally large enough to be seen from a considerable distance and are considered by most people to be an eyesore.

³⁵ Converted from £5178/ha/year (2007 prices) using the composite price index from the Office for National Statistics.

Quantification of this factor is challenging and will be dependent on the type and design of the structure, the beauty of the current landscape and the geography of the area. For example, a railway could have a large footprint, but can be hidden by landscaping and tunnelling, furthermore stations tend to be located in urban areas and, in the UK, are not usually particularly tall. In contrast, wind turbines have a relatively small footprint in comparison to their height and are often developed in rural, flat areas where they will be visible for miles.

Given the abstract nature of this factor, most studies have focused on SPM, attributing value by household or by hectare. In addition to residents and visitors, these studies have shown that values are also significant for non-use and existence³⁶. To provide more general figures, the Entec project reviewed 22 contingent valuation, discrete choice experiment and travel cost studies focusing on the more recent studies and, where possible, the UK case (Entec, 2004). Studies were divided into four types of site, 'natural and semi-natural land', 'agricultural land', 'forested land' and 'greenbelt land', with the most appropriate WTP value taken from the review³⁷. Results were then calculated for nine regions of England, weighted against the relevant population and the number of hectares of appropriate land within the region's urban fringe (see Table 5.5).

While the data focuses on development within the urban fringe (i.e. less than 2km from urban developments), it provides a reasonable starting point for a strategic level appraisal. We will therefore apply the Entec results in our appraisal.

³⁶ See Willis et al (1998) for a summary of values provided by five studies on the UK countryside, use values for visitors range from £179.00–1,514.78/ha/year, while existence and non-use values range from £451.50-2,963.00/ha/year.

³⁷ Natural and semi-natural land (Hanley and Spash, 1993); intensive agricultural land (Bowker and Didychuk, 1994), extensive agricultural land (Willis et al., 1995), forested land (Bishop, 1992) and greenbelt land (Hanley and Knight, 1992; Willis and Whitby, 1985).

Table 5.5 – WTP values for landscape preservation (values uprated to 2010 prices) (Entec, 2004)

Region	WTP £/ha/year (2010 values) ³⁸
North East	679
North West	986
Yorkshire and the Humber	700
East Midlands	646
West Midlands	774
East of England	552
London	932
South East	786
South West	758

5.4.4 Social indicators

Our second set of externalities represents the risk impacts that are created or diminished as a secondary effect of the infrastructure assets, either in their everyday use ('safety') or under extreme conditions ('security'). For example, while the primary purpose of a road may be increased accessibility, connectivity or reliability, its development will also create safety impacts which will vary according to demand (congestion), technology and legislation. As use of road transport increases, so do accident levels. Increasing rail usage also increases accident levels; however, if people are encouraged to convert from road to rail (a safer mode of transport) accident levels fall. The case study both increases road demand and encourages conversion to rail, therefore provides the potential for both increased and decreased levels of safety, depending on the users' mode of transport, although only the increased road use will be seen in the individual asset appraisals in this chapter³⁹. Here we will also include changes in employee risk, from encouraging employment in riskier sectors (air transport). Our second factor ('security') considers extreme events: the benefit of the barrier to the general population; and benefits to both the population and to property from a reduction in the severity of a terrorist attack on the airport.

³⁸ Converted from 2003 values using the composite price index from the Office for National Statistics.

³⁹ For conversion to rail see system effects in Chapter 6.

Safety

In the context of a developed country, the provision of additional infrastructure does not, in most cases, present a significant everyday safety risk to its users, either due to the service's inert nature (ICT, clean water), or existing safety measures (electricity, gas, waste). Transport provides an exception. Here, users have a greater degree of impact on the service provision and accidents can affect tens or hundreds of people. Furthermore, by providing greater capacity and reliability, we can encourage greater use, exposing new people to these risks. However, we can also encourage the movement to statistically safer modes of transport such as rail.

Accidents requiring emergency services or insurance claims are recorded, therefore given the age of the transport systems in the UK, a wealth of data is available on the statistical safety of the various modes of transport. This data is normally presented as the number injuries per distance travelled and can therefore be used to predict accident levels given the demand projections of a new development. However, the accuracy of the data can be questioned on three levels: firstly our demand projections are likely to be inaccurate (see utilisation critique); secondly, less severe accidents (minor damage only) may not be recorded and will therefore be under-represented; and finally, where accidents are recorded, they are recorded against the most severe injury present and therefore estimates of effects per injury type will tend towards the lower bound values. While all these factors will affect the accuracy of our estimate, statistical rates provide a simple indication of the effects of development and are usable with the limited information available at the strategic appraisal stage (see Department of Transport (2013; 2011a)).

When a transport accident occurs, there is the chance someone could be hurt, requiring emergency assistance and medical treatment. This can have knock on effects, creating stress for their family and lower productivity in their workplace. Even where no injury takes place there

can be damage to property, insurance costs and delay caused to other users as the incident is cleared. The valuation of accidents is therefore a multi-faceted problem with effects for both the individual and society, but the largest value component (and the most controversial) is the WTP to avoid injury and/or loss of life (Friedrich and Quinet, 2011).

Valuation of a life was initially estimated through their market productivity ('human capital approach'); however, this method prioritises improvements that will aid the wealthy and does not value the young, retired or unemployed, it is therefore normally considered unsuitable for social valuation (Andersson and Treich, 2011). It is now more usual to estimate an individual's WTP either through hedonic pricing⁴⁰ (Hanley and Barbier, 2009), or through stated preference methods, although the biases in the latter can still create greater valuations for the rich⁴¹. The WTP valuations generated are then used to calculate either a value of a statistical life (VSL) or a value of a statistical life year (VSLY) which can then be applied to the additional/reduced risk level. While VSL and VSLY may use the same valuation data, they can produce very different results for change in risk (Hammitt, 2007), with VSLY producing lower benefits to the elderly or infirm⁴². Given the ethical concerns of the human capital approach, it is perhaps not surprising that the VSL is more commonly proposed by Government guidance (Baker et al., 2008). VSLs can be seen to vary significantly from country to country (see Table 5.6), therefore it will be important that this value reflects the case study and is applicable to UK preferences for risk.

⁴⁰ In transport, this could include consumer decisions on features such as inbuilt measures within different car models (Atkinson and Halvorsen, 1990), or additional equipment such as helmets for cyclists (Jenkins et al., 2001).

⁴¹ See Andersson and Treich (2011) for discussion of these biases and their effects.

⁴² Baker et al. (2008) discuss WTP studies in the US and UK for different age ranges and the ethics of differentiating value of life based on age.

Table 5.6 – VSL for 13 European countries (2005 prices) (Friedrich and Quinet, 2011)

Country	Fatality/€	Severe Injury/€	Slight Injury/€
Belgium	1,603,000	243,200	15,700
Czech Republic	932,000	125,200	9,100
France	1,548,000	216,300	16,200
Germany	1,493,000	206,500	16,700
Greece	1,069,000	139,700	10,700
Italy	1,493,000	191,900	14,700
Latvia	534,000	72,300	5,200
Netherlands	1,672,000	221,500	17,900
Norway	2,055,000	288,300	20,700
Poland	630,000	84,500	6,100
Spain	1,302,000	161,800	12,200
Sweden	1,576,000	231,300	16,600
United Kingdom	1,617,000	208,900	16,600

In the UK, WTP valuations, along with average societal and emergency service costs have been derived for road accidents by the Department for Transport (2011a). While it is recognised that different sources of risk can be valued differently by individuals (see for example Carlsson et al.'s (2004) analysis of WTP for travelling by air or taxi), the Department recommends the use of the same figures for both air transport passengers and rail passengers⁴³. For road accidents, costs of police, insurance and property damage have also been collated (Department for Transport, 2011a); however, these are relatively minor compared to the WTP figures for risk reduction⁴⁴ and are only available on a 'per accident' basis, making them difficult to combine with the 'per injury' data.

Although the DfT figures include some societal values, others are not represented, particularly altruistic concerns for the safety of others (Andersson and Treich, 2011) and the general aversion for large loss of life⁴⁵. Despite these shortcomings, the DfT values can provide a

⁴³ For rail incidents, factors of 0.1 and 0.005 are applied to the fatality cost for serious and minor injuries respectively to reflect the lower severity of rail injuries compared with road injuries.

⁴⁴ For example, in 2010 insurance, police and damage costs totalled 0.2 per cent, 1 per cent and 5.6 per cent of total costs in the case of fatal, serious and slight accident severities respectively.

⁴⁵ For example, the societal risk curve produced by the UK Health and Safety Executive suggests that a single event with 100 deaths should be two orders of magnitude less frequent than a single event with 10 deaths (Center for Chemical Process Safety, 2009).

consistent, long-term estimate of the value of safety in the UK context and therefore will be used with the statistical accident rates to calculate the safety performance. However, given the known biases and limitations, the results will be treated as a lower bound value.

While users of infrastructure are in most cases protected from risk, those employed to operate the infrastructures are, in most cases, at a slightly higher risk than the average employee elsewhere (Health and Safety Executive, 2012). Therefore, where the developments propose significantly more employment than the base case, the values in Table 5.6 will also be used to assess the effects on safety from increased employment.

Security

Our second social factor is security of the population in the case of extreme conditions, which may be provided by infrastructure either by design (in the case of the barrier) or indirectly by the removal of risk. Considering the UK National Risk Assessment (Cabinet Office, 2012), only three of the most substantial risks are relevant to infrastructure⁴⁶: transport and industrial accidents (the former of which has been considered under safety and the latter of which is not relevant to the current case study); extreme weather (which is relevant to the barrier); and terrorist attacks.

While the existing level of infrastructure in the UK would suggest that further developments would not significantly affect the probability of terrorist attacks, they can affect their severity. Given our case study, the removal of flights over central London would indeed reduce the impact of such an event and therefore this will be considered alongside the barrier's security effects.

⁴⁶ The remaining three risks are disease outbreaks (human and animal), public disorder and disruptive industrial action.

To quantify these effects, we need an appreciation of both the population affected and a probability of the event. As discussed for the physical protection indicator, extreme events are inherently infrequent; projections of their impact and frequency are therefore difficult to validate and must be treated as highly uncertain. For the personal security provided by the barrier, we can apply the outputs of the TE2100 project, thereby maintaining consistency with the physical protection indicator. For the frequency and targets of terrorist activities, however, we have limited scope for estimation without consideration of historic cases. We assume that increased terrorist activities will promote stricter security measures and create a balancing effect over the long-term. We therefore draw on data from the Global Terrorism Database (University of Maryland, 2012) to estimate the likelihood of an airport attack in London.

Both an extreme weather event and a terrorist attack have the potential to cause harm and even fatalities. As noted in the safety critique, value of life has been estimated in a number of ways and varies from country to country. In the UK the most widely applied approach is that of the DfT; however, this may not be appropriate in the case of extreme events due to the 'dread' associated with the event. The UK HSE have commissioned research to investigate how the cause and circumstance of injury affect the perceived risk and already suggest taking it into account in the case of cancer risks⁴⁷; however, there is currently no direct evidence to support such adjustments. Indeed, comparing research by Magat and Viscusi (1996) with that of Van Houtven et al (2008) into the WTP to avoid cancer risks, results vary significantly, being similar to those for avoiding road accident risks in the former and three times this value in the latter. Therefore, in the absence of data on the value attributed to the avoidance of 'dread' and how this relates to the various infrastructure sectors, the DfT values will be used.

⁴⁷ The HSE's value for dying from cancer is double the normal value. Subjectively, 'perceived potential for catastrophic loss of life' has also been found to be one of the most influential factors on public perspectives of risk (see Slovic et al.'s (1980) review of the effects of fear on assessments of Nuclear power).

The physical protection provided by the reduction in terrorist event severity will be calculated using costings for the 9/11 terrorist event scaled down to a single aircraft to reflect the increased security measures (Hartwig and Wilkinson, 2012). These figures will then be scaled by residential population density to estimate a similar event in the Thames Estuary.

5.5 Limitations of aggregation

Having reviewed the potential effects of the case study and the various methods for quantification and monetisation, the remainder of this chapter will apply the indicators to the case study and review the results given the valuation uncertainties already discussed. We must first, however, note that straightforward addition of the indicators in itself is a simplification of the real values and that the further aggregation of factors into the four attributes will obscure some of the detail of the results.

We have noted above that the indicators are inherently coupled. Infrastructures provide a number of effects and externalities and while some can be varied by design, the choice is inevitably between the sum of the results or none of the results. Furthermore some of the effects are bound to each other; such as those discussed between reliability and utilisation, therefore the exact results are dependent on the behaviour of the users, the changes in the environment and the other effects generated. Finally, our valuations assume that factors are separable, that our enjoyment of the environment, for example, is a summation of parts with no additional value created by the whole (Hanley and Barbier, 2009), or reduction effect from substitution/over provision (Hanley et al., 2003)⁴⁸. The last of these simplifications is perhaps

⁴⁸ Santos (2000) provides an analysis of this independent variable and summation (IVS) bias for four contingent valuation studies in the UK and Portugal, finding the bias statistically significant but not sufficient to invert the resultant policy recommendation. He does, however, note that for cases where more than two or three non-market outputs are considered the biases will be greater.

the most concerning given our focus on the value of systems as a whole rather than their individual parts. It would therefore seem to be a valuable extension of the work, but is considered a necessary simplification if we are to first understand the system effects between the infrastructures.

In addition, the aggregation of benefits disguises the limitations of the analysis, particularly those factors which haven't been included. Our analysis of key performance indicators in Chapter 3, suggests that there will be a number of other indicators that will be of interest to more specialist stakeholders and further sector specific analyses are likely to be a necessary addition to the system analysis. In particular, the wider economic benefits of infrastructure have become a recent focus for governments, despite disputes over the size and causality of such effects (Priemus, 2010; Anderson and Lakshmanan, 2007) and the need for complementary policies and investments for them to be realised in developed countries (Beuthe, 2002; Banister and Berechman, 2003). While we ignore these factors in our initial analysis, we return to the subject of wider economic benefits as part of our spatial analysis in Chapter 8.

While obscuring some of the detail of the results, our aggregation into four attributes aids the decision maker by summing variables to a limited number of attributes, with results of comparable scales. Our analysis is aimed at the trade-offs between these attributes rather than between stakeholders; however, it will also be necessary to understand the latter if public opinion and investor interest are to be assessed. Therefore while the aggregated values are useful for initial decision analysis, we will maintain the ability to disaggregate for further review. Furthermore, we will consider how our choice of aggregation method affects how the results are perceived, returning to this factor after deriving results for each of the case study elements.

5.6 Appraisal methodology

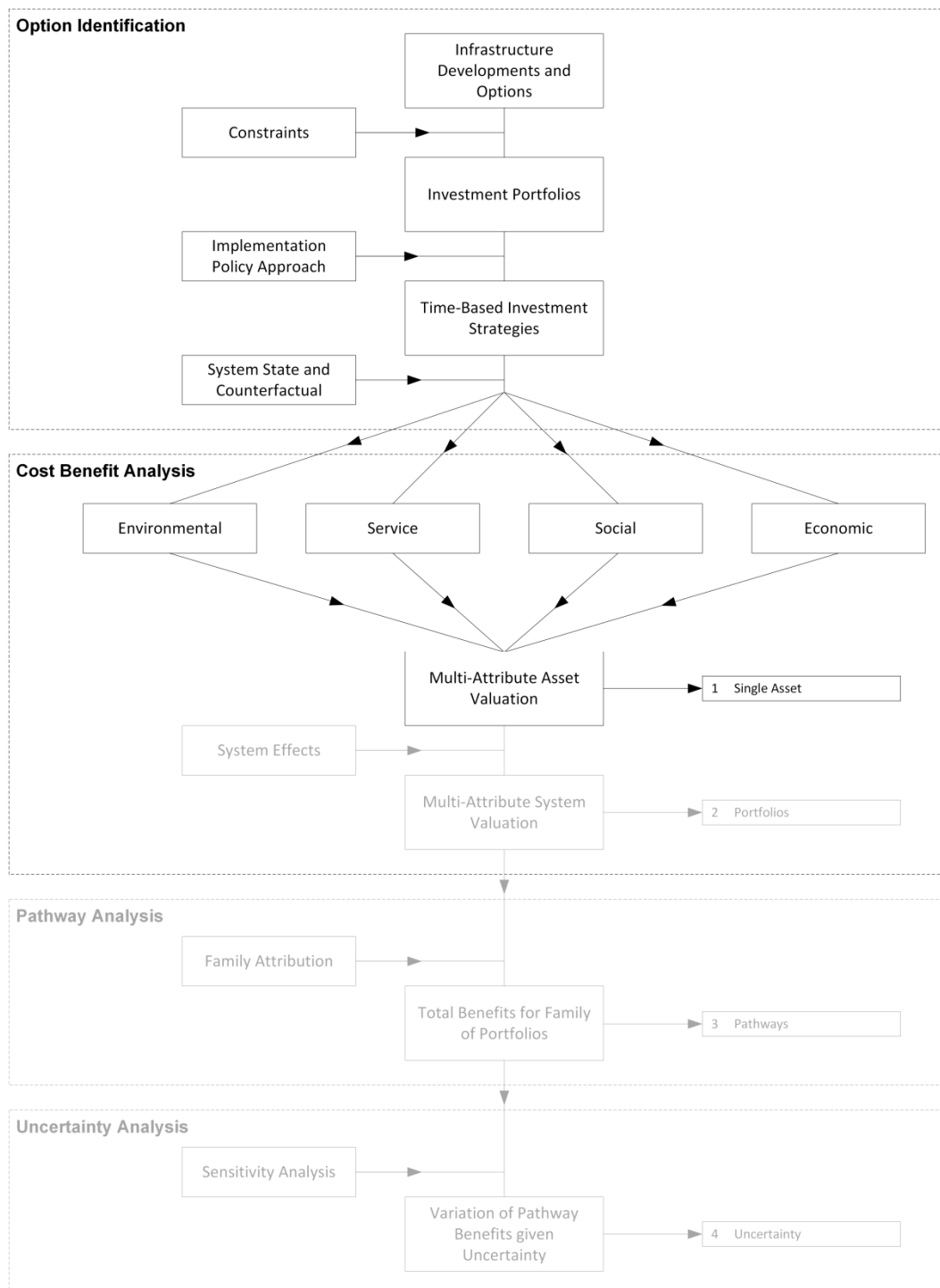
The performance indicators and valuation methods outlined in Sections 5.3 and 5.4 provide us with sufficient information to apply the first stage of the multi-sector, multi-attribute cost benefit analysis outlined in Chapter 3 (see Figure 5.7 for an overview). In the next sections we apply the methodology to each of the infrastructure elements as standalone assets in a similar manner to current appraisal methods. This provides the foundation for the portfolio and pathways analyses in Chapter 6 and a baseline that will allow us to derive the additional system effects captured.

However, before we can implement this first stage of the appraisal, we must first further define the time factors left open in Chapter 3 to allow them to be tailored to the case study. The total timeframe of the analysis was chosen in Chapter 3 to allow the case study data to be analysed. This was set to one hundred years in accordance with current UK infrastructure systems research through the Infrastructure Transitions Research Consortium. Earlier in this chapter we also set the discount rate to the descending discount rate stipulated in HM Treasury guidance (HM Treasury, 2003). This will therefore reflect UK sector specific appraisals.

We must now choose the starting date (for pricing and discounting) and, in preparation for the pathway appraisal, the time division between decision points (see Chapter 3). These factors should also be tied to the interests and governance of the country of concern and therefore we base those used herein on the UK context, applying:

- A starting year of 2010 in line with current HM Treasury appraisal; and
- Decision point divisions of five years, reflecting UK elections.

Figure 5.7 – Outline methodology, single asset appraisal elements highlighted (adapted from Young and Hall (2015))



Referring back to our formalisation in Chapter 3, our vector of delivery points (D) can now be defined as:

$$D = \{d_{2010}, d_{2015}, d_{2020}, \dots d_{2110}\}$$

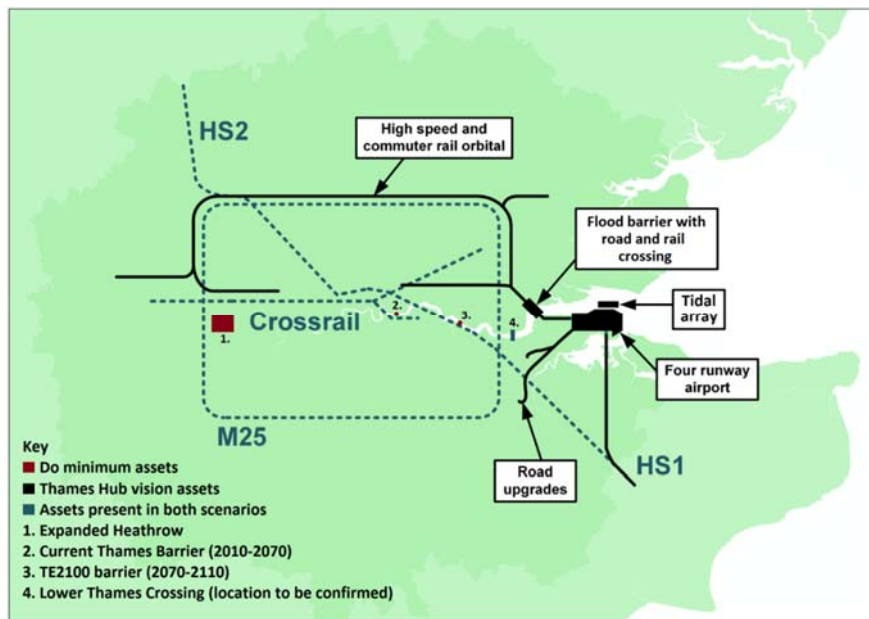
Our vector of assets (A) consists of the five Thames Hub Vision elements:

$$A = \{a_0, a_1, a_2, a_3, a_4\}$$

where a_0 - a_4 = each of the Thames Hub Vision elements

However, as we choose to implement each individually at this stage, we only produce five potential portfolios. As each portfolio has only one element, this results in five single asset strategies to compare to the 'do minimum' development pathway derived in Chapter 4 (see Figure 5.8). Each asset is assumed to be developed at its earliest possible implementation date⁴⁹ (applying an 'as soon as possible' implementation policy).

Figure 5.8 – 'Do minimum' and Thames Hub Vision infrastructure elements



Each of the indicators will be quantified (x) over the 100 year timeframe (t), using the system state conditions (w_ϵ) specified in our system characterisation in Chapter 3. These will then be aggregated into the four attribute impacts, such that the value of strategy s''_v under exogenous state conditions w_ϵ is shown by Equation 5.1:

⁴⁹ Road (2015), tidal array (2015), barrier (2016), rail (2019), airport (2028).

Equation 5.1 – Multi-attribute strategy valuation

$$V(S''_{\gamma, w_{\varepsilon}}) = \begin{bmatrix} v_{Environment}(S''_{\gamma, w_{\varepsilon}}) \\ v_{Economics}(S''_{\gamma, w_{\varepsilon}}) \\ v_{Service}(S''_{\gamma, w_{\varepsilon}}) \\ v_{Social}(S''_{\gamma, w_{\varepsilon}}) \end{bmatrix} \approx \begin{bmatrix} \sum_{ind_E=1}^6 \sum_{\delta=0}^n (x_{S''_{\gamma} t_{\delta} w_{\varepsilon}}) \\ \sum_{ind_M=1}^4 \sum_{\delta=0}^n (x_{S''_{\gamma} t_{\delta} w_{\varepsilon}}) \\ \sum_{ind_{Se}=1}^3 \sum_{\delta=0}^n (x_{S''_{\gamma} t_{\delta} w_{\varepsilon}}) \\ \sum_{ind_{So}=1}^2 \sum_{\delta=0}^n (x_{S''_{\gamma} t_{\delta} w_{\varepsilon}}) \end{bmatrix}$$

Results will be reported as a net present value (2010 prices).

5.7 Results and analysis

In Sections 5.3 and 5.4 we noted that each of the performance indicators would include inherent uncertainties, due to their quantification, their monetisation and the extended period of time over which the appraisal is being conducted. While limited and inaccurate data are a significant issue for infrastructure in mature economies such as the UK⁵⁰, most of the uncertainty is derived from our inaccurate estimation of infrastructure impacts (due to incomplete knowledge and understanding) and the values we attribute to them (due to ambiguity, subjective judgements and multiple rational perspectives) (Salling and Banister, 2010). Therefore, before comparing the results of each of the infrastructure elements, we first consider the uncertainty of the indicator results and our ability to draw conclusions based on the results. Where uncertainties are seen to affect multiple indicators, we consider whether this works to reduce or increase the uncertainty of the total value derived.

⁵⁰ See, for example, Apostolakis and Lemon (2005).

5.7.1 Monetary indicators

Table 5.7 presents individual appraisals for the five Thames Hub Vision infrastructure elements, expanding the monetary indicators, but providing the service, environmental and social aggregated results for reference. The barrier and airport results reflect the net value compared to their counterfactual developments.

Table 5.7 – Thames Hub Vision individual element appraisal results with segregated monetary indicators

Attribute	Indicator	Road (£bn)	Barrier (£bn)	Gen ⁵¹ (£bn)	Rail (£bn)	Airport (£bn)	Monetisation Method Uncertainty
Monetary	Cost	-1.95	-1.62	-1.70	-20.07	-19.85	+20% to +45%
	Revenue	-	-	0.90	-	21.50	-51% to +9%
	Tax	-	-	0.01	0.54	10.12	-51% to +9%
	Employment	-	-	0.04	1.50	23.41	Unknown
Service	Total	-	0.29	0.90	-	-43.65	-
Environment	Total	-0.85	-0.94	0.13	-1.92	-2.16	-
Social	Total	-	0.34	-	-	-3.64	-

As noted in Section 5.4.2, inherent demand for the road, rail and river crossing (barrier) has initially been ignored. In the model, there is therefore no potential to generate revenue from these infrastructures when developed as standalone assets⁵². While the operation of the rail system generates some employment and tax benefits, these only represent approximately 10 per cent of the costs. Therefore all three infrastructure developments present a significantly negative picture. However, as the assumption of no inherent demand is likely to be inaccurate, given the population growth predicted in and around London, we must consider whether this negative viewpoint is likely to substantially change once demand is predicted.

⁵¹ Tidal energy generation.

⁵² Induced demand from other developments will be considered in the next chapter as we begin to look at the system effects of infrastructure portfolios and pathways.

Despite changes in demand, unless a toll system is introduced, the road and river crossing (barrier) infrastructure will still not generate revenue. While tax will be generated by increased petrol usage, given the current usage of roads in the area, its monetary results are likely to remain strongly negative despite the unquantified benefit from inherent demand⁵³. Demand could, however be sufficient to counterbalance the cost overruns. For example, if the new roads experienced an inherent demand similar to that on the quieter surrounding roads (6,000 vehicles per day), drivers need only use the roads for between 0.1-0.3 hours per day to counterbalance a 20-45 per cent cost overrun. The total monetary result of the road development is therefore likely to be relatively stable⁵⁴.

The rail infrastructure has the potential to generate revenue through ticket sales and therefore its monetary result is likely to be less negative than that shown. However, given that only 1.6 per cent of the population of Medway and Gravesham commute to London by rail (Office for National Statistics, 2001), it is unlikely to produce sufficient additional demand to equal the costs in the short-term⁵⁵. The conservative assumption of no inherent demand will therefore not affect the nature of the result. However, the demand created by the rail developments could again be sufficient to counterbalance inaccuracies in the cost estimations (requires 5,000-11,000 journeys per day). The monetary results of the rail development are therefore also likely to be relatively stable.

⁵³ The surrounding roads only currently experience average daily traffic counts of between 6,000-20,000 vehicles (Department for Transport, 2012) and would need to would save approximately 3,500 hours per day (0.2-0.6 hours per vehicle) to have a 1:1 cost benefit ratio.

⁵⁴ Note that the tax benefit is to the Treasury, therefore, while the results above would be counterbalanced, the investment profile is only affected if publically funded.

⁵⁵ The population projections for Medway and Gravesham (Hall et al., 2012a), suggest an additional 1,300-10,800 journeys per day will be required by 2110. Network Modelling Framework (NMF) growth forecasts suggest a further 34-42 per cent increase in passenger miles by 2030 in South East England, raising this to 1,800-15,400 journeys per day. A 1:1 cost benefit ratio for the rail orbital requires 25,000 journeys per day.

The tidal array and airport both have the potential to generate income and have been proposed as suitable for private investment (Foster+Partners et al., 2011a). It will therefore be important that their *financial* result (cost against revenues) is not only positive, but sufficiently so to attract investors away from other investments. Both cost and revenue estimations are known to be highly inaccurate⁵⁶ with the combination of overestimated revenues and underestimated costs having been sufficient to reverse benefit ratios in a number of infrastructure developments (Ansar, 2014). This is seen in the case of the tidal barrage, where if the estimations are correct, the total of the cost, revenue and capacity utilisation⁵⁷ (see service attribute results) produces a benefit of £0.1bn; however, applying Flyvbjerg's average cost inaccuracies (20-45 per cent) and the lower bound average revenue shortfall (51 per cent) creates a total loss of £1.1-£1.6bn. Similarly for the airport, the cost, revenue and revenue related capacity utilisation produces a benefit of £6.0bn. Assuming the same bias as applied to the tidal array, costs increase by £4.0-9.0bn and benefits fall by £13.2bn creating a loss of £11.2-16.1bn. It would therefore appear that neither investment would be attractive to an investor in its standalone state. However, while Flyvbjerg suggests that the cost and revenue biases can be applied to other assets and sectors, they have been derived from road and rail infrastructures, where revenues are directly dependant on public use of the infrastructures. This is not true for tidal array and airport. In the case of the tidal array, there is the opportunity to directly supply the airport (which will have a relatively constant demand requirement) as well as feed into the national grid. In the case of the airport, demand related revenue is predominantly generated from airliner landing fees, therefore is dependent on the number of flights rather than the number of passengers. Furthermore, the early limitation of benefits due to capacity constraints⁵⁸, provides another

⁵⁶ Revenue and indirect tax effects are derived from the demand profiles, their uncertainty has therefore been approximated from Flyvbjerg's assessment of demand inaccuracy (Flyvbjerg, 2007).

⁵⁷ Remembering that this comprises half of the revenue benefit.

⁵⁸ Taking the DfT's central aviation demand profile (Department for Transport, 2011b), the airport will reach capacity (150mppa) in 2040. Even taking the DfT's low demand profile, demand has reached 98.9 per cent of capacity by 2050 (the current limit of the DfT projections).

level of protection against inaccuracies in the passenger demand profile. If we assume that the revenue estimations are accurate and just apply bias adjustments to the costs, the tidal array result remains negative, but far less so (varying from -£0.2 to -0.7bn), but the airport result is dependent on the accuracy of the cost estimations, varying from -£3.0bn to +£2.0bn.

For the tidal array, employment and related tax benefits are small but positive, further enhancing the monetary case (although not sufficiently to create a positive result given the uncertainty of results and not for private investors). The airport also produces employment benefits, but here 14 per cent of the tax benefit (£1.4bn) is due to the petrol duty paid by passengers travelling to and from the airport, as the airport is now located further away from most users. This factor will not contribute to the investor's case (unless publically funded) and can be seen to produce significant environmental disbenefits.

It should be noted that the results differ significantly from the Thames Hub Vision proposal documentation, which estimates £32 billion in benefits from the airport. This benefit, based on the increased air fares generated by removing current airport capacity constraints, would manifest; however, would accrue airlines using the airport. These companies are outside our model boundary (those investing in the airport infrastructure directly, the Treasury, users and the general public), their revenues may, however, feed into macroeconomic growth for the UK.

5.7.2 Service indicators

The assumption of no inherent demand for the road, rail and river crossing (barrier) results in zero utilisation and reliability benefit from these infrastructures when developed as individual assets (see Table 5.8). The service results therefore differ significantly from the benefit estimations within the Thames Hub Vision proposal, which are based on time savings generated

for users of these assets⁵⁹. It is, however, likely that development of these infrastructures will generate additional demand (see Section 5.7.1). Therefore, while we have chosen not to include time savings (see Section 5.4.2), the appraisal results for utilisation can still be assumed to be conservative. The additional road and rail capacity may also divert demand from existing routes, improving their reliability. Any inherent demand may also, however, add to current traffic levels counterbalancing any beneficial reliability effects⁶⁰. While not quantified by our methodology, the provision of a high speed rail service may also increase the perceived quality of service and thereby further increase value to users.

Table 5.8 – Thames Hub Vision individual element appraisal results with segregated service indicators

Attribute	Indicator	Road (£bn)	Barrier (£bn)	Gen (£bn)	Rail (£bn)	Airport (£bn)	Monetisation Method Uncertainty
Monetary	Total	-1.95	-1.62	-0.75	-18.03	35.18	-
Service	Cap' Utilised	-	-	0.90	-	-2.52	-51% to +9%
	Reliability	-	-	-	-	-41.13	-51% to +9%
	Protection	-	0.29	-	-	-	Unknown
Environment	Total	-0.85	-0.94	0.13	-1.92	-2.16	-
Social	Total	-	0.34	-	-	-3.64	-

The utilisation and reliability effects of the tidal energy generation and the airport are calculated based on available capacity and predicted demand. The energy generation capacity (525GWhr) is expected to be fully utilised as soon as it is available either directly by the airport or by the grid. Given the growth in electricity demand projected in the UK (Tran et al., 2014), this assumption seems reasonable; however, the quantity of energy generated and the market value could still be inaccurate. Having noted that the monetary benefit produced by this asset was already highly variable due to estimation uncertainty, the possibility for over-estimations of energy generated (due to technological uncertainty) or market value (due to social and

⁵⁹ £37 billion in road and rail benefits

⁶⁰ To estimate such effects, current spatial travel data would be required, we will therefore return to this factor in Chapter 8.

economic uncertainty) may ensure this is not a viable private investment without governmental guarantees of revenue.

Despite the increased capacity of the airport creating £3.4bn of capacity utilisation benefits and £0.6bn of reliability benefits (compared to an expanded Heathrow), the service attribute of the airport remains strongly negative. In the case of the capacity utilisation indicator, this is due to the additional travel required to reach the Thames Hub Vision airport, with -£0.3bn in additional pressure on the already constrained rail services through central London and -£5.6bn in additional travel time and cost for road users. This additional road demand also negatively impacts existing road reliability, creating a disbenefit that overwhelms the positive reliability benefits of the airport itself, giving a total reliability impact of -£41.1bn. We noted in our analysis of the finance indicators that airport revenues and utilisation are not linearly related to passenger demand. These passengers will, however, have a direct effect on the surface access transport servicing the airport. Inaccuracies in air passenger demand will therefore reduce the accuracy of the capacity utilisation and reliability results, although the inaccuracy is tempered by the early restriction of demand by the capacity limitations of the airport. Reducing our service results in accordance with Flyvbjerg's lower bound value⁶¹, the total service effect improves from -£43.7 to -£21.3bn. The effect of the uncertainty in airport costs and demand is therefore counterbalanced between service and monetary attributes, with the total impact of the two attributes only varying from -£29.7bn to -£34.7bn (a range of £5.0bn), despite the large impacts on the individual indicators. The model does, however, assume that the current modal share of rail passengers (23 per cent) is maintained. This may underestimate road demand, therefore taking Flyvbjerg's (2009) average inaccuracy for road transport (+9 per cent) we estimate the total impact on the roads (increase in demand) and the rail (reduction in demand) as -£4.2bn, or

⁶¹ Assuming less people travel to and make use of the airport.

-£2.1bn once the demand uncertainty is applied. The total variation in the combined monetary and service indicators is therefore £7.1bn.

The service benefit of the barrier is determined by the physical protection produced to extreme weather events. They are therefore dependent on the level of development, the frequency of extreme events and the intensity of those events. Given that our 'do minimum' case includes the current Thames Barrier until 2070 and a barrier at Long Reach from this point forward, the benefit represents that of building a barrier which provides greater protection⁶² from an earlier date. Impact costings are taken directly from the TE2100 project⁶³, where they were derived by expert estimation. Given the difficulty in validating predictions of extreme events, the uncertainty of this indicator is difficult to determine and while it will always be positive, the effect will be strongly affected by the accuracy of the risk profiles/event probabilities and the discount rate chosen. Further benefits could be derived by transport movement across the barrier (river crossing), but herein these have been attributed to the Lower Thames Crossing as the former investment. The magnitude of the service benefit is therefore likely to be less stable than those of the tidal barrage and airport and it may be useful to monitor climate changes and provide flexibility in design (see de Neufville and Scholtes (2011)) to allow for this uncertainty.

5.7.3 Environmental indicators

As expected, the environmental indicators are largely negative (see Table 5.9). The only positive effects of the developments are the reduction of carbon dioxide emissions due to tidal energy generation and the noise reduction from the reduced number of flights over central London.

⁶² Protects a larger area and from more severe events.

⁶³ Note only the physical damage results (and injury results as part of the security indicator) are shown, therefore this will be lower bound estimate of the benefit derived.

Table 5.9 – Thames Hub Vision individual element appraisal results with segregated environmental indicators

Attribute	Indicator	Road (£bn)	Barrier (£bn)	Gen (£bn)	Rail (£bn)	Airport (£bn)	Monetisation Method Uncertainty
Monetary	Total	-1.95	-1.62	-0.75	-18.03	35.18	-
Service	Total	-	0.29	0.90	-	-43.65	-
Environment	Air Quality	-	-	-	-0.14	-0.18 ⁶⁴	-22% to +14%
	CO ₂	-	-	0.15	-0.17	-2.51	-95% to +95%
	Habitat	-0.04	-0.00	-0.01	-0.17	-1.11	-76%
	Landscape	-0.06	-0.00	-0.01	-0.23	-0.18	-46% to -65%
	Noise	-0.75	-	-	-1.20	1.81	+464 to +1700%
	Water Quality	-	-0.93	-	-	-	-30% to +25%
Social	Total	-	0.34	-	-	-3.64	-

Noise impacts are by far the largest environmental impact for both the road and rail infrastructures, representing 89 per cent and 63 per cent respectively. Our use of hedonic pricing to value noise also suggests that these values could be under-estimated compared to contingent valuation, with Schipper (2004) finding differences of 1700 per cent for small changes and 464 per cent for larger changes. Most of those affected by noise increases will only experience a small change from the road and rail assets⁶⁵; however, with such large uncertainties this could raise this impact to similar or even higher levels than the monetary indicators, more than doubling the total negative effect of these developments. Both assets are therefore likely to remain strongly negative. While negative effects are also shown for habitat and landscape, these are far smaller and their valuation methodologies suggest that values may be over-estimated. The rail development also produces carbon dioxide and air pollution; however, these are again much smaller in magnitude and despite large uncertainties for the

⁶⁴ It is worth noting that the air quality impact is not less than £50m and therefore the use of a more complete spatial 'impact pathway' approach would be deemed necessary for the individual asset appraisal by Defra guidelines (see Section 5.4.3).

⁶⁵ Approximately 75 per cent of those affected by the noise of the road development are over 200m away and over 85 per cent of those affected by the rail development are over 400m away.

carbon dioxide valuation (Marcial Echenique and Partners Ltd, 2001), remain a small proportion of the total environmental costs.

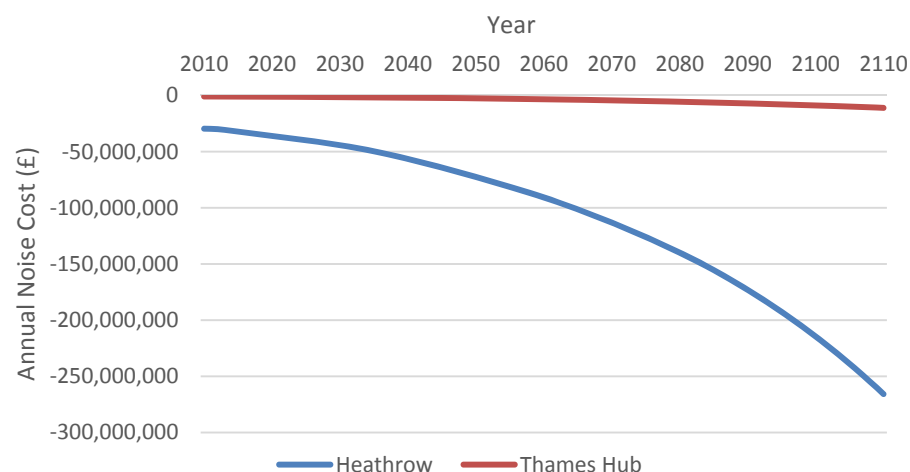
In contrast, as flights to an expanded Heathrow will affect a far greater population than those to the Thames Hub airport⁶⁶, noise is decreased by the development, producing a large positive result (see Figure 5.9). Here, the large uncertainty increases the positive effect and even at the lower bound of the uncertainty could result in a change from a net negative result, to a net positive result. The habitat destroyed by the development⁶⁷ and the carbon dioxide produced by passengers travelling to and from the airport⁶⁸ and aircraft take-off and landing operations are also significant inputs to the total result. Both are negative but have the potential to be reduced by the uncertainty surrounding their value, thereby reinforcing any impact of the noise uncertainty (and making the total environmental result more positive). However, the uncertainty surrounding carbon dioxide emission value could increase this cost (particularly given the previously discussed tendency to underestimate road usage), thereby counteracting some, but not all of the additional noise value. Taking the potential inaccuracies in the airport's environmental indicators together, the negative total environmental effect is likely to become less so, or even positive, improving the case for investment. However, the case hinges on the noise assessment, and disguises the spatiality between the benefits to west London and the costs to east London. It will therefore be important to understand stakeholder values by discussing the proposals with the local population.

⁶⁶ An additional 102,000-132,000 households depending on the year.

⁶⁷ 1000ha of intertidal habitat, 700ha of marshland and a further 2300ha of non-designated habitat.

⁶⁸ Approximately 1bn kg of CO₂ equivalent per year.

Figure 5.9 – Projected annual noise costs for Heathrow and Thames Hub Vision airports



The environmental effects of the tidal generation are mostly due to the reduction in carbon dioxide emissions resulting from replacement of a mix of electricity generation types with a renewable source. Its uncertainty is therefore related not only to monetisation of carbon dioxide emissions, but also the projection of future energy sources and their carbon emissions. While there are negative landscape and habitat effects, these only sum to 14 per cent of the carbon dioxide benefit and their uncertainties suggest their value is more likely to decrease than increase. Despite very high uncertainty levels for the carbon dioxide indicator, it is therefore likely that the environmental results of the tidal generation will remain positive, supporting its service results. Being six times smaller than the other aggregated attribute results, however, uncertainties in the environmental valuation are likely to only have a relatively small impact on the total economic case.

The barrier's environmental effects are almost entirely (over 99 per cent) due to the assumed levels of water pollution incurred. While the monetisation method is relatively stable compared to other indicators (-30 to +25 percent), as noted in Section 5.4.3, quantification of the water pollution was one of the key uncertainties of the TE2100 project and therefore could change significantly from the value estimated. However, as habitats, landscape and water quality will all

be degraded by creation of a barrier, this factor will remain negative and therefore the total effects of the barrier are unlikely to be substantially changed by the uncertainty.

5.7.4 Social indicators

Social indicators represent the costs of personal injuries suffered, or avoided, due to the presence of the infrastructures and any changes in physical damage due to indirect effects of the developments⁶⁹. With the assumption of no inherent transport demand for the road, river crossing (barrier) and rail, and no safety or security changes relevant to the energy generation, effects are limited to the direct effects of the barrier and the indirect effects of the airport (see Table 5.10).

Table 5.10 – Thames Hub Vision individual element appraisal results with segregated social indicators

Attribute	Indicator	Road (£bn)	Barrier (£bn)	Gen (£bn)	Rail (£bn)	Airport (£bn)	Monetisation Method Uncertainty
Monetary	Total	-1.95	-1.62	-0.75	-18.03	35.18	-
Service	Total	-	0.29	0.90	-	-43.65	-
Environment	Total	-0.85	-0.94	0.13	-1.92	-2.16	-
Social	Safety	-	-	-	-	-3.80	Unknown
	Security	-	0.34	-	-	0.16	Unknown

Safety is most strongly affected by the additional road traffic induced by the airport⁷⁰. As we noted in Section 5.4.4, the UK method of recording incidents against the worst injury present and the absence of costs for other users (delay) means that the results tend towards a lower bound estimate. Furthermore, inaccuracies in the demand profile will also affect the accuracy of the indicator and in the case of road transport would suggest higher levels of incidents than those estimated (+9 per cent, an additional cost of £0.3bn). However, given the magnitude of

⁶⁹ In our case study, the reduced severity of airport infrastructure terrorist attacks, due to the reduced need for flights over central London.

⁷⁰ -£3.5bn NPV for additional road and rail incidents, compared to -£7 million for air incidents and -£0.2bn for increased risk to airport employees over that of the average profession.

difference between the social factors and those of either the service or monetary factors, the total value proposition is unlikely to be substantially affected by these inaccuracies. The security benefits of the airport require the estimation of an extremely rare future event and are therefore highly uncertain. However, given the scale of benefit calculated, the reduction in flights over London is unlikely to counterbalance the detrimental safety impacts of the increased road traffic. The social dimension of the airport is therefore likely to remain negative and within the same order of magnitude.

The security effects of the barrier are equally affected by the need to estimate infrequent events, as the earlier an event occurs the less its effects will be discounted and the higher the value of avoiding it. This uncertainty is further exacerbated by the non-stationarity of the climate affecting our ability to estimate the frequency of such an event, and behavioural and policy factors which will affect its severity. The uncertainty of our valuation is therefore high, but difficult to estimate. The approach of monitoring and using flexible design will therefore be as relevant to this indicator as it was to the physical protection service indicator.

5.7.5 Reuse of calculation inputs

In addition to the uncertainty and biases of the individual data sources and monetisation methods, systemic error can be introduced if the same data is used for different indicators. It is therefore necessary to identify such data sources, and in a similar manner to the highly uncertain estimations (for example the extreme event frequency estimations in the case study), treat these variables as critical, monitoring their progress and considering how deviation from the applied projections will affect the total results. We can note from the above that demand projections are relevant to all four attributes and have considered how this uncertainty affects the results herein. However, it will be necessary to draw out other repeated data sets and

consider their inaccuracy. We will consider this further as part of our systems uncertainty analysis in Chapter 7.

5.7.6 Aggregated attribute results

As discussed in the Sections 5.7.1 to 5.7.4, while there are high levels of uncertainty surrounding many of the individual indicators, the aggregated attribute results appear to be relatively stable, with their component indicators either pointing generally in the same direction, being dominated by one factor, or, where they are balanced and opposed, ratios between costs and benefits are maintained by the relationships between the indicators. We can also see these relationships reflected in the three transport asset total valuations (see Table 5.11). Without inherent demand, both the road and rail infrastructures produce only negative results and are therefore stable. The airport produces a balance of costs and benefits, but the reliance of both the monetary and service attributes on demand profiles maintains this balance despite large uncertainties.

Table 5.11 – CBA attribute results for the five infrastructure elements of the Thames Hub Vision

Attribute	Road (£bn)	Barrier (£bn)	Generation (£bn)	Rail (£bn)	Airport (£bn)
Monetary	-1.95	-1.62	-0.75	-18.03	35.18
Service	-	0.29	0.90	-	-43.65
Environmental	-0.85	-0.94	0.13	-1.92	-2.16
Social	-	0.34	-	-	-3.64
Total	-2.79	-1.94	0.27	-19.95	-14.28

The barrier and generation also produce a mix of costs and benefits. However, here the uncertainties are sufficient to change the results. The barrier produces a negative total; however the magnitudes of the aggregated attribute results are quite similar given the high levels of uncertainty surrounding their calculation. Should current risk estimations be inaccurate and extreme events be more likely than predicted, it does not seem unreasonable that the

additional physical and life protection over that of the TE2100 barrier could total more than £1.9bn; particularly given that the damage is a lower bound estimate with further indirect effects possible on the economy. In contrast, the generation, while producing a positive result, is found to be sufficiently vulnerable to cost and demand estimation uncertainties to reverse this result.

Aggregation also assists in the comprehension of the results. Considering Table 5.11, we can see that despite six of the fifteen indicators falling within the environmental attribute, the results remain substantially smaller than the service and monetary results of the infrastructures where demand has been projected (generation and airport). As individual indicators these results would be likely to be entirely obscured by the other results; however, through aggregation, the results are brought closer to the scale of the other aggregated attributes and are therefore shown to be of a similar level of importance. This is particularly important for the environmental indicators which reflect the local population, who unlike the other stakeholder groups may receive no direct benefit from the infrastructure, but are exposed to the externalities. Furthermore, by aggregating to four attributes rather than a single cost benefit ratio, the factor impacts retain some of their definition and we are forewarned that despite a small potential monetary benefit, the social and environmental effects of the airport, could produce resistance to the scheme.

While clearly useful for comparison of output types, the aggregation into attributes does, however, hide some of the intricacies of the results, particularly the effects on specific stakeholder groups. For example the positive environmental benefit for the generation is dominated by a national benefit of carbon dioxide reduction. This disguises the landscape and habitat impacts which will be felt locally and may create opposition to the scheme. Similarly, the monetary attribute impact, not only includes the benefit to investors, but also the tax and

employment benefits to the Treasury and population. Furthermore, the revenue benefits are split between the monetary and service attributes. The aggregation could therefore create unwarranted confidence/concern regarding acceptance of a scheme, or the likelihood of private investment. However, it may also promote consideration of the wider picture rather than self-interest. As an aim of this research is to create a policy level decision-support tool, it is hoped that by presenting a more regional result that this will assist communication with stakeholders and discussions between interest groups. However, it may be necessary to conduct additional stakeholder specific versions of the analysis to consider equality of impacts.

Comparing between the elements, Table 5.11 also shows a mix of benefits and costs across the attributes. While benefits are small in the current case, this suggests there may be the potential to bundle investments to achieve a balance of benefits between attributes, stakeholder groups or locations. For example a less beneficial development may support the operation of the other infrastructures, if they are designed with this in mind, creating demand (as the airport creates surface access demand) or the potential to reduce operational issues (for example some of the airport check-in could be undertaken at the rail park and ride stations to ease congestion at the airport). Alternatively by combining generation within the barrier design, funding for the barrier may be assisted by private investment, while local approval of the generation may be swayed by the flood benefits. Where investments support each other, they may also improve the risk profile of the investment (see Torrance (2009) for an investor's perspective of the relative risks of various infrastructure assets). This ability to consider portfolios of investments is only possible due to the common appraisal methodology and will be the focus of the next chapter.

5.8 Conclusions

In this chapter we have presented a common cross-sector, multi-attribute appraisal methodology for infrastructure investments and demonstrated it against the Thames Hub Vision. The difficulties in providing such a methodology are an extension of those for any multi-attribute decision analysis; primarily that of encompassing the most important features of the design without the creation of so much data that it no longer informs the decision maker. In particular, the need to capture multiple viewpoints and aggregate values either through translation to a consistent indicator, such as for cost benefit analysis or through weighting, such as for quantified multi-criteria analysis. The need for the methodology to be common across multiple sectors requires further refinement of these indicators, and its application to infrastructure requires the consideration of multiple stakeholders with different perspectives on which factors are important and how they should be valued. Furthermore, it requires quantification of outputs over the long-term and therefore under deep uncertainty.

Having chosen to use a cost benefit approach, we have explored the additional uncertainty created through the need to quantify and monetise both market-based and non-marketable impacts and how their valuation over the long-term can affect the viability of the assessments. Furthermore we have reviewed the need to aggregate indicators, how this can obscure the intricacies of the appraisal (particularly where costs and benefits are felt) and the relationships between indicators⁷¹.

Despite the identified uncertainties, the methodology described in Chapter 3 has successfully appraised the Thames Hub Vision elements. We have confirmed that the fifteen indicators identified in Chapter 3 capture the main impacts and benefits of the case study and are

⁷¹ We delay considering the effect of re-use of data until we have a systems perspective (see Chapter 7).

therefore applicable to multiple sectors and viewpoints. We have identified suitable monetisation methods for each of the fifteen performance indicators and found their results to be remarkably stable in many cases despite the high levels of uncertainty. Furthermore, our review has identified critical variables that will need further consideration (common inputs such as demand) or monitoring (extreme event estimations) to ensure the appraisal is accurate and robust to change and two assets whose value is strongly dependent on estimation uncertainties (generation and barrier).

Our four aggregated attribute lenses reinforce the stabilising effect seen between the indicators and aggregate values such that the results can be more easily considered by the decision maker; yet they provide sufficient segregation that the 'less valuable' local effects (social and environmental) can still be considered against the larger user and investor benefits (service and finance). The results therefore give us an indication of different stakeholder viewpoints without only defining costs and benefits in these terms. It is therefore hoped that the results will promote stakeholder engagement and communication, breaking down some of the barriers created by self-interest. The aggregation does, however, obscure some of the detail of the effects and may create unwarranted confidence or concern over conclusions such as public acceptance of the scheme or the likelihood of private investment. While the methodology cannot, therefore, replace the stakeholder specific appraisal required to understand sector specific effects, equality of impacts or individual perspectives (for example that of a private investor), it provides a useful tool for strategic policy support, which is the emphasis of this research.

Finally, our standardised method has allowed comparison of elements of the case study and therefore would provide a useful tool in prioritising projects between infrastructure sectors. Furthermore, it allows consideration of groups of projects. While the standalone assets present

little opportunity for balancing benefits or reducing the risk profile of the investment, this may be possible if assets were designed with this in mind and treated as portfolio investments. The methodology proposed therefore provides a platform for the more complex systematic appraisal of infrastructure interdependencies to be developed in Chapters 6 and 7.

6 Cross-Sector and Systems Appraisal Through Pathway Analysis

6.1 Introduction

In Chapter 3 we outlined an appraisal framework designed to more completely assess the value of infrastructure developments. In Chapter 5 we presented the first stage of this analysis, successfully demonstrating a common cross-sector appraisal methodology and providing the foundation for the consideration of groups of infrastructure assets. In this chapter we undertake the second stage of the framework, extending the analysis to consider how the infrastructure developments interrelate across sector boundaries and the effects of these interdependencies on the value derived. We undertake the work in two stages, firstly considering portfolios of infrastructure investments, their aggregated impact, the additional effects that may occur due to their interactions and how these results may change over time. We then develop these portfolios into pathways, considering how assets constrain and enable future developments. The work therefore brings robust decision making principles (see Chapter 2) into the appraisal process, capturing the opportunity value of an infrastructure asset and, through this, the flexibility it provides for the future development pathway to meet highly uncertain future needs.

The objective for this chapter is therefore to test the second stage of the theoretical cross-sector appraisal methodology developed in Chapter 3. Using the Thames Hub Vision proposal introduced in Chapter 4 we aim to determine whether the methodology is capable of more fully representing the system effects of infrastructure than the standalone asset appraisals, particularly:

- The total required resources and impacts of a set of infrastructure systems;

- The emergent effects of infrastructure asset interactions and how these are affected by the timing and order of development; and
- The 'opportunity' value of an investment through its ability to restrict or enable further developments.

We start by outlining potential system effects relevant to infrastructure developments, investigating these interactions through our case study by comparing the outcome of the single asset assessments in Chapter 5 with that of a portfolio infrastructure development. We proceed by exploring the temporal nature of the interactions, conducting an initial review on the Thames Hub airport and railway infrastructures. Finally, we draw on these outputs to consider the optionality of infrastructure, particularly its role as an enabler of future infrastructure development. We do this by undertaking the second stage of our appraisal methodology, a pathways analysis adapted from real options 'in' projects (Wang and de Neufville, 2005). By demonstrating this methodology on our Thames Hub Vision case study, we draw conclusions regarding the opportunity value of the various infrastructure elements.

6.2 Cross-sector and system effects on infrastructure appraisal

While infrastructure assets are normally appraised as standalone assets, they do not operate as such. Each asset adds to its own network providing additional services, but it also puts pressure on the other sectors and uses resources that may restrict other developments. Our appraisal methodology is designed to allow these interactions to be captured; however, thus far we have constrained our portfolios to include only a single asset. Taking advantage of our common indicators and methodology (see Chapter 5) we could compare and combine results of different individual asset appraisals and theoretically find the best economic developments in and across sectors. However, there is no guarantee that these could all be realised, and if they could,

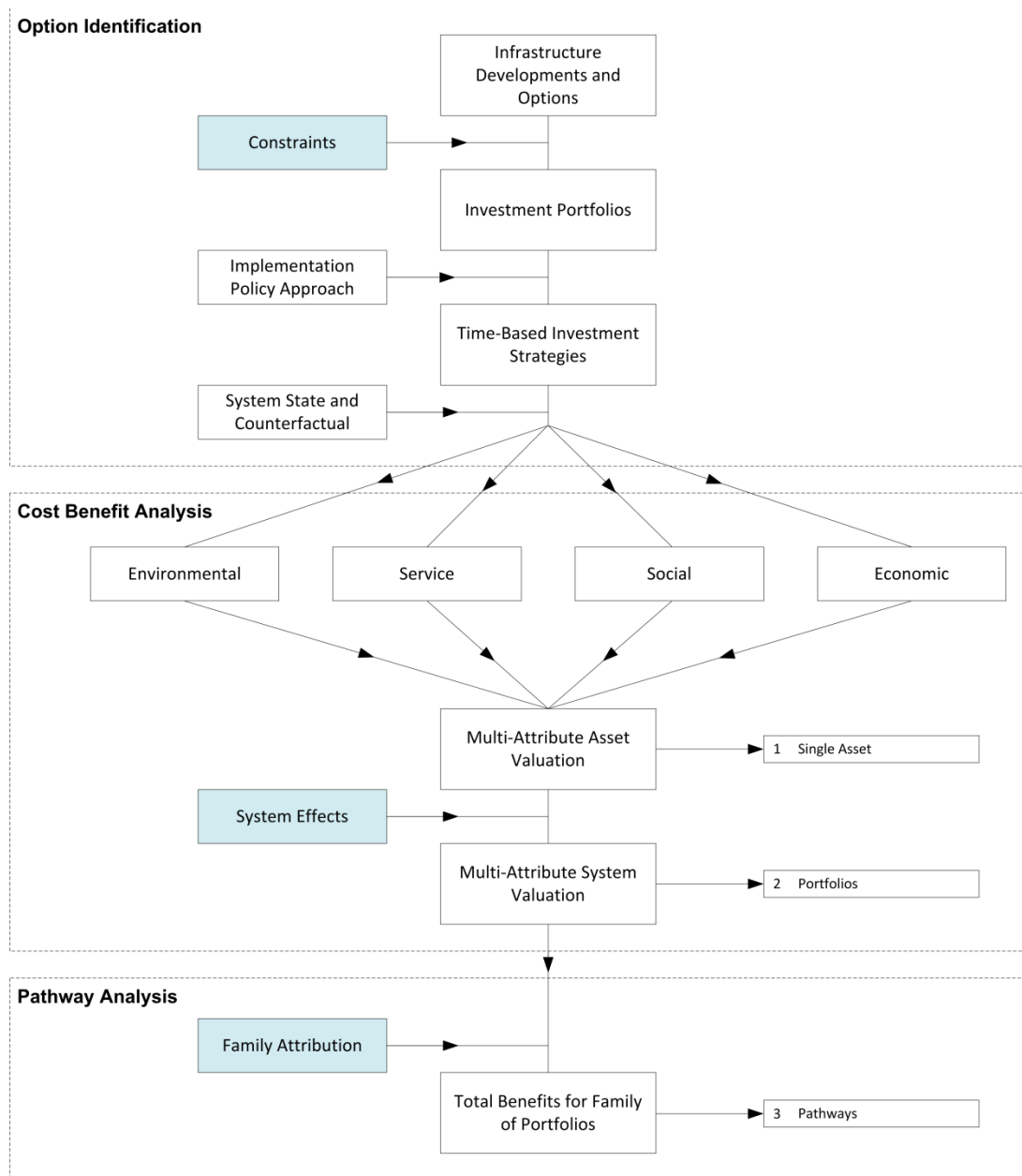
whether they would function as an efficient set of infrastructure systems. The infrastructures could, for example, require the same resources, demand services from the other sectors that exceed available capacity, or collectively produce emissions in excess of legislative restrictions. If we wish to include more assets within each of our portfolios, we must therefore consider infrastructure developments not only as individual investments but also the interdependencies between them and how they enable or constrain the performance and development of the system as a whole. In terms of our formalised methodology, we need to further define our array of system constraints (C), add any system effects to our system valuation ($V(s'')$) and collate the results into development pathway families to understand the opportunity for future development (see Figure 6.1).

6.2.1 Limitations of aggregating individual asset appraisal results

As noted above, straightforward aggregation of the single asset appraisal results ignores the interdependencies between them, providing an over-simplified assessment of the system value. We can compare this simplification to the aggregation of individual indicators into attributes in Chapter 5, for which we noted three concerns. These can be directly translated to the aggregation of asset appraisal results:

- The assets are inherently coupled, therefore the valuations may not be entirely separable, but may assume the presence or absence of other infrastructure assets;
- Assets may only be possible when developed together, or may be mutually exclusive; therefore the choice may be between a sum of effects or none of the effects; and
- The valuations may not be a simple summation of those for each asset, but rather there may be system effects in addition to those ascertained by the individual appraisals.

Figure 6.1 – Outline of appraisal methodology (system and cross-sector inputs highlighted) (adapted from Young and Hall (2015))



The first of these issues is difficult to determine, particularly for non-marketable effects:

‘omitted variable bias’ is a known issue for revealed preference methods and despite careful framing of stated preference methods, the respondent can make assumptions about the presence or absence of other factors when making their valuation. We have, however, investigated the uncertainty of the valuations with respect to other methods and to each other in Chapter 5 and found them to be relatively robust to change. Therefore, we will assume that

the metric valuations are separable for each asset, but that the analysis must be extended to capture the latter two issues (aggregated/exclusive assets and emergent effects); our 'system effects' in Figure 6.1. We start by examining which constraints can cause assets to be mutually exclusive and the types of system effects that we should look for when considering our portfolios of assets. Within the next section we consider the former: the resources key to appraisal, how they differ and how the information provided by the existing analysis can help us identify which assets can co-exist.

6.2.2 Cross-sector effects: Use and presumed availability of resources

We have seen in previous chapters that there is a large amount of commonality in the demands of the various infrastructure sectors; in particular their high reliance on ICT and energy, which in turn are reliant on each other. Should insufficient capacity be available to support this demand, decisions would need to be made about how and where to restrict availability, which, in the case of infrastructure, would in turn have knock-on effects on the other sectors. The first system effect we therefore need to consider is that of constrained resources¹. While the division is not clear cut, resources can be split into two groups, those where only limited quantities are available (hereafter referred to as 'finite resources') and those where the availability can be increased (referred to as 'variable resources').

Raw minerals are one of the few examples of truly finite resources and while substitutions, further reserves, or methods to create minerals artificially may be found in the future, these are not currently available. Other resources may come under this first category through Government legislation, for example carbon dioxide emissions, or through the cost required to

¹ The need to more fully understand what resources (financial, institutional, personnel, legal etc) are required by an infrastructure development was a key finding in the OMEGA project review of mega transport project appraisal (Dimitriou et al., 2013).

alleviate the constraint, for example increasing land availability through reclamation.

Consideration of finite resources in appraisal requires a common methodology, such that projects can be prioritised across sectors, a process that prior to this research was made almost impossible due to the mix of appraisal methods, timeframes and assumptions used in the different sectors (Beuthe, 2002). Furthermore, while Cost Benefit Analysis (CBA) is the methodology preferred by the UK sectors, it relies on market prices. These will only reflect the rarity of a resource as its availability is constrained, therefore prices will be dependent on the decisions made (Squire, 1975). Optimal use of finite resources requires a strategic approach to their use which may not therefore reflect their current market price, but rather the long-term demand from the system as a whole.

Variable resources are those where we can alter the available volume of the resource, such as skills, finance and outputs of production such as electricity². The extended timeframe of infrastructure developments creates the opportunity to plan for and maximise benefit from a known future requirement for such resources, yet appraisal methodologies do not normally consider potential future developments³. Without consideration of interdependencies, many of these resourcing opportunities will be missed and may instead become risks, invalidating the business case for the developments or making their actualisation impossible. For example, while the level of reliability of each of the infrastructures is not normally guaranteed⁴, historically high levels of service (Infrastructure UK, 2011) and a 'predict and provide' approach to procurement has created an environment where provision of unrestricted levels of service is assumed.

² Similar to our first group of interdependencies, the definition is not straightforward. There is likely to be a threshold volume after which the resource becomes finite. For those factors included within this group, it is not thought likely that this will be reached within the 100 year timeframe considered here.

³ For example, while the potential for an additional runway at Heathrow has been debated for decades and current demand projections suggest that the airport will reach capacity in the next decade (Tran et al., 2014), the Crossrail development has not been designed with the capacity to support an expanded Heathrow (Transport for London, 2014).

⁴ The Thames Barrier is perhaps the exception, being built to ensure protection from a 1/1000 year storm surge event (Reeder and Ranger, 2011).

Economic, social and environmental constraints are unlikely to allow this level of service to continue. Therefore, with the high level of reliance between the infrastructure sectors⁵, it is essential that future appraisal methods can capture requirements on, and from, other infrastructure sectors, to prevent an assumption of unachievable levels of service provision undermining the resilience of the dependant sectors⁶.

6.2.3 System impacts: Efficiencies, connectivity and aggregation

Our second issue with straightforward aggregation of values is due to the system effects created by infrastructures when operated together. The ‘emergence’ of these impacts may simply be due to the incomplete consideration of the constituent flows; a process output that is not useful may not be considered as part of the appraisal, particularly if there is no disposal cost, and the cost of creating a valuable product is prohibitively high, as in the case of waste heat from energy generation. However, by planning infrastructure as portfolios, additional value (or ‘efficiencies’) can be created through industrial symbiosis. For example, the integration of a Combined Heat and Power (CHP) plant and a Liquefied Natural Gas (LNG) plant on the Isle of Grain (see current case studies in Chapter 4), achieved an efficiency of 72 per cent (E.ON, 2010) as compared to the 67 per cent national average (Department of Energy and Climate Change, 2011), while maintaining the ability for each to function independently. The CHP plant produces more revenue from each unit of input and the LNG plant has a cheaper source of heat than buying energy from the grid, therefore both generate benefit from the integration. Considering investments as a portfolio can therefore change the attractiveness of an investment (Raven and Verbong, 2009), and can introduce new investors from previously disparate sectors. For

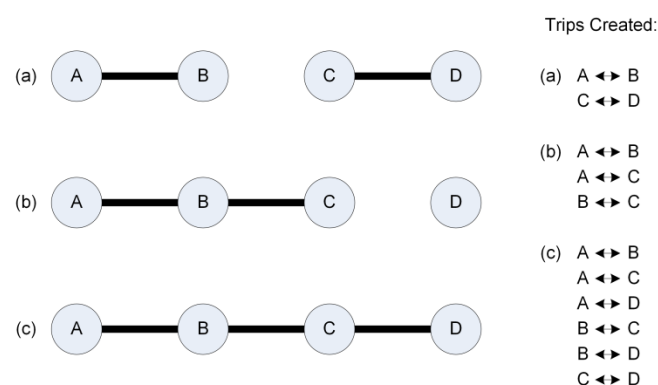
⁵ For example, two of the largest consumers of electricity are transportation and water treatment.

⁶ It has been noted that many of the problems in the transport sector emanate from decisions made in other sectors (Banister, 2008) and that future energy generation strategies may require increasing tidal and coastal water abstraction by up to almost 400 per cent (Byers et al., 2014).

example, in the UK, energy generation from biogas was spearheaded by the waste sector rather than the energy sector. Indeed the combination of sewage treatment with biogas energy generation at Wessex Water's Bristol Plant, allows it to produce sufficient energy to meet its total energy demands (Wessex Water, 2011).

Some infrastructure benefits emerge by the assets working together as a system, creating opportunities that exceed the linear outputs expected from incremental investments (referred to herein as 'connectivity'), or do not manifest until a given level of infrastructure is created (referred to herein as 'aggregation'). A simple example of the emergence of connectivity benefits is the road network. Building roads connecting A to B and C to D in Figure 6.2 (development (a)) may require the same length of road to be laid as connecting A to B and B to C (development (b)), yet development (b) creates a greater number of potential trips. Furthermore, while development (c) may only require 50 per cent more road to be laid than either development (a) or development (b), it creates three times the number of trips as development (a) and twice the number of trips as development (b).

Figure 6.2 – Example of connectivity benefits



'Aggregation benefits' are analogous to the single sector case of a high capital cost of infrastructure, but can also occur across sectors. For example, the procurement of one

capability may not be possible without another in a different sector⁷. Alternatively, aggregation benefits can be far less tangible. For example, the linkage between infrastructure development and the economy is not straightforward for mature economies, but macro-scale impacts, such as economic growth can manifest where projects and policies are complementary (Beuthe, 2002; Banister and Berechman, 2003). Therefore, given the appropriate level of consistent, complementary infrastructure investment, economic growth should be seen; however, until this level is reached, no wider economic benefits are created by the investments.

6.2.4 Development of a systems appraisal methodology

We can conclude from the above sections that both finite and variable resources can undermine the future viability of an asset and limit future development (Roelich et al., 2014). We therefore need to include both within our systems appraisal methodology. There are also a number of system effects that can provide benefits over and above those captured through the amalgamation of single asset assessments, which will only be captured if we consider the system as a whole.

Considering the appraisal methodology outlined in Chapter 5, we have already included many of the factors necessary to capture these resource constraints and system benefits:

- A number of resources that may be considered ‘finite’ due to current regulation are calculated directly, including noise, air quality, water quality and carbon dioxide emissions;

⁷ See for example the Channel Tunnel Rail Link (CTRL) Interconnector project in Chapter 4, which would not have been possible without CTRL.

- Impacts are recorded under aggregated attribute headings, such that ‘finite’ environmental or social resources can be considered separately to the more variable monetary and service resources;
- Utilisation is recorded directly and includes the knock-on requirements on other sectors; and
- Impacts are calculated and recorded in a consistent manner. As such, assets can be combined into portfolios to consider the total sum of impacts against regulatory thresholds⁸ and where thresholds are exceeded, the consistent methodology allows comparison and prioritisation.

We therefore have the potential to investigate the effects of constrained resources by the creation of portfolios of infrastructure investments. Indeed, we have already recognised the potential for this approach in Chapter 5 under the guise of sharing benefits between stakeholders and lowering the risk of investments. We have also noted that there may be the potential to mitigate effects, such as the carbon dioxide, by joining together net producers (such as transport investments) with reduction measures (such as tidal energy generation).

Our analysis of the case study thus far has not necessitated a temporal description of the development of the system and an understanding of the alternatives available, making it difficult to explore the emergent system impacts. Even for the aggregation impacts, which we have seen in the case study through the barrier, it is difficult to understand the magnitude of their benefits without a number of alternative developments with less aggregation. We therefore need to extend the analysis to capture possible alternative developments, the portfolios that can be created from these developments and their temporal profiles. We can then compare these

⁸ Indeed thresholds were proposed as one of the main decision criteria in the methodology formalisation in Chapter 3.

temporal portfolios (referred to herein as ‘pathways’) to determine the value provided by the infrastructures which enable them.

The focus of the remainder of this chapter will therefore be on the demonstration of this methodology; developing the single asset appraisal in Chapter 5 into the temporal pathway analysis outlined in Chapter 3 and ensuring it is suitable for quantifying the system benefits of groups of infrastructures and understanding the opportunity value they provide. We will first consider the interactions of portfolios of infrastructure and how their shared resources may restrict which portfolios are viable. We then investigate the order of implementation, its impacts on the system effects and further ramifications for the potential implementation pathways. Finally we review the alternative developments necessary to fully investigate potential system effects, their constraints and prerequisites, before applying the theoretical pathway appraisal outlined in Chapter 3 to the case study.

6.3 A static portfolio analysis of infrastructure

As discussed, in Section 6.2, one of the fundamental benefits of the common appraisal methodology described in Chapter 5 is that we can start to combine infrastructure assets into portfolios. Through this, we can consider the effects of the system as a whole and how these may differ from a straightforward summation of the constituent elements. In this section we therefore investigate the difference between the single asset assessments in Chapter 5 and a portfolio appraisal⁹, through application to our case study. Specifically, we consider the Thames Hub Vision airport and how its effects are dependent on prior infrastructure decisions.

⁹ One portfolio is investigated in this static state before we move onto considering dynamic portfolios (pathways) in Section 6.4.

Returning to the results of the airport's single asset appraisal from Chapter 5, we are reminded that there are beneficial effects for investors (monetary) and the Treasury (monetary), but negative effects for users (social and service) and the local population (environmental). The largest negative result of the single asset appraisal was for the service attribute, which, as we've noted, was largely due to increased distance and congestion for road users. Therefore, by considering the airport as part of a portfolio of infrastructure developments including non-road surface access developments, we have the opportunity to affect the appraisal results. We can illustrate this, by considering a portfolio of the airport and rail infrastructure elements of the case study.

The presence of the rail infrastructure has the potential to divert traffic from the roads. Indeed, the intention within the Thames Hub Vision is to use active traffic management to ensure a 60 per cent modal share of passenger access by rail (Foster+Partners et al., 2011a). By limiting road use we reduce its negative externalities (air pollution, carbon dioxide emissions, congestion and traffic accidents) and provide additional demand for the rail infrastructure, increasing the service and revenue benefits, but we also reduce petrol usage, limiting taxes paid to the Treasury.

In Table 6.1 we have quantified these effects using our common multi-attribute cost benefit analysis. Assumed journey changes were based on the case study characterisation in Chapter 3 and are fully detailed in Appendix B. The first row of data repeats the 'individual asset' assessment from Chapter 5, assuming no interaction with other potential developments (equivalent to developing the airport with only existing access routes). The second row of data accepts that infrastructures may be procured in parallel and therefore presents a future where the decision to proceed with the rail upgrade has also been taken. The costs and inherent impacts for rail have been excluded; however, the system effects of the two infrastructures being implemented together (such as the derived rail demand from the presence of the airport)

are included. The difference between the first and second rows denotes these system effects.

The remainder of this section considers these effects and how they manifest in the systems case.

Table 6.1 – CBA for the airport as a single asset and as part of a portfolio of infrastructure investments (Young and Hall (2015))

	Environmental (2010 prices, £bn)	Monetary (2010 prices, £bn)	Service (2010 prices, £bn)	Social (2010 prices, £bn)	Total (2010 prices, £bn)
Airport (individual asset)	-2.16	35.18	-43.65	-3.64	-14.28
Airport (portfolio)	-0.32	37.49	-4.48	-0.85	31.85
Difference (system effects)	1.84	2.32	39.18	2.80	46.13

6.3.1 Cross-sector effects

As noted in Section 6.3, the individual asset appraisal results in a large negative service result of -£43.7bn. Despite £4.0bn in service benefits from the additional 20 million passengers per annum airport capacity, the remote location of the airport and the high modal use of road transport to access it¹⁰, increases travel distances by 76 per cent and creates a large negative service impact on road users (-£47.3bn). Furthermore, additional pressure is put on the already constrained central London rail services (-£0.3bn). As expected, the reduction in road traffic in the portfolio case reduces emissions (1.84bn in environmental benefits)¹¹, improves safety (£2.8bn in social benefits), and reduces petrol costs and road congestion (£39.2bn in service benefits). While the net results of these three attributes remain negative, each is an order of magnitude smaller than in the individual asset appraisal; a change sufficient to reverse the outcome of the analysis from a net negative of -£14.3bn to a net positive result of £31.9bn.

¹⁰ Assumed to be 77 per cent of non-interlining passengers, the same as Heathrow (Civil Aviation Authority, 2003).

¹¹ Nitrogen oxides, particulate matter and carbon dioxide.

It is important, however, to consider how and by whom these benefits will be felt. For example, the negative environmental effects of the airport are almost balanced by the positive environmental effects of the portfolio case. The environmental results have substantially changed for the better; however, the perspectives of the different stakeholder groups are more complex. Ninety eight per cent of the portfolio benefit is derived from a reduction in carbon dioxide emissions. The welfare benefit produced is therefore spread over the whole population. This change may help to sway public opinion of the scheme generally and reduces the effects of increased airport capacity on the UK's climate change targets. These latter two factors are not valued by the analysis, but are of interest to the UK Government and to investors respectively, suggesting their benefits are also increased by the portfolio case. However, while the aggregated environmental effects are much improved, as the negative effects experienced by residents living close to the new airport site have not changed, their opinion of the scheme is unlikely to be affected.

The shift from road to rail also provides enhanced utilisation of the new rail infrastructure, increasing revenues from fares, resulting in a net monetary benefit of £2.3bn. Therefore, while the portfolio approach clearly changes the value proposition of the airport; it has also affected the viability of the rail element. According to standard UK appraisal practice, such system effects would only be applied to the latterly implemented asset (in this case the airport) and may not be captured at all unless the first development was sufficiently complete to be included within the 'do minimum' case. Therefore, to be approved for development, both assets must be viable as standalone investments, with system effects ignored. By recognising that the first asset creates the *opportunity* for system benefits, and appraising the portfolio case, we can try to optimise the system benefits and consider whether they are sufficient to change the assessment of either, or both, of the two assets. In the portfolio case above, the total result of the individual rail

infrastructure assessment (see Chapter 5) was -£19.7bn¹². Introducing an airport with 60 per cent modal split by rail induces a demand of over 50 million passengers per year by 2110, generating £11.2bn in service and monetary benefits, counterbalancing over 55 per cent of this negative impact. The system effects therefore substantial change the risk profile and the investment value of the rail infrastructure. Furthermore, it highlights the interdependencies of the two investments, which may encourage cross-asset investment, or bundling of projects, either by the investor to achieve better risk profiles or revenues, or by the Government to achieve a greater balance between local and national, or between public and private benefits.

Finally, it is worth considering the magnitude of each of the aggregated impacts. As noted in Chapter 5, the environmental and social attribute impacts can be seen to be at least an order of magnitude smaller than either the service or the monetary aspects and are completely obscured in the total benefits column. From a resource efficiency perspective this result is important, because our finite resources¹³ will be contained within the two 'hidden' impact attributes. The necessity of maintaining some segregation between impacts is therefore particularly important if we are to assess the full effects of the planned developments in the context of the environmental or legislative limitations. Furthermore the reliance on CBA creates additional uncertainties. Firstly, the use of 'willingness to pay' estimations ignore duty of care considerations on the part of the UK Government¹⁴, obscuring part of their value. Secondly, the marginal change assumptions of CBA do not capture the changing value of restricted resources as they become rarer or more heavily legislated. The valuations for the social and environmental factors are therefore likely to be more uncertain than the monetary and service attributes and become more so over the appraisal period. By maintaining segregation between

¹² Assuming no latent demand.

¹³ May be truly finite such as habitats or limited by regulatory thresholds such as air quality.

¹⁴ For example personal safety from harm, be that from the developments directly, or from a polluted natural environment.

our finite (environmental and social) and more variable resources (monetary and service) we therefore allow for greater inaccuracy within the former, identifying the trade-offs and allowing stakeholders to draw their own conclusions about the value created/removed over time.

6.3.2 System effects

While the system effects are more difficult to quantify in this simplified analysis, the cross-sector benefits of the portfolio approach introduce a number of opportunities for improvement compared to the current siloed approach. For example, our greater understanding of interdependencies may encourage further stakeholder engagement and/or inter-infrastructure investment, creating the potential for greater dialogue between the project teams and integrated operations. Such interactions create an environment where industrial symbiosis or other system efficiencies can start to be discussed and designed into the projects. This could allow services to be distributed between assets, such as providing a bag drop facility, or airline ticket check-in at the stations, or could be used to encourage take up of other assets, for example providing reduced rail tickets as part of flight booking in a similar manner to that used for the London Olympics (see Chapter 4). Furthermore, we can see whether infrastructure developments are complementary and therefore provide an opportunity for realisation of wider economic impacts such as economic growth or agglomeration (Banister and Berechman, 2003).

Considering the full Thames Hub Vision case study, aggregation effects can be seen through the combination of the road and rail crossing with the new flood barrier. Similar projects are already being considered separately for the road (Lower Thames Crossing) and flood (TE2100 Long Reach Barrier) infrastructures. Such integration of infrastructure developments can induce vulnerabilities that must be considered carefully; however, they may also produce benefits. Combining the projects may induce construction efficiencies, lowering the total cost, and

combining the experience and budgets of two government agencies (Highways England and the Environment Agency in this case) may provide operational efficiencies or earlier investment, for example allowing the barrier to be introduced before planned, reducing the need for additional flood maintenance between the new and existing barriers and increasing London's resilience to extreme weather. Simply including provision for further development can also be valuable if considered appropriately. For example, inclusion of the potential for a rail crossing as part of the Tagus River road bridge in Portugal, meant that 30 years later, a cable system, railway deck and additional lane for road traffic could be added to the bridge without interrupting traffic flow (Gesner and Jardim, 1998)¹⁵.

Taking the portfolio approach, aggregation effects can also be considered in light of investments made in other sectors. For example, the cost of land reclamation and creation of compensatory habitat¹⁶ would be impossible to absorb for a small project; however, with that necessitated by (and included within) the Thames Hub Vision airport proposal, smaller, less urgent or non-essential infrastructure developments may become possible¹⁷. In addition, the construction of habitat could be viewed as an opportunity to provide a new area of protected habitat in a location that is less industrially focused and with a greater resilience to the expected sea level rise, erosion and coastal squeeze that will eventually occur in the Thames Estuary (English Nature, 2006). Such an opportunity would not be feasible under the prioritisations and budgets of the Environment Agency alone.

To understand connectivity effects we must consider the characteristics of the infrastructure assets and how these might be varied. For example, what benefit would be produced by only

¹⁵ See Chapter 4.

¹⁶ As required by the EU Habitats Directive (see European Commission (2007)).

¹⁷ Perhaps linking into access requirements for the Thames Tideway drainage project, or providing options for the nearby DP World port facilities, see Chapter 4.

providing a high speed rail connection, or only providing a commuter rail orbital, compared to that of the full rail proposal? Such considerations are beyond a simple portfolio analysis. If we wish to consider the quantitative effects of alternative developments, the potential provided by investments for future development, or possible industrial symbiosis, we need to more fully understand the system interactions and how these develop over the time period. In short, we need to consider the development pathway of the system.

6.4 Towards a pathway analysis of infrastructure as a system of systems

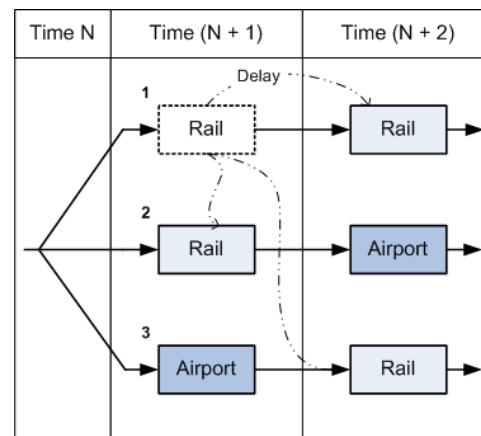
Through our portfolio analysis in Section 6.3, we have a more complete valuation of the total required resources of our case study and have started to qualitatively assess the remaining system impacts. With this information we can start to implement the theoretical pathways analysis outlined in Chapter 3, allowing us to quantify the remaining systems effects (aggregation and connectivity) and therefore capture the full opportunity value created by each element of the portfolio.

However, before undertaking the pathways analysis, we first require a greater temporal understanding of the system. Our aim is to extend the methodology to consider the temporal development of the infrastructure portfolio, therefore we must first understand whether and how time can affect the cross-sectoral and systems effects we have already identified. In our portfolio analysis we assumed that the airport was implemented after the rail infrastructure was in place; however, this may not need to be the case. If the order were to be reversed, would the system effects identified in by the portfolio analysis change, or would they remain constant? Before undertaking our pathways analysis, we investigate the importance of order for system effects, using two of the Thames Hub Vision elements (the airport and the rail orbital) as a case study.

6.4.1 A temporal study on the rail and airport infrastructure

We have already noted the inter-relationship between the value propositions of the rail and airport infrastructures in Section 6.3; therefore, in this section we take the case of the rail element and qualitatively compare the results of delaying its development, of introducing a second element (the airport) and of switching the implementation order such that the airport is delivered before the rail element (see Figure 6.3).

Figure 6.3 – Qualitative temporal analysis of rail and airport infrastructures (adapted from Young and Hall (2014))



The effect of delaying an investment on the value proposition (assuming a benefit cost ratio is used) is relatively minor, as net present value (NPV) discounting will be applied to both costs and revenues. From a capital expenditure perspective, the costs are reduced and therefore the investment may be considered less risky. More importantly, however, the delay reduces the uncertainty regarding the environment the investment will be operating under. The benefit of greater information or understanding is termed the 'value of information' within the decision analysis literature and is explored through real options analysis as the 'option to delay', see Chapter 2. In many cases such delaying tactics are found to be very valuable, particularly in the case of phased implementation which can reduce down-side risk whilst still allowing for future growth (de Neufville et al., 2006; de Weck et al., 2004).

If, however, we introduce a second infrastructure asset, in this case the airport, we can start to understand the impacts of delay on the system benefits of the two assets. A delay to the development of the rail infrastructure will still provide valuable information regarding possible population levels and, through this, potential demand for rail; however, this delay now impacts on the development of the other asset. Taking Case 2 of Figure 6.3, we assume the rail infrastructure is a prerequisite for delivery of the airport. Therefore any delay in the rail infrastructure will produce a knock-on impact for the airport, delaying delivery of their individual impacts, but also any system impacts such as agglomeration or economic growth. Should the assets involve private investment, it is likely that, should such a relationship exist between the rail and airport infrastructures, appropriate mitigations would be sought, either encouraging airport investors to cross-invest in the rail infrastructure to ensure timely delivery, or otherwise, requiring the creation of legal agreements to ensure that knock-on delays resulted in fines for the rail development company. In the latter case this may decrease the attractiveness of the rail investment, thereby counteracting the reduced risk created by the delay.

In Case 3 we assume that the rail infrastructure is not a prerequisite for the airport and the delay causes the airport to be delivered first. Again we retrieve valuable information regarding population growth that could impact on rail demand, but we can also gather information regarding the potential demand from passengers travelling to and from the airport. Similar to our first case, the rail investment risk is reduced due to the additional information, although the delivery of system benefits is also delayed. The presence of a new airport, however, requires behaviour change on the part of the population and the delay in the rail investment may necessitate additional surface access investments to be made to satisfy demand, increasing system costs. The passenger behaviour patterns formed in the absence of the rail investment (for example, driving to the airport) may also be difficult to change once it is implemented¹⁸;

¹⁸ Car use in particular has been noted to be habitual, see for example Gärling and Axhausen (2003).

therefore, the delay could reduce future rail demand. Finally, if the airport is to be delivered in phases, delays in the rail investment could affect further expansion of the airport, either due to road congestion or emission targets. Such delays would affect the projected revenues of the airport, again encouraging mitigation actions on the part of the airport investors and making the rail investment less attractive.

While the above is only a very simplified analysis of the temporal behaviour of interdependent infrastructure assets, it highlights a number of issues for our methodology:

- The time of delivery compared to other elements of the portfolio significantly effects the impacts of the asset and therefore the methodology must allow exploration of ordering;
- We must clearly state which assets are prerequisites of others and maintain delivery ordering where this is the case; and
- Where assets can be implemented in either order, we must consider the knock-on effects on the impacts of the two infrastructures and whether this impact is short-lived or for the lifetime of the asset.

We therefore need to understand when, and in what order, the elements are implemented and the constraints implied by these developments, in other words, the development pathway of the system as a whole.

6.4.2 Creation of alternative infrastructure developments and pathways

Having confirmed the importance of order on the system analysis, we must determine the constraints and prerequisites on the elements of the full case study. We start by considering possible alternatives to the original Thames Hub Vision elements. While there are a number of

methods for identifying project options for real option analysis¹⁹, as we wish to explore the potential aggregation and connectivity effects, we review the decisions of the designers in firstly integrating infrastructures and secondly deciding on the final size of the assets²⁰. We therefore:

- Split the road development into the minor developments necessary to allow the creation of assets in the local area and the full developments necessary to support surface access to the airport;
- Produce five mutually exclusive development alternatives for the flood barrier, including barrier generation to a similar level to the original tidal array proposed, a road crossing, a rail crossing, or a fully integrated barrier in line with the Thames Hub Vision;
- Create five rail development alternatives, consisting of only commuter or only high speed lines, each of these single line assets, but with the option to upgrade at a later date and the original full rail proposal with both commuter and high speed lines; and
- Consider development of the airport in two phases, first creating a two runway airport, then upgrading to the full four at a later date.

Our vector of infrastructure developments (A) is therefore extended from the five elements in Chapter 5 to the 16 elements shown in Equation 6.1:

Equation 6.1 – Infrastructure development vector (A) for pathways analysis:

$$A = \{a_0, a_1, a_2, a_3, \dots a_{15}\}$$

where: a_0 = minor road development;
 a_1 = major road investment;
 a_2 = flood barrier with no generation;
 a_3 = flood barrier with generation only;

¹⁹ Rogers and Duffy (2012) suggest three methods: using the experience of the decision maker and relevant experts; comparing the proposed solution to other successfully delivered projects; and examining relevant literature.

²⁰ The options outlined in this chapter have been created by the author and are not part of the Thames Hub Vision proposal. They have, however, been chosen to reflect those that would typically be considered by the designers in creating the integrated assets and in deciding on the size of the assets.

a_4 = flood barrier with generation and road crossing;
 a_5 = flood barrier with generation and rail crossing;
 a_6 = fully integrated barrier (flood protection, generation, road and rail crossings);
 a_7 = commuter rail only;
 a_8 = commuter rail with option to expand to include high speed line;
 a_9 = upgrade of commuter rail to include high speed line;
 a_{10} = high speed rail only;
 a_{11} = high speed rail with option to expand to include commuter line;
 a_{12} = upgrade of high speed rail to include commuter line;
 a_{13} = full rail orbital (commuter and high speed lines)
 a_{14} = hub airport (2 runways)
 a_{15} = upgrade of hub airport to 4 runways

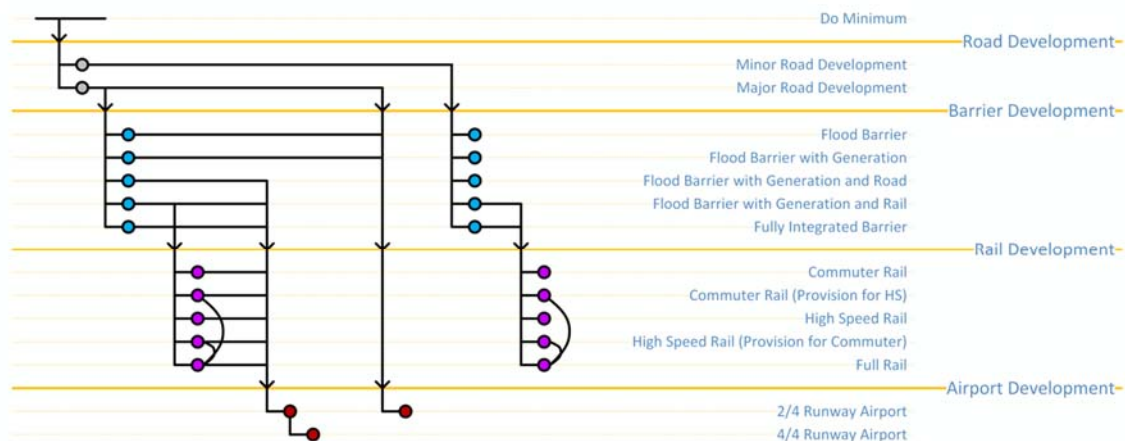
Without constraints, this results in tens of thousands of potential portfolios (P) and potential strategies (S). However, each of the assets is constrained by its earliest possible implementation date (derived from its minimum construction time). Furthermore, the order in which the assets can be implemented is constrained by the spatial and operational requirements of each asset implemented (see Chapter 3). Some of these are self-evident from the developments chosen: a barrier with the potential for a rail crossing is assumed necessary if a rail orbital is to be built; and the five barrier alternatives are assumed to be mutually exclusive, as are the rail developments which do not make provision for later expansion. In addition, we also assume that minor road upgrades are necessary for the construction of the larger assets and that major road upgrades with either a road or rail river crossing are necessary to support the airport's surface access demands.

Our array of system constraints (C) therefore include 16 earliest implementation date constraints, two general system constraints (developments, once taken, are final and cannot be reversed or delayed; and once selected, a development cannot be selected again) and 27 ordering constraints (see Appendix A for full list of constraints):

$$C = \{C_0, C_1, C_2, C_3, \dots C_{45}\}$$

Applying C to the vectors of potential portfolios (P) and strategies (S), we create a vector of 77 possible portfolios and 644 possible implementations of these portfolios (our possible strategies (S')). These strategies are depicted by the pathway diagram in Figure 6.4. It should be noted that the diagram depicts the various pathways to create a final system and not necessarily the order of implementation. Equally it is not necessary within the methodology for the pathways to be followed to an end point and therefore the model (and the following analysis of the pathway 'families') includes pathways with stopping points after each branch division.

Figure 6.4 – Pathway analysis of Thames Hub Vision proposal and additional development alternatives (Young and Hall (2015))

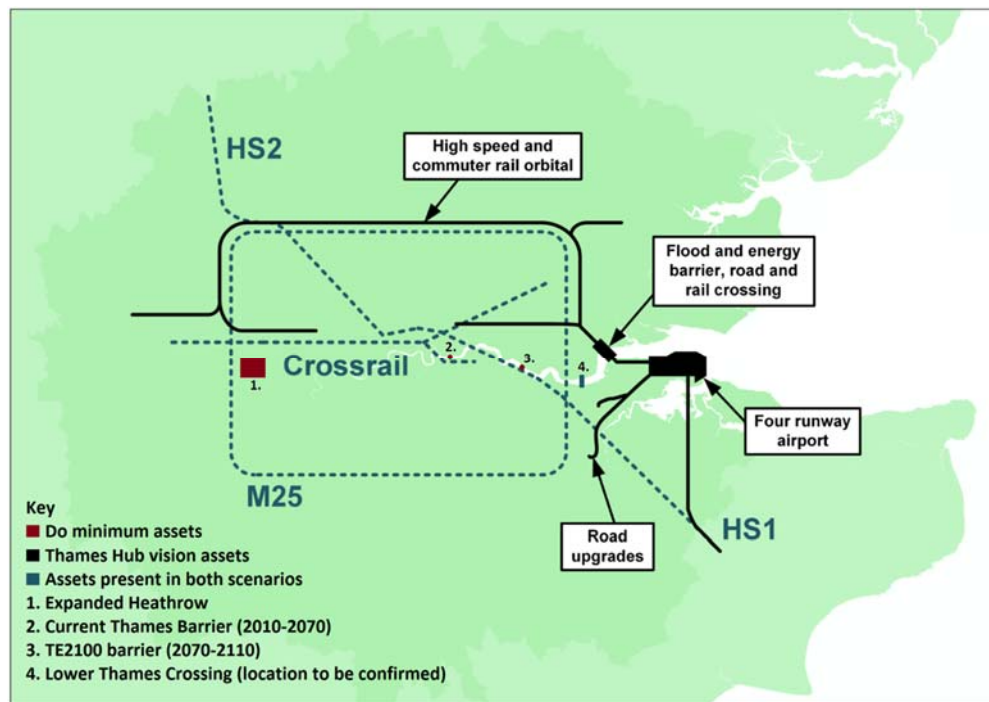


6.4.3 Pathway approach

Having developed a full list of possible strategies, we can now apply the theoretical pathways appraisal developed in Chapter 3 (see Figure 6.1). As evident from the pathway analysis above, we apply a slightly different case study from Chapter 5, considering the energy generation through the barrier rather than a separate tidal array (see Figure 6.5)²¹. This allows us to further explore the potential aggregation benefits of the barrier.

²¹ Both barrier and tidal array generation are considered within the Thames Hub vision (Foster+Partners et al., 2011a).

Figure 6.5 – ‘Do minimum’ and Thames Hub Vision infrastructure elements (pathway analysis) (adapted from Young and Hall (2015))



We apply the delivery point array derived in Chapter 5:

$$D = \{d_{2010}, d_{2015}, d_{2020}, \dots, d_{2110}\}$$

and an implementation policy allowing implementation of asset development groups at the earliest delivery point that maintains the order specified by the strategy and meets all asset ‘earliest implementation date’ conditions (see Chapter 3, Figure 3.8 for further explanation).

Results are compiled into ‘pathway families’, denoted by the infrastructure asset(s) they have in common and including all asset development pathways made possible by that/those common asset(s). Results depict the range of results possible within a single pathway family (see Equation 6.2). This allows comparison between alternative family paths, in particular, how the range of possible impacts changes as additional decisions are made and hence the opportunity and flexibility provided by each element.

Equation 6.2 – Range of attribute values created by the pathway family of development a_θ

$$(\min(v_{\text{attribute}}(s''_{w_\varepsilon}|a_\theta \in s''_{w_\varepsilon})), \max(v_{\text{attribute}}(s''_{w_\varepsilon}|a_\theta \in s''_{w_\varepsilon})))$$

6.5 A pathways analysis of the Thames Hub Vision case study

6.5.1 Comparing single asset and pathway family impacts

Having created a pathway analysis we can collate information for whole families of pathways. In doing so, we look at the future opportunities enabled by each stage in the pathway, rather than simply what that element provides in itself. For example, when considered as standalone investments, the two alternatives for road development are relatively similar. As no latent demand has been estimated, the social and service effects are zero in both cases and the environmental effects are simply those attributable to land take. The difference between the single asset assessment totals is therefore the sum of the difference in cost and land take effects (-£1.06 bn). However, as the first step in all Thames Hub Vision pathways, the road developments have the potential to enable or inhibit further development. Their pathway impacts therefore show a much wider range in results (see Table 6.2).

Table 6.2 – Single investment and pathway impacts for the two road infrastructure development alternatives (asset groups implemented as soon as possible while sustaining group and order restrictions)

	Environmental Impact			Social Impact		
	Single Asset (£bn)	Pathway Minimum ²² (£bn)	Pathway Maximum (£bn)	Single Asset (£bn)	Pathway Minimum (£bn)	Pathway Maximum (£bn)
Minor Road	-0.39	-2.41	-0.39	0.00	0.00	0.33
Major Road	-0.78	-4.58	-0.79	0.00	-3.33	0.33
Difference	-0.39	-2.17	-0.39	0.00	-3.33	0.00

²² Pathway 'minimum' reflects the most negative/least positive result and pathway 'maximum' the least negative/most positive result.

	Monetary Impact			Service Impact		
	Single Asset (£bn)	Pathway Minimum (£bn)	Pathway Maximum (£bn)	Single Asset (£bn)	Pathway Minimum (£bn)	Pathway Maximum (£bn)
Minor Road	-1.22	-19.72	-0.86	0.00	0.00	1.04
Major Road	-1.89	-20.39	22.87	0.00	-41.01	1.04
Difference	-0.67	-0.67	23.73	0.00	-41.01	0.00

For the environmental impact, all additional developments produce a negative impact, causing the single asset assessments to be the maximum (least negative) output for the pathway. This is unsurprising given that all investments must have a spatial footprint (and will therefore have negative habitat and landscape impacts) and many use electricity (therefore will contribute to a negative carbon dioxide impact). The road infrastructure, by enabling further developments lead to minimum pathway family environmental effects an order of magnitude worse than their individual assessments.

The lack of an inherent demand for the road leads to zero social and service impacts in the single asset case, which in contrast to the environmental impact, becomes the minimum for the minor road pathways. The major road pathways partially enable the full airport development and therefore significantly increase road demand in the no-rail airport development pathways. Increases in congestion and accident levels in these pathways lead to a decrease in the social and service results (-£3.3bn and -£41.0bn difference respectively). The pathway maximums also reflect the road's enablement of other infrastructure, in this case the barrier, with the social maximum reflecting the security benefits and the service maximum reflecting the energy generated. However, given that both road developments enable the development of the barrier, the difference in maximum opportunity is zero, the same as the single asset case.

The single asset results represent neither the minimum nor maximum pathway results for the monetary effects. By enabling the rail investment (with no inherent demand), both road

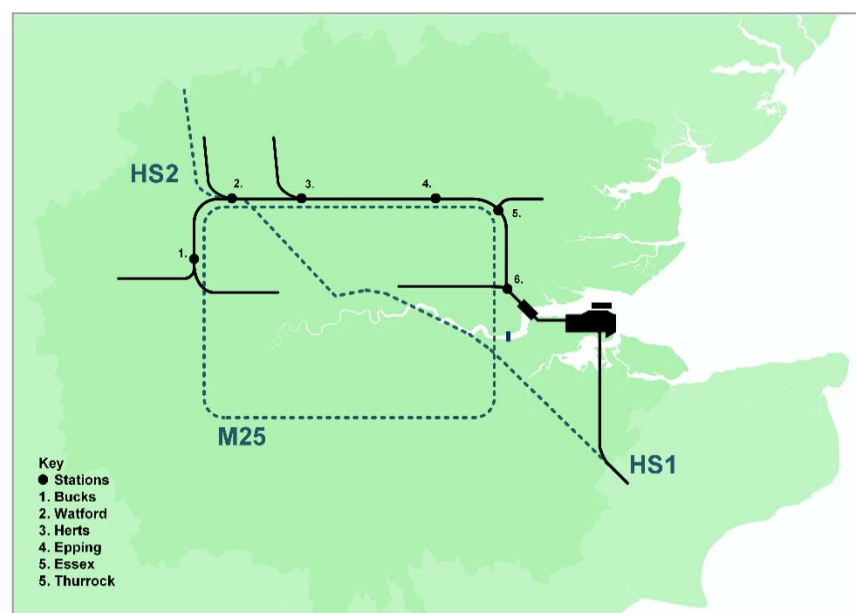
investments have a pathway minimum equal to the cost of the road, barrier and rail developments. The difference in the pathway minimum monetary result is therefore equal to the difference in individual road development costs (reflecting the difference in the single asset monetary results). However, while the minor road investments only enable the implementation of energy generation revenues and employment, the major road investments also enable the airport, with associated revenues and secondary benefits through the induced rail demand. The pathway maximum for the major road investment is therefore an order of magnitude larger than those generated by the road directly and over 20 times that for the minor road pathway.

As noted in Chapter 3, these differences between the individual asset and pathway results represent the opportunity value of the developments, our derived pathway equivalent of option values (see real options discussion in Chapter 2). However, while option values are attributable to a single investment option, the opportunity values shown above represent the entire pathway and are therefore attributable to the system as a whole not a single asset. In the Thames Hub Vision case, we can see this 'opportunity' is can be both positive and negative, increasing the range of results achieved in both the maximum and minimum cases.

6.5.2 System effects

Through our development alternatives we can also start to examine our final system effect, that of connectivity. The high speed and commuter line rail developments both follow the same route, with a station at Watford to connect the new orbital line to High Speed 2 services. However, in the case of the commuter rail we build an additional six stations (see Figure 6.6), each with significant park and ride facilities, therefore increasing the construction costs. Our pathways analysis allows us to weigh up this cost against the impacts delivered and enabled by the infrastructure development.

Figure 6.6 – Thames Hub Vision rail orbital stations (Foster+Partners et al., 2011a)



Passenger travel behaviour has been modelled using that recorded for Heathrow in 2003 (Civil Aviation Authority, 2003), using the rationale outlined in Chapter 3 and detailed in Appendix B. In the high speed case we assume that passengers travelling from the main High Speed 2 stations (Manchester, Birmingham, Sheffield and Leeds) by car (personal or taxi)²³ can be converted to either only rail travel or to park and ride at Watford, reducing those travelling to the airport by car and increasing use of the orbital. We also assume that passengers already using rail for such routes are converted from use of London Underground and central London trains ('Tube/Train' in Table 6.3) to the orbital, freeing up rail capacity in central London. Applying the assumptions in Appendix B we gain a 3 per cent modal use of the rail orbital in the high speed only case (see Table 6.3).

²³ Passengers using hire cars or airline cars are not assumed to change mode.

Table 6.3 – Connectivity impacts of the high speed and commuter line rail infrastructures

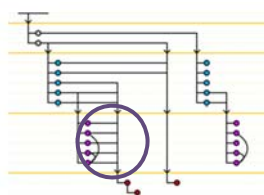
	Heathrow (2003 data)		Thames Hub					
			No Rail		HS Rail		Commuter Rail	
	Modal Split	Million Road km Travelled	Modal Split	Million Road km Travelled	Modal Split	Million Road km Travelled	Modal Split	Million Road km Travelled
Bus/Coach	13%	25	11%	39	11%	37	7%	24
Car	64%	3,111	66%	5,485	65%	5,382	32%	2,211
Park & Ride	0%	-	0%	-	0%	-	18%	825
Orbital	0%	-	0%	-	3%	-	25%	-
Tube/Train	23%	-	23%	-	21%	-	18%	-
Total	-	3,137	-	5,524	-	5,419	-	3,060

Through implementation of the commuter rail service, we open the orbital to those in the vicinity of the additional six stations. Again car users are encouraged to switch to park and ride and rail users to convert from central trains and the London Underground to the orbital. However, given the population affected, we now achieve an estimated 25 per cent modal share for the orbital directly and 18 per cent for park and ride (see Table 6.3). With the remaining 18 per cent use of central London trains, this is in line with the Thames Hub Vision proposal's aim to have a 60 per cent of passengers using rail transport.

In Table 6.4, we can see the pathway impacts of implementing these high speed and commuter line rail developments, implementing either line with the potential to expand at a later date, or implementing the full rail orbital in one stage²⁴.

²⁴ The results shown assume the 'major road' and 'integrated barrier' option routes have been taken, using a 2010 starting date and provisioning option groups as soon as possible while maintaining asset order restrictions (see highlighted section of pathway diagram).

Table 6.4 – Pathway impacts for the five rail infrastructure developments



	Environmental Impact			Social Impact		
	Pathway Minimum (£bn)	Pathway Maximum (£bn)	Range (£bn)	Pathway Minimum (£bn)	Pathway Maximum (£bn)	Range (£bn)
High Speed Rail	-4.58	-2.47	2.10	-3.20	0.29	3.49
High Speed Rail with Option to Expand	-4.58	-2.47	2.10	-3.20	0.29	3.49
Commuter Rail	-3.20	-2.44	0.75	-0.61	0.29	0.90
Commuter Rail with Option to Expand	-3.33	-2.44	0.88	-0.61	0.29	0.90
Full Rail	-3.33	-2.55	0.78	-0.61	0.29	0.90

	Monetary Impact			Service Impact		
	Pathway Minimum (£bn)	Pathway Maximum (£bn)	Range (£bn)	Pathway Minimum (£bn)	Pathway Maximum (£bn)	Range (£bn)
High Speed Rail	-14.48	13.10	27.58	-40.13	0.90	41.03
High Speed Rail with Option to Expand	-20.39	11.30	31.70	-40.13	0.90	41.03
Commuter Rail	-16.26	13.56	29.81	-2.43	0.90	3.33
Commuter Rail with Option to Expand	-20.39	13.26	33.65	-2.43	0.90	3.33
Full Rail	-18.26	11.87	30.13	-2.43	0.90	3.33

Introduction of the additional six stations decreases the potential negative effect of the infrastructure, reducing the minimum values (and hence the range) of the environmental, social and service impacts. The sum of these effects is an order of magnitude greater than the additional cost of the stations (£1.4bn, £2.6bn and £37.7bn for the environmental, social and service respectively, compared to an additional cost of £1.8bn). The investment therefore reduces both the maximum disbenefit and the variability of these factors, making the outputs more certain and less negative. Introduction of the stations also increases the maximum monetary and environmental benefits by £0.5bn and £0.03bn respectively. In the case of the monetary result, the greater potential cost of the scheme and greater potential benefit results in a greater range of outputs. In part this is due to the assumption of no latent demand. However,

typically investors prefer investments with more stable results and it will be important to communicate any such limitations in the estimates so that the greater range is understood.

The results of the commuter rail development over those of the high speed rail development suggest that the increased connectivity provided by simply implementing more stations is worthwhile. Given the scale of these benefits compared to the additional cost, it suggests the commuter rail should be the priority rather than the high speed rail. Indeed, expanding to include high speed rail as well (or provision of options for expansion) creates potential disbenefits, suggesting that latent demand in addition to that required by the airport would be necessary to make the scheme worthwhile. Furthermore, this illustrates the non-linear nature of connectivity costs, whereby increasing connections to the north of England may not provide substantial benefits for transport to and from the airport. While implementing the full rail development offers some savings over the developments with options to expand, in comparison to the commuter rail only development, monetary and environmental effects are reduced.

6.5.3 Adapting the pathway analysis for decision-support

The pathway analysis has clearly provided us with a greater level of information on the future impact of infrastructure and how this is effected by our decisions; however as we move through the pathway, more data must be compared by the decision maker and/or more assumptions must be made about the decisions taken. For example, Table 6.4 only displays five of the rail pathways. There are four different paths to each of these five rail developments, two of which have further rail development potential (twenty eight paths in total). The methodology then also allows us to investigate the effects of different start dates and different periods between group investments. If we wish to provide a useful tool for decision-support it needs to be able to divide the decision space into manageable and meaningful assessments and display the

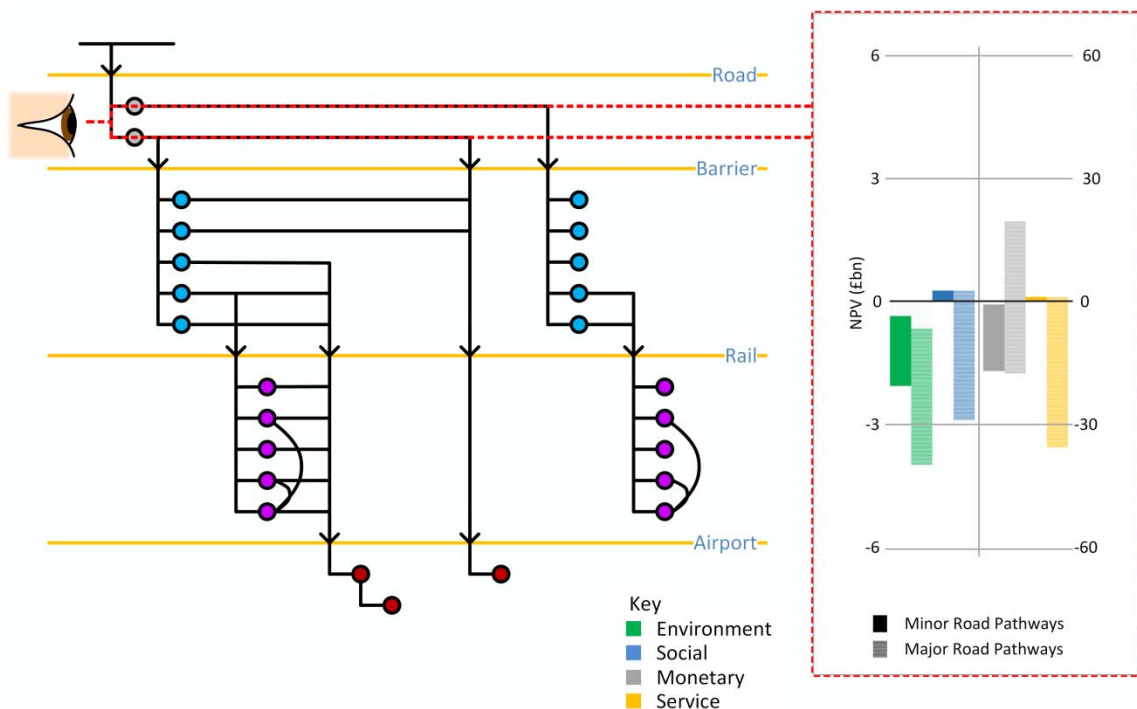
information graphically, taking account of the different order of magnitude of the ‘finite’ (environmental and social) and ‘variable’ (monetary and service) impacts.

In Figure 6.7, we have combined the pathway analysis with a graph of the outputs for the road infrastructure pathways. The graph has been manipulated through the use of different scales for the ‘finite’ and ‘variable’ impacts. While this must be explained to the users, it represents all factors in one graphic, allowing the variability of all impacts to be considered together. The bars represent the range of impacts provided by each pathway, with the difference between pathways showing the additional opportunity provided by the different developments under consideration. We can therefore quantify the asset’s value in enabling future infrastructure; a value akin to the value of flexibility in real options ‘in’ projects analyses. Taking the monetary impact as an example, we can see that the opportunity provided by the major road infrastructure is approximately £24bn greater than that provided by the minor road infrastructure. The graphic can therefore be used to concentrate the decision on the opportunities the decision maker wishes to leave open.

Taking the first of our proposed decision criteria from Chapter 3, we can consider these opportunities through thresholds. For example in Figure 6.7 we can place a threshold monetary benefit at £5bn:

$$\max(v_{economic}(s''_{w_{\varepsilon}} | a_{\theta} \in s''_{w_{\varepsilon}})) \geq 5 \times 10^9$$

Figure 6.7 – Decision analysis of major and minor road improvements (adapted from Young and Hall (2015))

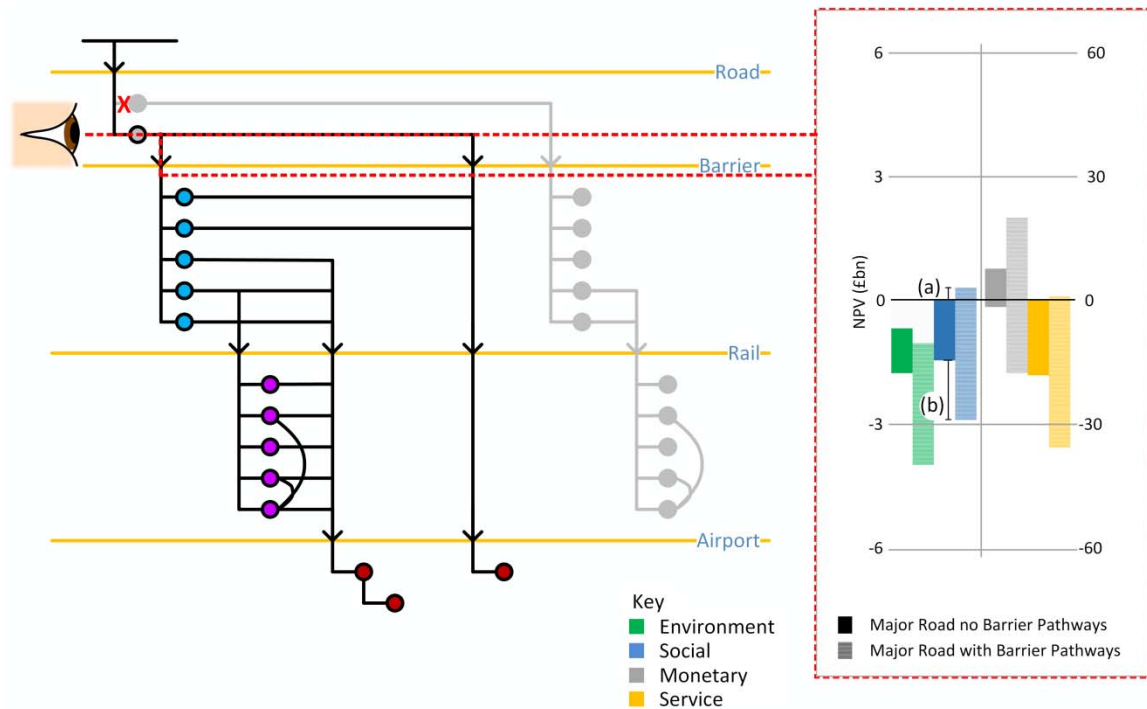


Comparing the two pathways to the threshold, only the major road benefits can provide this opportunity, therefore we must dismiss the minor road developments, find more alternatives for development, or accept the lower monetary benefit. Assuming that all development alternatives were considered at the option development stage, either our decision space is reduced (dismissal of the minor roads), or we have achieved a greater understanding of the bounds of the development.

Assuming we wish to keep the opportunity to achieve monetary benefits over £5bn, we can remove a branch of our pathway analysis (investment in minor roads), reducing our decision space. In Figure 6.8 we consider the next decision, that of whether we wish to invest in a flood barrier or not. We can now see that both pathways provide the opportunity to achieve a

monetary benefit of £5bn²⁵. We must therefore add additional thresholds if we wish to reduce the decision space further.

Figure 6.8 – Decision analysis of the barrier element (adapted from Young and Hall (2015))



Our representation also allows the decision maker to compare impacts between infrastructure sectors. For example, taking our third decision criteria from Chapter 3, we can review the difference in pathway maxima and minima and the assets that create these effects:

$$\begin{aligned} O_{attribute}^{+}(road\ no\ barrier) &\geq O_{attribute}^{+}(road\ with\ barrier) \\ O_{attribute}^{-}(road\ no\ barrier) &\geq O_{attribute}^{-}(road\ with\ barrier) \end{aligned}$$

Referring this back to our case study, in Figure 6.8, there is a £0.3bn increase in the social impact when the barrier is included in the evaluation (notation (a)), due to its inherent security benefits. However, pathways including the barrier also provide the opportunity for a more negative social impact by enabling the airport, thereby increasing road use and accident rates (notation (b)).

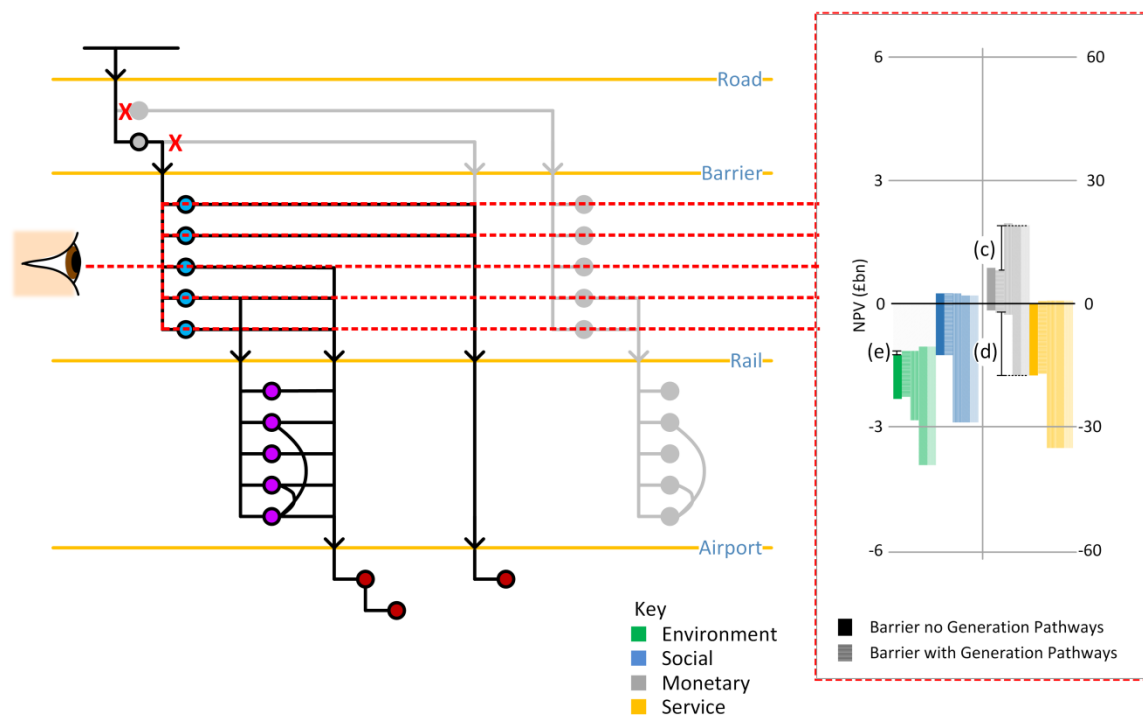
²⁵ A maximum monetary opportunity of £9.5bn without the barrier, or £22.9bn with the barrier.

The social benefit of the barrier can be seen to be only a small fraction (approximately 20 per cent) of this £1.6bn disbenefit.

In Figure 6.9 we have assumed we wish to maintain pathways with the potential for monetary benefits greater than the £9.5bn achieved by the 'without barrier' pathways. We have therefore decided to build a barrier, again removing a branch from our pathway analysis. We can see from the graph that two of the five pathways²⁶ offer a similar level of monetary benefit to the 'without barrier' pathways, with the remaining three offering the opportunity for monetary benefits of over £22.0bn. By highlighting the additional opportunity provided by the different developments and the decision maker can assess which they wish to keep available for future consideration. For example, applying our range decision criteria again, the opportunity (increase in maxima) created by including a rail crossing as part of the barrier is £12.6bn (notation (c)). This is over 70 per cent of the cost of implementing the full rail development (the £17.9bn shown as the change in pathway minimum, see notation (d)). If we wish to keep this option open, designs for the barrier should include alternatives with the rail included and/or with the option to expand to include these crossings at a later date (see, for example the Tagus River Bridge (Gesner and Jardim, 1998)). This suggests that increased engagement between the Environment Agency and Highways England on their existing barrier and crossing projects is a priority. Furthermore, through such stakeholder interaction we can identify review points and decision triggers to ensure that such options are not closed off unintentionally.

²⁶ Options from left to right: barrier with no generation, barrier with generation, barrier with generation and road crossing, barrier with generation and rail crossing, fully integrated barrier (generation, road and rail).

Figure 6.9 – Decision analysis of the barrier developments (adapted from Young and Hall (2015))



Finally, Figure 6.9 also displays the environmental benefit of the renewable energy generation (notation (e)) against the effects of the system as a whole. This £0.1bn benefit reflects one dimension of our ability to correct the negative impacts of infrastructure development, in this case carbon dioxide emissions. We can see that this benefit is dwarfed by the system environmental effects, representing less than 10 per cent of the minimum disbenefit. It also highlights the importance of the valuation methods used within the appraisal. The methodology uses the predicted market prices of carbon to estimate individual willingness to pay, valuing the benefit at £0.1bn. However, if we instead used the actual cost of implementing infrastructure to negate carbon dioxide²⁷ (in this case the cost of the barrier) the result would be an order of magnitude greater. Furthermore, we would need to consider the constraints of implementing the assets, such as prerequisite conditions (in this case the minor road investment), space limitations and the opportunity cost of the resources required. Such conclusions reaffirm the

²⁷ Averting behaviour approach, see Chapter 2.

necessity of keeping the less certain finite resource valuations separate from the more certain variable resources (in this case cost).

6.6 Conclusions

In this chapter we have demonstrated the theoretical portfolio and pathway analyses developed in Chapter 3 using the Thames Hub Vision case study. We have found that the appraisal methodology demonstrated in Chapter 5 provides a suitable baseline for these analyses. Indeed, that the attribute totals chosen split impacts into finite and variable resources, focusing attention on the former (despite their much smaller valuations) and giving the stakeholder the opportunity to re-evaluate their value given that marginal change assumptions of CBA may be broken.

We have found that there are system effects not recognised by the single asset appraisals, but that a number of these can be quantified through a portfolio analysis. Through our case study we have determined that these system effects are significant, affecting the risk and viability of the individual asset investments and changing the appraisal result from a net negative to a net positive. Furthermore, by capturing the total system resources, the portfolio approach allows these to be compared to those available, both in regard to future developments in other sectors and regulatory thresholds, highlighting shortcomings of the planned developments. It also suggests whether developments are complementary and may therefore contribute to wider economic impacts. Finally the portfolio analysis gives us a greater understanding of the interplay between assets and the trade-offs between attribute impacts, helping to engage stakeholders in a useful dialogue over their priorities and making different sectors aware of the potential need for future developments.

By extending the analysis into a pathways approach and through the consideration of alternatives to, and options on, the original case study elements we have captured system benefits not visible through the portfolio approach, in particular the effects of aggregation and connectivity. We have quantified these against a development timeline and noted the effects and importance of the order of implementation. Furthermore, by undertaking the analysis, we have noted the value of the option to expand (particularly in the case of transport crossings as part of the barrier, or inclusion of commuter stations as part of a high speed rail orbital) and the significant opportunity value provided by assets over and above their individual effects (as demonstrated by the comparison of the minor and major road investments). This is in direct contrast to current techniques, which would apply system effects to the latterly implemented infrastructure. We have shown, through our case study, that this opportunity value may be up to an order of magnitude greater than the individual assessment results. Therefore the opportunity provided by an asset (its ability to enable or constrain future developments) may be of greater importance than its standalone appraisal results.

Finally, through the combination of a pathway diagram and the outputs of the pathway analysis, we have developed a decision-support tool capable of displaying the opportunity value provided by assets and their ability to restrict or enable further developments. The tool encourages stakeholders to look past individual elements to the full effects of the system as a whole. It therefore highlights options we may wish to keep open, encouraging an ongoing dialogue between stakeholders to enable the maintenance of these options across sectors, a process that has historically proved difficult (de Neufville and Scholtes, 2011), particularly in public policy, where option and pathway analyses have seen little application (Farrow, 2004)²⁸.

²⁸ Kruger (2012), for example, notes that municipalities in Sweden have recently given away land-development concessions for free, arguing that undeveloped land is worthless.

7 Assessing System Uncertainty: A Sensitivity Analysis of Key Variables

7.1 Introduction

In Chapter 6 we successfully applied the pathway appraisal methodology to the Thames Hub Vision case study, deriving the potential benefits of a whole system of infrastructure assets. The valuation uncertainties of this appraisal were considered in Chapter 5; however, the remaining model uncertainties have not, thus far, been considered. Indeed, such consideration was purposefully delayed until it could be conducted on the system as a whole (as shown by the outline methodology, see Figure 7.1). With the results of Chapters 5 and 6, this is now possible.

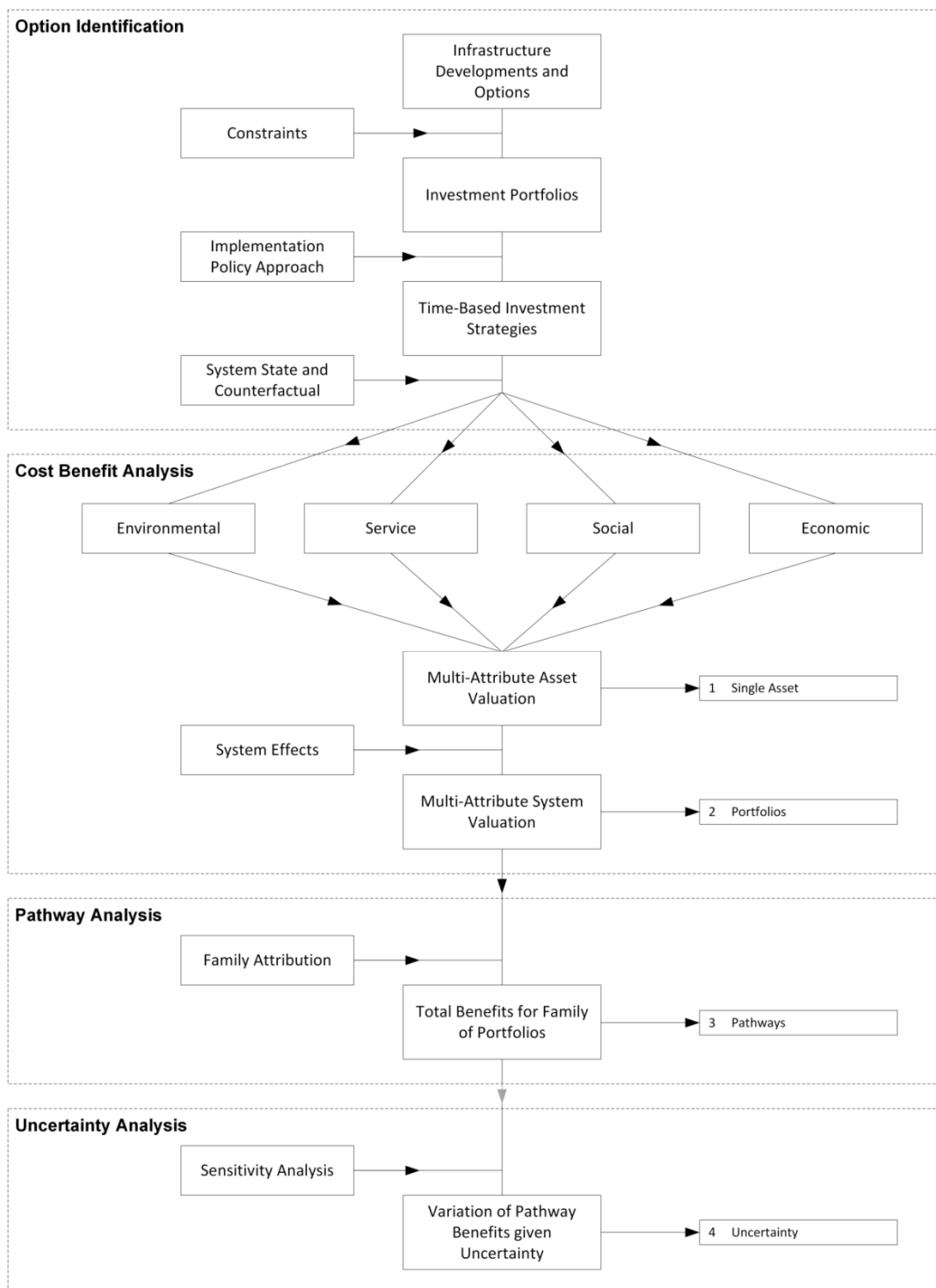
The purpose of this chapter is therefore to analyse the uncertainty of the model, determining how this uncertainty propagates through the system, and its effects on the appraisal results.

The objectives are to determine:

- What are the sources of uncertainty within the appraisal methodology;
- Which of these uncertainties have the most significant effects on the appraisal results;
- and
- How this effect manifests for the different pathways and attributes over time.

We first review types of uncertainty intrinsic to models and particularly long-term infrastructure appraisal. We consider the stages of the model and the type of uncertainties introduced at each stage. Collating these input and aggregation uncertainties, we assess which has the greatest influence on the results. Our first uncertainty surrounds the discount rate, identified in Chapter 2 as a highly debated factor with significant effects on the results of the appraisal.

Figure 7.1 – Outline methodology, systems uncertainty appraisal (adapted from Young and Hall (2015))



Our second uncertainty is that surrounding the population projection, which is deemed to be a key variable, affecting estimations of both the demand for infrastructure and valuation of its impacts. For each uncertainty we consider the range of plausible values and conduct a

sensitivity analysis on the system results, reviewing how the uncertainty impacts the different attributes and pathways, and the change in the resulting appraisal value.

7.2 Types of uncertainty

Our definition of ‘deep uncertainty’ in Chapter 1 (see Hallegatte et al. (2012)) consisted of three components, all of which were applicable to infrastructure investment decisions:

- Multiple valid but divergent perspectives regarding value or success;
- Decisions which are complexly inter-related and can change over time; and
- ‘Knightian uncertainty’ i.e. uncertainty that cannot be reliably quantified.

Our appraisal methodology has been developed to encompass different stakeholder priorities, system effects and decisions which change over time; however the ‘Knightian uncertainty’ remains¹. This uncertainty will affect all the long term projections on which an appraisal is based and while it will be partially mitigated by our active approach, it will also be increased by our 100 year appraisal time-frame.

Within traditional appraisals, this certainty is often tested through sensitivity analysis of the cost or revenue estimates. Indeed, in Chapter 5 we used Flyvbjerg’s data on the statistical inaccuracy of cost and demand estimations to consider the stability of our estimates (Flyvbjerg, 2009; 2007). However, by simply applying a statistical uncertainty to the outputs of the appraisal we

¹ Such uncertainties, which cannot be reduced with further modelling and/or research are sometimes referred to as ‘aleatory’, ‘ontological’ or ‘stochastic’ and include: behavioural variability; societal variability; technological developments; economic and/or political change/events; environmental change/events; natural randomness and chaotic dynamics (see Salling and Banister (2010)).

do not consider the underlying causes of the uncertainty and how it propagates through the appraisal attributes and assets.

De Neufville and Scholtes (2011) note this need to understand the underlying uncertainty of forecasts. They give multiple examples of real future projections where there has been a high degree of inaccuracy and show that this inaccuracy is not improved over time (see Figure 7.2 and Figure 7.3 for example).

Figure 7.2 – Forecast and actual oil prices (de Neufville and Scholtes, 2011)

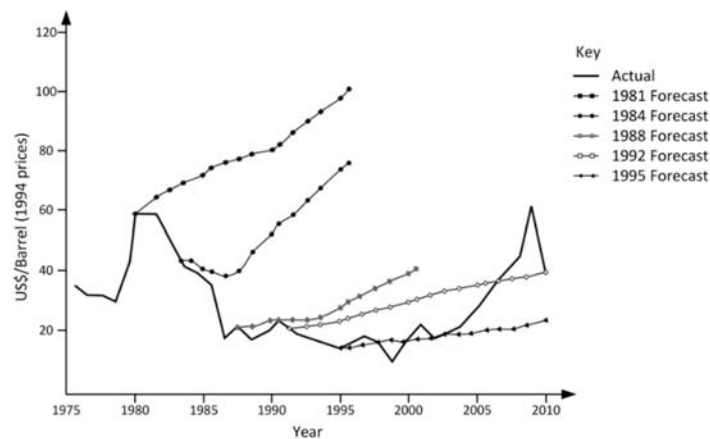
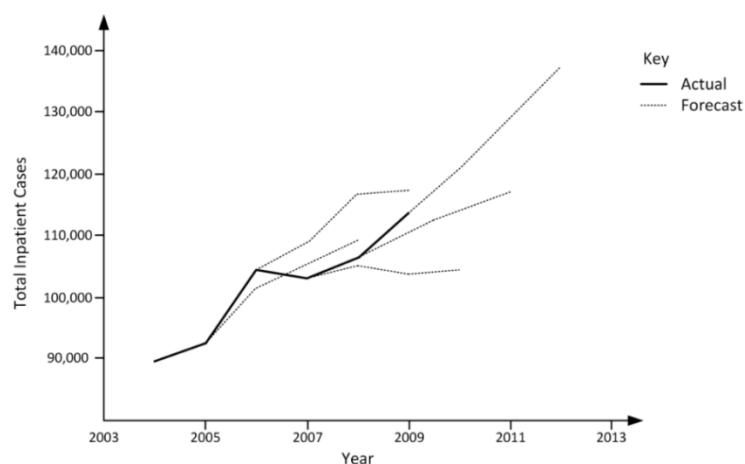


Figure 7.3 – Forecast and actual inpatient cases (de Neufville and Scholtes, 2011)



Their review shows that appraisals have tended to insufficiently consider these uncertainties, relying on projection accuracy for choosing between alternative designs/courses of action. This

has led to decisions that are not robust to change and, in many cases, to the (financial) failure of the designed assets. Their examples highlight the main uncertainty relevant to decision making under deep uncertainty:

- Technology change or discoveries, as exemplified by calculations of oil reserves in the North Sea (de Neufville and Scholtes, 2011, p25) and the obsolescence of satellite phones after the development of mobile phones (de Neufville and Scholtes, 2011, p4);
- Other 'trend-breakers' such as economic crises, political shifts, climate change, or new regulations, leading, for example, to large fluctuations in housing price markets (de Neufville and Scholtes, 2011, p31-32);
- Stakeholder decisions/behaviour, which, in the case of Boston airport led to an increase in passenger density on larger jets, exacerbating the effects of over estimation of demand by removing the need for small regional flights (de Neufville and Scholtes, 2011, p28);
- Changing requirements, for example the use of unmanned aerial vehicles which have gone from slow, low load monitoring devices to those able to carry armaments and fly sufficiently fast to evade enemy fire (de Neufville and Scholtes, 2011, p29) or GPS, which was not originally perceived to have commercial applications, therefore did not have facilities built in to track or charge for usage (de Neufville and Scholtes, 2011, p4); and
- Relationships and dependencies such as that between behaviour and the cost of resources, as shown by the Boston sewerage system, which was designed based on current water usage and population growth, but created a 20 per cent drop in consumption when costs were increased to pay for the new facility (de Neufville and Scholtes, 2011, p75).

De Neufville and Scholtes' (2011) study only considers the financial success of the assets; however, as we have seen throughout this thesis, the effects of infrastructure are much wider than just their financial success. Furthermore we have seen in Chapter 6 that such developments also affect infrastructure assets that are built in parallel, those that will come to rely on these assets in the future and those that can no longer be built because of the decision to build the first. Each uncertainty therefore has the potential to influence a much wider array of factors and the whole pathway of infrastructure developments; a much wider remit than that commonly considered within current appraisal uncertainty analysis.

7.2.1 Uncertainty within infrastructure appraisal

The de Neufville and Scholtes' (2011) review identifies five key uncertainties (technology change or discoveries, other trend breakers, stakeholder decisions/behaviour, changing requirements and relationships and dependencies). Each of these is applicable to infrastructure decisions; however, if we wish to understand the uncertainties within infrastructure systems appraisal we must consider the uncertainties specific to long-term infrastructure decision making more carefully.

While technology change is a general uncertainty that can affect any engineering system, in the case of infrastructure in the UK, currently used assets could have been built over a century ago and their state of repair and, in some cases, location are not fully understood. This situation is not unique to the UK with Apostolakis and Lemon (2005) estimating that 10% of natural gas distribution lines and up to 20% of water distribution lines in the United States are undocumented. Furthermore, where the knowledge is available, it must be collected from the disparate series of owners and regulators who have owned or operated the assets over their life. These stakeholders may not wish to reveal it for commercial or security reasons (Apostolakis and

Lemon, 2005). In addition to future technology change, there is also, therefore, uncertainty surrounding current assets, the technologies these use and their remaining operational lives.

Given the long operational lives of infrastructure assets the likelihood of technology change or another trend breaking event occurring is much higher than for other assets. Furthermore, future decisions can influence and will be influenced by climate and socio-economic change. These are unpredictable even in the short-term (Weaver et al., 2013), yet infrastructure assets can be very sensitive to such events (Hall et al., 2012b). Furthermore, given the magnitude of the effects of infrastructure, the opportunity for public and political opinion or for regulations to change is much greater. Decisions must satisfy multiple stakeholders with different expectations of the future and be resilient to change in each of their spheres of interest (Hall et al., 2012b). An appraisal must therefore provide information that is consolidated, but sufficient for each of these stakeholders. As seen in Chapter 5, the aggregation of values through monetisation or weighting produces additional uncertainties. The use of shadow pricing and discounting for example (see Chapter 2), are particularly controversial and in the latter case has been found to create significant changes in the results (Beuthe, 2002; Bickel et al., 2006).

Infrastructure services are reliant on their appeal as a service to the general population and, particularly in the case of transport, the service provided is dependent on the population's response to them. The ability to design engineering systems that rely on interaction with the public for their success is greatly challenging (Collingridge, 1981), particularly over the long-term, where demand has been seen to frequently vary from that originally anticipated and to sufficient extents to undermine an asset's viability (de Neufville et al., 2006). However, public opinion not only drives demand for an infrastructure's services, it also changes the perceived cost of its impacts. The size and opinions of the general population therefore affect two sides of an infrastructure asset's value chain.

Finally, the relationships and dependencies of infrastructure assets are extensive and complex. They have strong interdependencies with their socio-economic environment (through, for example, their demand and value, as noted above) and with their environment through their impacts (such as climate change). However, as seen in Chapter 6, they are also interdependent within and between networks, relying on the services supplied by other sectors and requiring the same constrained resources. The opportunity for investment is therefore dependent on prior choices made and their future value is dependent on the timing and sequencing those made subsequently. Prediction of benefits relies on projecting how the system will develop and its interactions.

7.3 Uncertainty within the appraisal methodology

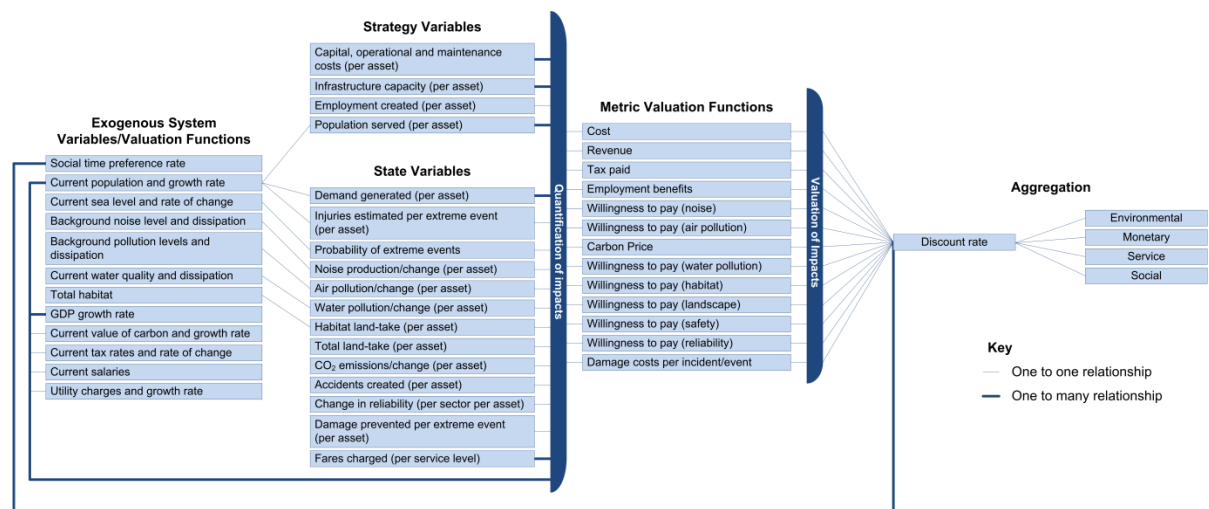
By understanding the impacts assets are putting on the current (and future) system, our appraisal methodology more fully allows for uncertainties surrounding the current state of infrastructure. Furthermore, by allowing decisions to be actively changed over time, pathways can be altered as more information becomes available, or to adapt to changes in values/behaviour, the environment or in technology. However, the uncertainties identified can still strongly affect the results. It is therefore useful to understand where uncertainty is created within our appraisal methodology and examine the effects of this uncertainty on the system as a whole.

Our model can be split into five components (see Figure 7.4):

- Exogenous system variables/valuation functions, the assumed states of nature, these are externally generated and the same for all pathways including the 'do minimum' case;
- Strategy variables, which are specific to a given set of assets; and are used to derive the

- State variables, the system response and associated quantified impacts in comparison to the 'do minimum'²;
- Valuation functions, which are used to monetise the quantified impacts; and
- Aggregation functions, which are used to aggregate the indicators into a more concise form to allow effective decision making.

Figure 7.4 – Model inputs and components



Thus far only the uncertainties of the valuation functions have been considered (see Chapter 5) and, although some were large, none were found to change the individual asset appraisals sufficiently to affect the results of the appraisal. If we consider Figure 7.4, this is likely to be because most of the uncertainties considered only affected one indicator and are introduced towards the end of the model. In contrast, the demand uncertainty, which was used to assess multiple indicator uncertainties in Chapter 5 is introduced as a state variable. This is earlier in the model and therefore has the opportunity to affect more of the model outputs. If we wish to find the uncertainties that produce the most significant system effects we must interrogate Figure 7.4 for those inputs and components with the most influence on the model, either being

² Strategy and state variables which are dependent on the exogenous system variables and valuation functions are linked by blue lines in Figure 7.4.

used in multiple places or being integral early in the analysis and compounded over the different indicators.

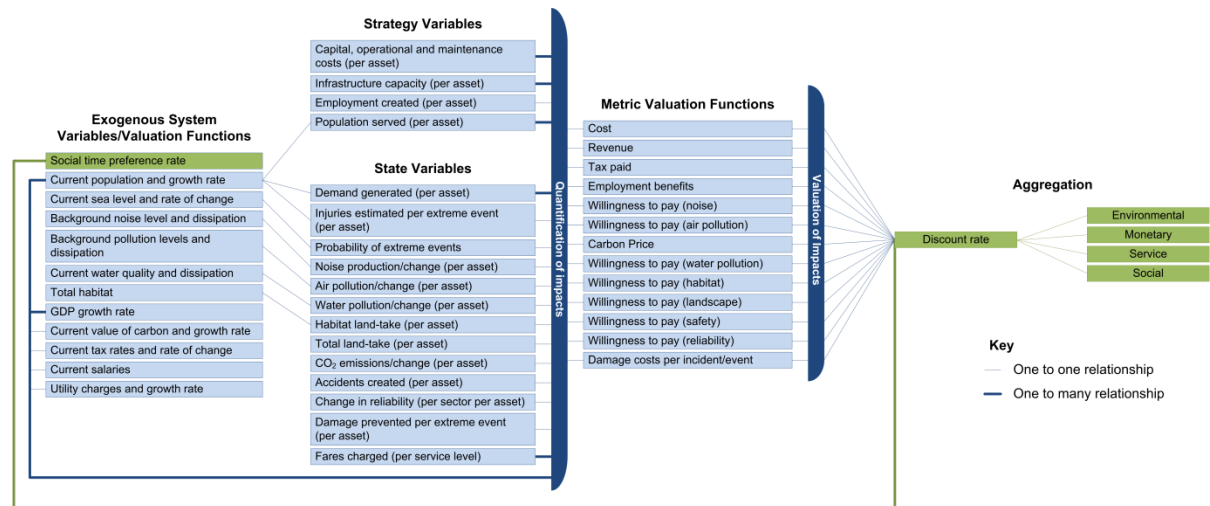
7.3.1 Key uncertainties

We assume that the inputs with the greatest system effects are those which affect the most indicators. Considering Figure 7.4 there are eight inputs which have multiple effects (see thicker 'one to many' relationship lines). Of these, three are introduced at the first stage as exogenous system variables/valuation functions, therefore have the greatest opportunity to affect the model. These are the social time preference rate, current population and growth rate and the GDP growth rate. Each of these is uncertain. Five more inputs with multiple effects are introduced at the second stage, either through the strategy variables (costs, capacity and population served) or through the state variables (demand and fares charged). We can immediately dismiss one of these inputs (capacity), which is a feature of the engineering design, therefore its uncertainty is limited and its effects have been investigated through the different development alternatives.

The first of our multiple effect inputs is the social time preference rate. By feeding into the discount rate used to aggregate the results this affects all fifteen indicators and therefore all four attributes (see Figure 7.5). The controversy of the discount rate was discussed in Chapter 2 with large differences in proposed rates noted. Yet even small changes in the discount rate have been proved to cause significant effects (see Bickel et al. (2006)). This uncertainty is now starting to become recognised in appraisals. In the United States, for example, the costs and benefits of all the public investments must be sensitivity tested against both a 3 and a 7 per cent discount rate (World Bank Climate Change Group, 2014). This input therefore offers the

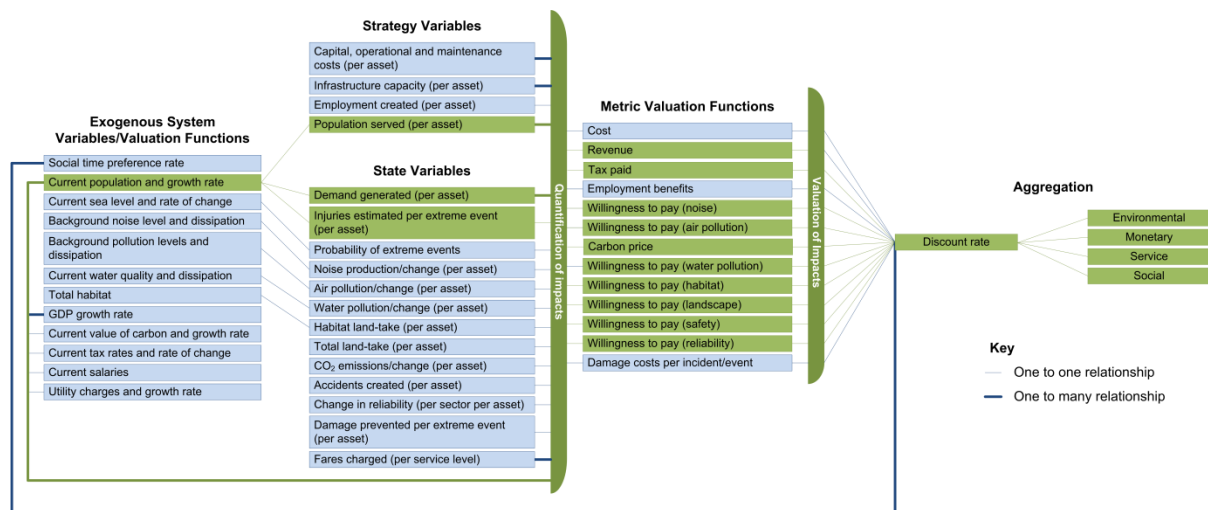
opportunity consider a known current issue and to re-examine a large single asset appraisal uncertainty against the systems case.

Figure 7.5 – Propagation of discount rate uncertainty through the model



The second multiple effect input is current population and population growth. Here the uncertainty is the population growth rate. As we noted in Section 7.2.1, population affects both the demand for infrastructure services and the valuation of impacts. Current population and population growth are therefore recognised as two of the most important factors influencing infrastructure development decisions (Thekdi and Lambert, 2012). Considering the effects of the input within our model, population can be seen to influence two other multiple effect inputs (population served and demand) and the quantification of all impacts based on individual willingness to pay (see Figure 7.6). It therefore impacts all four attributes, although not all fifteen indicators.

Figure 7.6 – Propagation of population growth rate uncertainty through the model



The final multiple effect system variable is the GDP growth rate. This doesn't affect any second stage inputs directly in the system model, but is important in projecting value over the time period, being used as a proxy for household wealth. It thereby affects all indicators valued through willingness to pay, with impacts on all four attributes. The number of valuation functions affected by GDP growth is therefore the same as the population growth rate; however, its effects are limited to this stage. As population growth also affects the second stage inputs through demand, population served and extreme event injury levels, its system interactions are larger.

The remaining two multiple effect inputs (the costs and fares) are in the second stage, therefore have less opportunity to affect the total system. Indeed, their effects are limited to the monetary and service attributes. Their influence on the total system is therefore likely to be less than the discount rate, population growth rate or GDP growth rate.

As the remaining variables only have one to one relationships, their ability to affect the system as a whole is likely to be smaller than any of those discussed. Of these, the discount rate and population growth rate appear to offer the greatest opportunity to investigate system

uncertainty. Both inputs are known to strongly affect current single asset appraisals and will affect all four attributes within the model. Furthermore the discount rate affects all fifteen indicators and the population growth rate has the most system interactions. We will therefore use these two inputs to investigate the uncertainty of the pathway appraisal. It should, however, be noted that the model is a simplification of reality and therefore known interactions between variables are missing. For example, GDP growth will affect disposable income and through this population growth, infrastructure demand (particularly in the transport sector) and uptake of technologies such as electric vehicles. Furthermore, at the macro level, it can affect spending on infrastructure and innovation and therefore both the potential for development and the performance of infrastructure assets. Each of these facets could affect the need for future infrastructure. While such integration between the system projections are not considered within this work, they are seen as a valuable extension, particularly if combined with pathway methods for dealing with ensembles of possible futures, such as Adaptation Pathways and Dynamic Adaptive Policy Pathways (see Haasnoot et al. (2013)).

7.3.2 Investigating the uncertainties

In Chapter 3 we chose to use sensitivity analysis to investigate the system uncertainties. The method is a simple assessment, chosen to balance the complexity elsewhere in the appraisal framework. The choice recognises that, through use of our active approach to appraisal, the consideration of vast arrays of possible futures (as used in other deep uncertainty methods, see Chapter 2) is no longer necessary; however, that it is still useful to understand uncertainty of the system as a whole over the long-term.

The method involves varying key model inputs to ascertain their effect on the model outputs (in our case the attribute valuations). By choosing a maximum and minimum value for the model

input, the possible range of model outputs is produced, identifying the uncertainty derived from the given model input. Over the next two sections we will therefore estimate a maximum and minimum value for each of our two key uncertainties (discount rate and population), then re-run the appraisal with these values, examining the effects on the portfolio and pathway results.

7.4 The system effects of an uncertain discount rate

7.4.1 The uncertainty of the discount rate

To perform a sensitivity analysis on the discount rate we must choose two rates which represent the minimum and maximum extremes of plausible rates. However, the discount rate is not a variable that can be verified. While many economists base their rates on the cost of capital, it also relies on understanding individual time preference and how this should be adapted to account for the needs and rights of future generations. It is therefore strongly debated³ and cannot be estimated through methods such as analysis of historical accuracy (see de Neufville and Scholtes (2011)).

The discount rate used thus far in our analyses is that stipulated for use on public or governmentally regulated projects in the UK (see HM Treasury (2003))⁴. However, other rates have been used historically, recommended by studies and are used by other countries.

Examining the literature, discount rates used by mature economies tend to be between 3 and 7 per cent, while those in developing economies are higher (8 to 15 per cent) reflecting the higher opportunity cost of capital (World Bank Climate Change Group, 2014). However, authors have also suggested the use of rates outside of these ranges, particularly in reference to climate change, where effects are long-term (therefore very heavily discounted), but can be

³ See Chapter 2 for a full discussion.

⁴ A rate of 3.5 per cent which descends over time (see Chapter 2).

catastrophic. Stern is perhaps the most well-known proponent of this perspective, with his independent review for the UK Chancellor of the Exchequer recommending a rate of 1.4 per cent (Stern, 2006a).

Considering our case study, the Stern recommendation provides a plausible minimum discount rate. His review was specifically focused on the UK and his rate represents the lowest found within our review of mature economy appraisals. By contrast, our review found that discount rates at the higher end of the mature economy range tended to be based on the weighted cost of capital (Pearce and Turner, 1990). We could therefore use 7 per cent, the maximum ascertained for developed economies by the World Bank Climate Change Group (2014) and representing the maximum rate used in the US appraisal sensitivity analysis. However, as the UK rate is lower than that used in many other mature economies (see Bickel et al. (2006)), it may be argued that the UK plausible maximum rate would be lower than elsewhere. We therefore choose to use the 6 per cent rate proposed by Weitzman, calculated based on what ‘most economists might think are decent parameter values’ (Weitzman, 2007). This is also the discount rate that was specified for use on UK public sector projects prior to the revision of HM Treasury’s guidance in 2003 (Headicar, 2009).

7.4.2 The effect of discount rate uncertainty on the system model

As shown in Figure 7.5, the discount rate affects all model attributes, being applied at the end of the appraisal to all indicators. Present values are calculated through Equation 7.1 (see Chapter 2). There is therefore an inverse power relationship between the present value and the year in which the benefits or costs are realised. This causes the value recognised to rapidly decline, significantly reducing the effect of the medium and long-term impacts (see Figure 7.7).

Equation 7.1 – Calculation of present values using a discount rate

$$V_0 = V_n \times \frac{1}{(1 + r)^n}$$

where V_n = Value received in year n
 r = discount rate
 n = year benefit/cost is received
 V_0 = Present value (value in year 0) of V_n , if received half way through year n

Figure 7.7 – Percentage of in-year value recognised by each discount rate over time

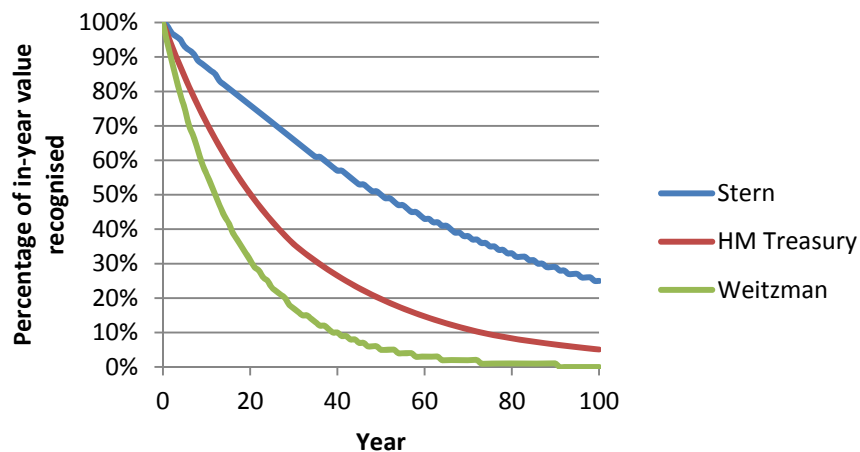


Figure 7.7 compares the effect of the three discount rates considered herein over the timeframe of the appraisal. As can be seen, the HM Treasury and Weitzman rates cause present values to fall to 50 per cent or less within the first 20 years. Indeed the Weitzman rate recognises less than 10 per cent of any value realised after 40 years and no value after year 91. In contrast, the Stern rate causes a much lower rate of decline, recognising over 50 per cent of the value realised at year 40 and still recognising 25 per cent of values realised at year 100.

We can also compare how the values change over time. The Stern values rise to 31 per cent greater than the HM Treasury values in year 41, after which point the HM Treasury values decrease more slowly than the Stern values, reducing the difference to 20 per cent by the end of the timeframe. In contrast the Weitzman values decrease to 20 per cent less than the HM

Treasury rate in year 21, slowly increasing to only 5 percent less by year 100⁵. We can therefore expect the effects of the two discount rates to change over time, with a bias towards effects near year 41 for the Stern discount rate and near year 21 for the Weitzman discount rate.

Comparing the results of the three discount rates on the on the individual asset appraisal, we indeed see this relationship (see Table 7.1). In all but two cases the Stern results magnify the impacts and the Weitzman results diminish them. Attributes with values weighted towards the beginning of the period vary little. For example, the capital costs the rail asset are over 80 per cent of the monetary attribute indicator values and are constrained to the first 10 years of the assessment. While most other values vary by over 30 per cent⁶, the monetary attribute of the rail asset varies only 10 per cent in the Weitzman case and 11 per cent in the Stern case.

Table 7.1 – Individual asset appraisal results with three discount rates applied

Asset	Discount Rate	Environmental (£bn)	Social (£bn)	Monetary (£bn)	Service (£bn)	Total (£bn)
Road	Stern	-2.12	0.00	-1.96	0.00	-4.08
	HMT	-0.85	0.00	-1.95	0.00	-2.79
	Weitz	-0.36	0.00	-1.93	0.00	-2.29
Barrier	Stern	-1.79	0.49	-0.30	0.62	-0.98
	HMT	-0.94	0.34	-1.62	0.29	-1.94
	Weitz	-0.53	0.20	-2.25	0.12	-2.46
Barrage	Stern	0.21	0.00	-0.81	1.77	1.17
	HMT	0.13	0.00	-0.75	0.90	0.27
	Weitz	0.08	0.00	-0.71	0.47	-0.16
Rail	Stern	-4.61	0.00	-20.06	0.00	-24.67
	HMT	-1.92	0.00	-18.03	0.00	-19.95
	Weitz	-0.83	0.00	-16.28	0.00	-17.11
Airport	Stern	-5.62	-10.54	99.90	-107.02	-23.29
	HMT	-2.16	-3.64	35.18	-43.65	-14.28
	Weitz	-0.74	-1.01	9.51	-15.70	-7.94

⁵ Note the HM Treasury rate reduces to 3.0 per cent in year 31 and 2.5 per cent in year 75, creating a slight movement towards the Stern rate and away from the Weitzman rate in each case.

⁶ The exceptions are the road monetary attribute, which is the most stable (varying only 1 per cent as it contains only capital costs which are assumed to occur in the first four years) and the barrage monetary attribute which is balanced by the interaction of positive and negative impacts.

The first exceptional result is for the barrier, where the Weitzman total result is larger, and the Stern total result smaller, than that for the HM Treasury rate. This is because of its monetary attribute and indicators. The capital cost of the barrier is assumed to occur in the first year and therefore 100 per cent of its value is recognised in all three discount cases. In contrast, the operational benefits of the barrier (through avoided flood maintenance) occur in later years and are discounted. These positive benefits are therefore smaller in the Weitzman case and larger in the Stern case. This results in the monetary attribute being more negative in the Weitzman case where there are less benefits to balance the operational cost, and less negative in the Stern case when the benefits are more highly recognised. These monetary attribute results are sufficiently large to create a similar effect in the total results.

The second exceptional result is for the barrage, where the total result becomes negative in the Weitzman case. This is due to the balancing effect of positive and negative indicators within the monetary attribute. The (negative) monetary attribute result therefore remains relatively stable while the (positive) service and environmental attribute results fluctuate with the discount rate, becoming larger in the Stern case and smaller in the Weitzman case. This leads to a much larger positive total result in the Stern case (4.3 times the HM Treasury result) and a negative result in the Weitzman case.

7.4.3 The results of discount rate uncertainty on the portfolio appraisal

Comparing the results of the airport's individual asset appraisal with its portfolio equivalent (see Table 7.2)⁷ we can see that the total portfolio result is less stable as the discount rate changes. In the single asset appraisal, the monetary and service attribute results continue to balance each other under the magnification of the Stern rate and reduction of the Weitzman rate. The

⁷ Equivalent to our portfolio analysis in Chapter 6.

Weitzman total result is therefore only approximately half that of the HM Treasury total result and the Stern total result is only 1.6 times greater than the HM Treasury total result. In comparison, in the portfolio case, the service impacts are significantly reduced and no longer balance the large monetary benefits. The portfolio Weitzman total result is therefore less than a quarter of the HM Treasury total result and the Stern total result is over 3 times greater than the HM Treasury total result.

Table 7.2 – Individual asset and portfolio appraisal results for the airport with three discount rates applied

Asset	Discount Rate	Environmental (£bn)	Social (£bn)	Monetary (£bn)	Service (£bn)	Total (£bn)
Airport (Individual asset)	Stern	-5.62	-10.54	99.90	-107.02	-23.29
	HMT	-2.16	-3.64	35.18	-43.65	-14.28
	Weitz	-0.74	-1.01	9.51	-15.70	-7.94
Airport (Portfolio)	Stern	-1.16	-2.52	107.05	-7.48	95.87
	HMT	-0.32	-0.85	37.49	-4.48	31.85
	Weitz	0.01	-0.22	10.07	-2.44	7.42

A lower discount rate is usually associated with a more environmentally sustainable approach (see Chapter 2); however, two results within Table 7.2 call this into question. Firstly, the Weitzman rate causes the environmental effects of the portfolio airport to become positive. In the HM Treasury and Stern cases the positive result of the noise indicator is slowly eroded by growth in the other (negative) environmental factors⁸. The yearly environmental total becomes negative in 2036, with the negative effects accrued after this point overwhelming the previously accrued benefits. In the Weitzman case, the present value in 2036 is only 22 per cent of the in-year value realised. The negative effects are therefore more strongly affected by the discount rate, allowing the total result to remain positive.

⁸ Particularly the carbon dioxide emissions, where the positive reduction in airport electricity use is eroded by the increased use of road transport as demand for the airport grows.

The second effect is that the Stern rate causes the monetary benefits of the airport to increase their domination of all other results. Here, while the low discount rate allows long-term effects to the environment and future catastrophic events to be captured, in the case of assets with decadal operational lives it also captures their service and monetary benefits over this period. The low discount rate does not prioritise projects with low long-term environmental impacts in this case, but rather those with long-term benefits which outweighing these effects. It must therefore be remembered that in the case of assets with long operational lives, a low interest rate will prioritise intergenerational equity, but not necessarily environmental sustainability.

7.4.4 The results of discount rate uncertainty on the pathway appraisal

The pathway results are shown in Table 7.3 - Table 7.6. A negative percentage change reflects that the result is of smaller magnitude than the HM Treasury case (as would be expected in the Weitzman case) and a positive percentage change reflects that the result is of larger magnitude than the HM Treasury case (as would be expected in the Stern case). Shading has been used to indicate whether the change improves the pathway result (green) or worsens the pathway result (red). Starred values indicate that the change is sufficient to reverse the result of the attribute⁹.

⁹ Negative change of greater than 100 per cent.

Table 7.3 – Base population pathway results for environmental attribute with percentage change for Weitzman and Stern discount rates

Pathway Family	Base Result for Environmental Minima (£m)	Change in Environmental Minima		Base Result for Environmental Maxima (£m)	Change in Environmental Maxima	
		Wietzman	Stern		Wietzman	Stern
Minor Road	-£2,405.2	-66.3%	165.9%	-£392.5	-63.3%	161.8%
Minor Road, Flood Barrier Only	-£1,094.4	-58.1%	133.6%	-£1,065.8	-59.3%	136.8%
Minor Road, Flood Barrier with Gen	-£990.4	-59.8%	140.0%	-£961.9	-61.1%	143.8%
Minor Road, Flood Barrier with Gen and Road	-£990.4	-59.8%	140.0%	-£961.9	-61.1%	143.8%
Minor Road, Flood Barrier with Gen and Rail	-£2,405.2	-66.3%	165.9%	-£859.0	-65.5%	157.7%
Minor Road with Fully Integrated Barrier	-£2,405.2	-66.3%	165.9%	-£859.0	-65.5%	157.7%
Minor Road with Fully Integrated Barrier and Comm Rail	-£2,274.3	-66.7%	167.6%	-£2,106.0	-69.7%	178.2%
Minor Road with Fully Integrated Barrier and HS Rail	-£2,313.0	-66.5%	167.0%	-£2,136.6	-69.6%	177.8%
Minor Road with Fully Integrated Barrier and Full Rail	-£2,405.2	-66.3%	165.9%	-£2,212.0	-69.5%	177.3%
Major Road	-£4,575.6	-68.4%	170.5%	-£784.9	-63.3%	161.8%
Major Road, Flood Barrier Only	-£2,716.5	-65.0%	157.8%	-£1,429.8	-61.3%	146.1%
Major Road, Flood Barrier with Gen	-£2,612.5	-65.9%	161.2%	-£1,325.8	-62.7%	151.9%
Major Road, Flood Barrier with Gen and Road	-£3,319.4	-67.2%	164.0%	-£1,325.8	-62.7%	151.9%
Major Road, Flood Barrier with Gen and Rail	-£4,575.6	-68.4%	170.5%	-£1,196.3	-66.9%	165.3%
Major Road with Fully Integrated Barrier	-£4,575.6	-68.4%	170.5%	-£1,196.3	-66.9%	165.3%
Major Road with Fully Integrated Barrier and Comm Rail	-£3,195.1	-67.1%	167.5%	-£2,443.4	-69.8%	179.1%
Major Road with Fully Integrated Barrier and HS Rail	-£4,575.6	-68.4%	170.5%	-£2,473.9	-69.7%	178.8%
Major Road with Fully Integrated Barrier and Full Rail	-£3,326.0	-66.8%	166.3%	-£2,549.4	-69.6%	178.3%
Major Road with Airport	-£4,575.6	-68.4%	170.5%	-£2,014.6	-68.4%	171.7%
Major Road, Flood Barrier and Airport	-£2,716.5	-65.0%	157.8%	-£2,716.5	-65.0%	157.8%
Major Road, Flood Barrier with Gen and Airport	-£2,612.5	-65.9%	161.2%	-£2,612.5	-65.9%	161.2%
Major Road, Flood Barrier (Gen and Road) and Airport	-£3,319.4	-67.2%	164.0%	-£2,612.5	-65.9%	161.2%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£4,575.6	-68.4%	170.5%	-£2,536.2	-67.2%	165.2%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£4,575.6	-68.4%	170.5%	-£2,536.2	-67.2%	165.2%

Table 7.4 – Base population pathway results for social attribute with percentage change for Weitzman and Stern discount rates

Pathway Family	Base Result for Social Minima (£m)	Change in Social Minima		Base Result for Social Maxima (£m)	Change in Social Maxima	
		Wietzman	Stern		Wietzman	Stern
Minor Road	£0.0	0.0%	0.0%	£327.6	-41.2%	47.3%
Minor Road, Flood Barrier Only	£327.6	-41.2%	47.3%	£327.6	-41.2%	47.3%
Minor Road, Flood Barrier with Gen	£327.6	-41.2%	47.3%	£327.6	-41.2%	47.3%
Minor Road, Flood Barrier with Gen and Road	£327.6	-41.2%	47.3%	£327.6	-41.2%	47.3%
Minor Road, Flood Barrier with Gen and Rail	£288.4	-43.3%	49.9%	£288.4	-43.3%	49.9%
Minor Road with Fully Integrated Barrier	£288.4	-43.3%	49.9%	£288.4	-43.3%	49.9%
Minor Road with Fully Integrated Barrier and Comm Rail	£288.4	-43.3%	49.9%	£288.4	-43.3%	49.9%
Minor Road with Fully Integrated Barrier and HS Rail	£288.4	-43.3%	49.9%	£288.4	-43.3%	49.9%
Minor Road with Fully Integrated Barrier and Full Rail	£288.4	-43.3%	49.9%	£288.4	-43.3%	49.9%
Major Road	-£3,327.8	-74.9%	202.7%	£327.6	-41.2%	47.3%
Major Road, Flood Barrier Only	-£1,474.9	-77.2%	214.9%	£327.6	-41.2%	47.3%
Major Road, Flood Barrier with Gen	-£1,474.9	-77.2%	214.9%	£327.6	-41.2%	47.3%
Major Road, Flood Barrier with Gen and Road	-£3,327.8	-74.9%	202.7%	£327.6	-41.2%	47.3%
Major Road, Flood Barrier with Gen and Rail	-£3,327.8	-74.9%	202.7%	£288.4	-43.3%	49.9%
Major Road with Fully Integrated Barrier	-£3,327.8	-74.9%	202.7%	£288.4	-43.3%	49.9%
Major Road with Fully Integrated Barrier and Comm Rail	-£613.8	-84.9%	253.3%	£288.4	-43.3%	49.9%
Major Road with Fully Integrated Barrier and HS Rail	-£3,200.3	-75.0%	203.2%	£288.4	-43.3%	49.9%
Major Road with Fully Integrated Barrier and Full Rail	-£613.8	-84.9%	253.3%	£288.4	-43.3%	49.9%
Major Road with Airport	-£3,327.8	-74.9%	202.7%	-£117.9	-129.9%*	485.8%
Major Road, Flood Barrier and Airport	-£1,474.9	-77.2%	214.9%	-£1,474.9	-77.2%	214.9%
Major Road, Flood Barrier with Gen and Airport	-£1,474.9	-77.2%	214.9%	-£1,474.9	-77.2%	214.9%
Major Road, Flood Barrier (Gen and Road) and Airport	-£3,327.8	-74.9%	202.7%	-£1,474.9	-77.2%	214.9%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£3,327.8	-74.9%	202.7%	-£117.9	-129.9%*	485.8%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£3,327.8	-74.9%	202.7%	-£117.9	-129.9%*	485.8%

Table 7.5 – Base population pathway results for monetary attribute with percentage change for Weitzman and Stern discount rates

Pathway Family	Base Result for Monetary Minima (£m)	Change in Monetary Minima		Base Result for Monetary Maxima (£m)	Change in Monetary Maxima	
		Wietzman	Stern		Wietzman	Stern
Minor Road	-£19,723.7	-17.9%	18.6%	-£861.8	28.3%	-117.3%*
Minor Road, Flood Barrier Only	-£1,057.8	40.0%	-104.8%*	-£861.8	39.4%	-117.3%*
Minor Road, Flood Barrier with Gen	-£1,706.7	18.2%	-56.7%	-£1,510.7	15.0%	-57.6%
Minor Road, Flood Barrier with Gen and Road	-£2,099.7	12.0%	-43.3%	-£1,903.7	8.8%	-42.6%
Minor Road, Flood Barrier with Gen and Rail	-£19,611.4	-18.9%	19.2%	-£2,467.9	-9.9%	-11.3%
Minor Road with Fully Integrated Barrier	-£19,723.7	-17.9%	17.8%	-£2,580.2	-2.3%	-20.7%
Minor Road with Fully Integrated Barrier and Comm Rail	-£15,588.3	-16.6%	15.1%	-£13,260.6	-24.8%	26.0%
Minor Road with Fully Integrated Barrier and HS Rail	-£13,810.5	-16.1%	14.2%	-£11,760.6	-24.2%	24.7%
Minor Road with Fully Integrated Barrier and Full Rail	-£17,590.3	-17.6%	17.3%	-£14,950.0	-25.8%	28.4%
Major Road	-£20,391.2	-15.2%	17.7%	£22,867.7	-93.8%	261.5%
Major Road, Flood Barrier Only	-£1,725.4	76.1%	-67.5%	£9,921.3	-116.8%*	344.1%
Major Road, Flood Barrier with Gen	-£2,374.2	50.6%	-43.1%	£9,440.3	-120.8%*	358.6%
Major Road, Flood Barrier with Gen and Road	-£2,767.2	41.3%	-34.8%	£22,867.7	-93.8%	261.5%
Major Road, Flood Barrier with Gen and Rail	-£20,279.0	-16.2%	18.3%	£22,027.7	-96.1%	269.9%
Major Road with Fully Integrated Barrier	-£20,391.2	-15.2%	17.0%	£21,954.1	-97.1%	271.8%
Major Road with Fully Integrated Barrier and Comm Rail	-£16,255.8	-13.3%	14.1%	£13,557.7	-146.3%*	446.3%
Major Road with Fully Integrated Barrier and HS Rail	-£14,478.1	-9.7%	13.1%	£13,104.5	-143.4%*	434.0%
Major Road with Fully Integrated Barrier and Full Rail	-£18,257.9	-14.6%	16.3%	£11,868.3	-162.4%*	503.0%
Major Road with Airport	-£9,582.0	80.4%	-258.4%*	£19,709.6	-106.2%*	299.1%
Major Road, Flood Barrier and Airport	£8,938.7	-134.0%*	387.6%	£8,938.7	-134.0%*	387.6%
Major Road, Flood Barrier with Gen and Airport	£8,289.8	-143.1%*	416.2%	£8,289.8	-143.1%*	416.2%
Major Road, Flood Barrier (Gen and Road) and Airport	£7,896.8	-149.5%*	436.2%	£19,709.6	-106.2%*	299.1%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£9,469.7	79.5%	-260.3%*	£18,991.3	-108.4%*	307.9%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£9,582.0	80.4%	-259.9%*	£18,879.1	-110.0%*	311.1%

Table 7.6 – Base population pathway results for service attribute with percentage change for Weitzman and Stern discount rates

Pathway Family	Base Result for Service Minima (£m)	Change in Service Minima		Base Result for Service Maxima (£m)	Change in Service Maxima	
		Wietzman	Stern		Wietzman	Stern
Minor Road	£0.0	0.0%	0.0%	£1,035.6	-55.0%	114.7%
Minor Road, Flood Barrier Only	£279.4	-57.9%	119.0%	£279.4	-57.9%	119.0%
Minor Road, Flood Barrier with Gen	£1,035.6	-55.0%	114.7%	£1,035.6	-55.0%	114.7%
Minor Road, Flood Barrier with Gen and Road	£1,035.6	-55.0%	114.7%	£1,035.6	-55.0%	114.7%
Minor Road, Flood Barrier with Gen and Rail	£899.1	-59.6%	127.9%	£899.1	-59.6%	127.9%
Minor Road with Fully Integrated Barrier	£899.1	-59.6%	127.9%	£899.1	-59.6%	127.9%
Minor Road with Fully Integrated Barrier and Comm Rail	£899.1	-59.6%	127.9%	£899.1	-59.6%	127.9%
Minor Road with Fully Integrated Barrier and HS Rail	£899.1	-59.6%	127.9%	£899.1	-59.6%	127.9%
Minor Road with Fully Integrated Barrier and Full Rail	£899.1	-59.6%	127.9%	£899.1	-59.6%	127.9%
Major Road	-£41,005.2	-65.3%	149.7%	£1,035.6	-55.0%	114.7%
Major Road, Flood Barrier Only	-£20,655.9	-65.3%	149.7%	£279.4	-57.9%	119.0%
Major Road, Flood Barrier with Gen	-£20,116.3	-65.4%	149.9%	£1,035.6	-55.0%	114.7%
Major Road, Flood Barrier with Gen and Road	-£41,005.2	-65.3%	149.7%	£1,035.6	-55.0%	114.7%
Major Road, Flood Barrier with Gen and Rail	-£41,005.2	-65.3%	149.7%	£899.1	-59.6%	127.9%
Major Road with Fully Integrated Barrier	-£41,005.2	-65.3%	149.7%	£899.1	-59.6%	127.9%
Major Road with Fully Integrated Barrier and Comm Rail	-£2,432.9	-50.3%	63.3%	£899.1	-59.6%	127.9%
Major Road with Fully Integrated Barrier and HS Rail	-£40,126.2	-65.2%	149.1%	£899.1	-59.6%	127.9%
Major Road with Fully Integrated Barrier and Full Rail	-£2,432.9	-50.3%	63.3%	£899.1	-59.6%	127.9%
Major Road with Airport	-£41,005.2	-65.3%	149.7%	-£830.2	-43.9%	26.7%
Major Road, Flood Barrier and Airport	-£20,655.9	-65.3%	149.7%	-£20,655.9	-65.3%	149.7%
Major Road, Flood Barrier with Gen and Airport	-£20,116.3	-65.4%	149.9%	-£20,116.3	-65.4%	149.9%
Major Road, Flood Barrier (Gen and Road) and Airport	-£41,005.2	-65.3%	149.7%	-£20,116.3	-65.4%	149.9%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£41,005.2	-65.3%	149.7%	-£830.2	-43.9%	26.7%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£41,005.2	-65.3%	149.7%	-£830.2	-43.9%	26.7%

As expected, in most cases, the Weitzman rate causes the magnitude of the pathway result to decrease and the Stern rate causes the magnitude to increase. The Stern rate therefore magnifies the existing results (positive become more positive, negative become more negative) while the Weitzman rate reduces them.

The largest effect is shown from the Stern rate acting on the social attribute maxima (see Table 7.4) for the major road, barrier with rail crossing/integrated barrier and airport pathway family (486 per cent increase in cost) and the monetary attribute maxima (see Table 7.5) for the major road, integrated barrier and full rail pathway family (503 per cent increase in benefit). In both cases the pathways allow for the maximum number of assets, creating the opportunity for costs and benefits to be delayed until the discount rate is greater, increasing its effect on them. In the case of the social maxima, the barrier is implemented as soon as possible, maximising its security benefit, while the airport is implemented as late as possible minimising its safety effect. The percentage change is more than twice that of the other airport pathway families (215 per cent change) where two fewer assets can be implemented and therefore the airport safety impacts are brought forward by two delivery points (10 years). In the case of the monetary maxima, all assets are delayed, being developed only when the airport is implemented. This minimises the effect of the asset costs, while ensuring the benefits of the airport are created as soon as possible, maximising their benefit.

Step changes can also be seen when indicators within one attribute group balance each other, reducing the impact of the discount rate change. For example, in the Stern case, the service attribute minima (see Table 7.6) for the major road with fully integrated barrier and commuter rail/full rail pathway families show a percentage change of only 63 per cent, while that for the similar pathways with the high speed rail development show a 149 per cent change. The high speed rail development does not offer the potential for more asset developments than the

commuter rail, therefore the difference is purely due to the calculation of the service attribute indicators. In both cases, the negative capacity and reliability effects of the airport on the existing road network are partially balanced by the positive service benefits of the airport itself and the rail development. However, the positive and negative effects are more closely balanced in the commuter rail and full rail pathways. Here, the multiplication effect of the Stern discount rate affects the two counteracting indicators more evenly and the resulting percentage change is much smaller. Similar effects can be seen in the Stern service maxima pathways for the airport (Table 7.6), with those allowing rail investment (and hence with more balanced service indicators) showing a smaller percentage change¹⁰. This is despite these pathways requiring more assets to be implemented and therefore the potential for effects to be delayed until the discount rate has a greater effect.

Exceptions to the expected relationship are highlighted in the monetary attribute results (see Table 7.5). The relationship is reversed for four groups of pathway families: both the minor and major road pathway families with barrier but no rail crossing (minimum monetary results); the minor road with no rail crossing pathway families (maximum monetary result); and the major road, flood barrier with rail crossing and airport pathway families (minimum monetary result)¹¹. The first three of these pathway groups reflect the reversal seen in the barrier single asset appraisal monetary result (see Table 7.1). However, the effect is magnified in the pathways where more assets can be implemented, without introducing large long-term benefits. The (negative) capital costs are therefore larger than in the single asset case and remain largely unaffected by the change in discount rate, being early in the appraisal period. In contrast, the long-term (positive) monetary benefits of the barrier are still strongly affected by the discount rate change. The positive benefits are therefore smaller in the Weitzman case making the

¹⁰ 27 per cent compared to 150 per cent.

¹¹ Note this includes the major road with airport pathway as that highlighted also includes the other assets.

monetary result *more* negative, and larger in the Stern case, making the monetary result *less* negative.

The final reversal group reflects a similar case. The minimum monetary result for the major road, flood barrier with rail crossing and airport pathway family is where the full rail development is implemented in two stages (taking the option to expand) and the airport is only developed to phase one. The delay in implementing assets causes the change in discount rate to have a greater effect on the long-term benefits. The Weitzman results are therefore *more* negative than the HM Treasury case (benefits are more highly discounted), while the Stern results sufficiently recognise the benefits for the monetary minima to become positive.

In addition, for two pathway families, the monetary maxima is improved by both the Stern and Weitzman rates. These are the minor road with flood barrier and rail crossing pathway family and the minor road with fully integrated barrier pathway family (see Table 7.5). Under both discount rates the maxima pathway is where the road and barrier assets are implemented together in one group with no other assets implemented. We would expect the Stern rate to magnify the effects of the HM Treasury rate, giving a larger negative result. However, in line with the reversal discussion above, the Stern rate magnifies the monetary benefits of the barrier making the result more positive. In the Weitzman case, where the long-term benefits of the barrier are reduced, so too are the capital costs. These are relatively small and as both are delayed until the barrier can be implemented, both are reduced by the larger discount rate. This reduction is sufficient for the long-term benefits of the barrier to become comparatively larger, again reducing the HM Treasury negative result.

The reversal of a benefit to a cost and vice versa is seen in 23 pathway families, of which 13 are within the monetary maxima (Table 7.5). Eleven of these are due to the Weitzman rate

discounting the long-term benefits of the assets and two are from the Stern rate magnifying the cost savings of the barrier. Seven of the pathway families are within the monetary minima, with three (as already discussed above) due to the Weitzman rate discounting the long-term benefits of the airport and rail pathways. Together this means that all of the rail and/or airport pathways give a negative monetary result in the Weitzman case. Indeed only the social maxima is positive for the airport pathway families in the Weitzman case (see Table 7.7). These social maxima results are the final three reversed results, with the Weitzman rate heavily discounting the safety costs of the airport such that they are outweighed by the security benefits of the barrier.

Table 7.7 – Major road with airport pathway results for the three discount rates

Discount Rate	Pathway Family Result	Environmental (£bn)	Social (£bn)	Monetary (£bn)	Service (£bn)
Stern	Minima	-£12.4	-£10.1	£15.2	-£102.4
	Maxima	-£5.5	-£0.7	£78.7	-£1.1
HMT	Minima	-£4.3	-£3.3	-£9.6	-£41.0
	Maxima	-£2.0	-£0.1	£19.7	-£0.8
Weitz	Minima	-£1.4	-£0.8	-£17.3	-£14.2
	Maxima	-£0.6	£0.0	-£1.2	-£0.5

Considering the effects of the rate changes on the pathways more generally, Table 7.7 suggests that use of the Weitzman rate would deter investment in any airport pathways; however, the maxima are small and investment may be taken forward on other political or macro-economic grounds. The maxima in the Stern case are favourable; however the minima for the service attribute would outweigh any other benefits, therefore would need to be explored.

7.5 The system effects of uncertain population change

7.5.1 The uncertainty of the population projection

Our first step in undertaking a sensitivity analysis of the population projection is to estimate its uncertainty, producing a bounding of its possible values over time. This is more straightforward than estimating the uncertainty of the discount rate, particularly in the short-term where previous estimates can be examined for accuracy¹². However, population predictions are not normally made for the 100 year timeframe considered herein and simple extrapolations of shorter projections are likely to produce very wide estimates that may not reflect actual long-term projections.

An alternative approach is to vary the parameters of an existing population projection to account for their uncertainty. We choose to take this approach, making use of the high and low population projections developed from the UK census model, the base projection of which is already used within our system model and prior analyses. As we noted in Chapter 4, the UK census is the most complete dataset of the UK population. Their associated population projections are validated against this dataset and are updated regularly in line with the results of each census. As the government approved dataset they also form the basis for all sector projections, providing internal consistency. The high and low census population projections have been geographically disaggregated by the Infrastructure Transitions Research Consortium (ITRC) Fast Track Analysis (Hall et al., 2012a), allowing us to apply the disaggregated projections for South East England and London (see Figure 7.8 and Figure 7.9 respectively) in the same manner as that used for the base projection in our prior analyses¹³.

¹² See de Neufville and Scholtes' (2011) for a worked example of this method.

¹³ The disaggregated projections are applied at a local authority level using the 2011 Census data as a datum and keeping values constant after 2080.

Figure 7.8 – ITRC population projections for South East England

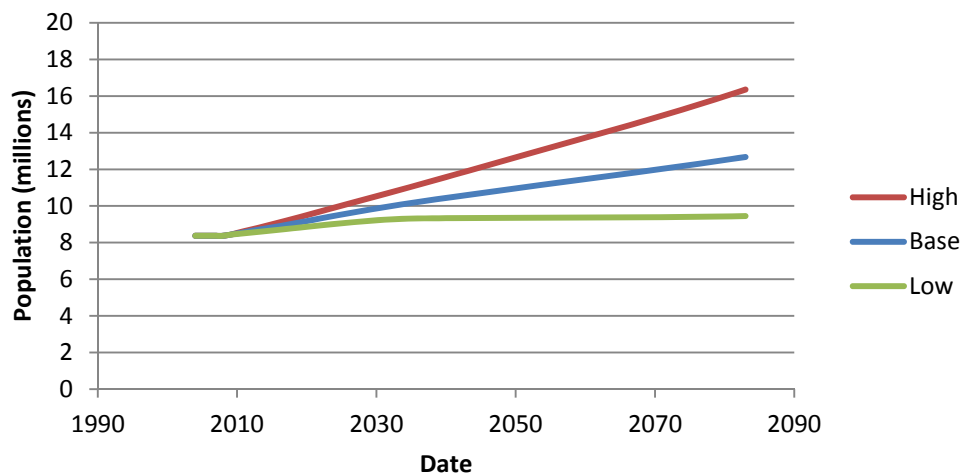
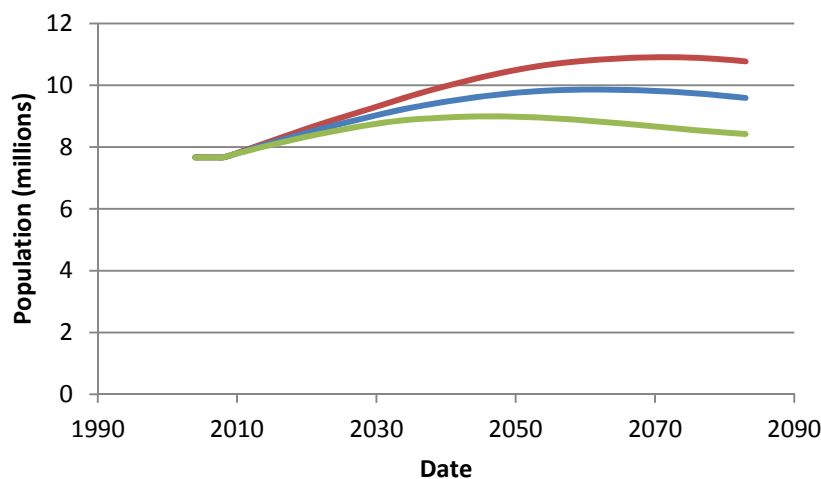


Figure 7.9 – ITRC population projections for London



7.5.2 The effect of population uncertainty on the system model

As noted in Section 7.2.1, population affects the system model in two ways. Firstly the population creates demand for the infrastructure services, utilising the capacity created by the developments. The magnitude of eight of the model indicators are directly or partly reliant on this capacity utilised¹⁴. Secondly, population density determines the number of people affected

¹⁴ In our model: Revenue, petrol taxes, air and water pollution created, carbon dioxide emissions, capacity utilised, reliability and use related safety.

by the externalities and physical protection effects of the infrastructure assets. As these social and environmental effects are valued through individual willingness to pay, their indicator values will be directly related to population.

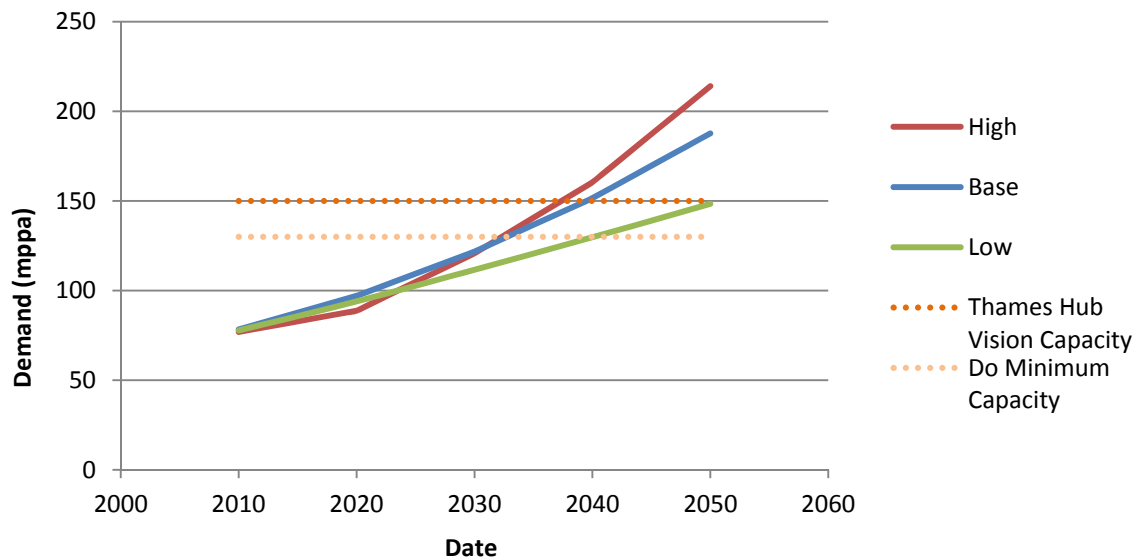
We can therefore expect each of the individual infrastructure assets in our case study to be impacted by a change in the population projection. The inherent demand for the road and rail assets would be expected to increase with population; however, as this is not included within the model, impacts will initially be limited to the direct effects of noise on the surrounding population¹⁵. As demand for the road and rail developments is increased by the system effects of the airport, more of the indicators will be impacted. For example, local externalities such as water and air pollution will be generated by this demand, but are also valued based on the population affected. In contrast, carbon dioxide emissions, as a national concern, are valued based on estimated emission trading prices rather than individual willingness to pay (see Chapter 5). It is therefore only dependent on demand rather than population directly. Similarly, the service effects (capacity utilised and reliability indicators), revenue and associated taxes (petrol duty) and impacts on safety will only be influenced via the demand generated.

In alignment with the method applied in Chapters 5 and 6, demand for air transport will be derived from the 2011 Department for Transport (DfT) UK aviation projections (Department for Transport, 2011b), with demand held constant after 2050. This dataset contains base, high and low demand requirements in accordance with census population projections. They will therefore be applied in the same manner as for the prior analyses, with the London hub airport assumed to remain at a consistent 64 per cent of total demand (Civil Aviation Authority, 2012). Demand will be limited by the available airport capacity. This will strongly constrain both the base and high population projections (see Figure 7.10). Therefore, for these two projections we

¹⁵ It is assumed that this noise is derived from demand transferred from other road or rail routes.

can expect a noticeable difference between the indicators that are affected by population directly and those that are affected by demand.

Figure 7.10 – London hub airport requirements (Department for Transport, 2011b)



It can also be seen from Figure 7.10 that the high population projection has a slower initial population growth than the other projections. However, the earliest implementation date for the Thames Hub Vision airport is 2028 (see Appendix A), by which point the high population projection is only 2.4 million passengers per annum less than the base projection. The two projections equalise in 2031, with the high projection reaching the airport's capacity limit in 2038, two years prior to the base projection. The effect of the high projection's lower growth rate is therefore likely to be strongly constrained by the implementation time of the airport.

In contrast, while the tidal generation does produce a demand dependant service, it is predicted that this will be fully utilised in all three population projections. As noted in Chapter 4, energy demand is increasing in the UK while capacity is being reduced by the closure of old plants (Infrastructure UK, 2011). There is therefore likely to be a strong demand for new sources of generation to provide for the deficit and future growth. In addition, the tidal generation would be favoured by carbon dioxide emission reduction legislation, prioritising its use over electricity

generated from fossil fuels. The utilisation of the energy generated by the tidal array/barrage is therefore assumed to be independent of population and will not be affected by the projections.

Whether tidal generation can be included either as part of the barrier or a separate array, the integrated/separate asset(s) will cause water pollution. As the water quality indicator is monetised on the basis of the local population's willingness to pay (see Chapter 5), this will be affected by the population projections. The security provided by the barrier would also be affected by the population projections. However, this data is taken from the TE2100 estimates and the risk profiles for the modelled extreme events are unknown. Without this data (which would have been highly uncertain, see Chapter 5 discussion), the change in security effects¹⁶ cannot be predicted¹⁷. They have therefore been assumed to be the same for each of the population projections.

We can see the effects of population on the modelled assets by considering the change in the single asset appraisal (see Table 7.8). As noted, many of the road, barrier, barrage and rail model indicators are not dependent on population in this state with induced demand ignored (road and rail) or assumed constant (barrier and barrage). Differences can only be noted in the environmental attribute, with increasing population magnifying the impacts of the road, barrier and rail assets.

In contrast, all of the airport's attributes are dependent on population, it therefore has a higher total uncertainty than the other assets. Two attributes (social and service) follow the expected relationship with increasing population magnifying the attribute impacts/benefits. However, the

¹⁶ Change in population living on the Thames floodplain and therefore protected by the barrier.

¹⁷ An early event would show little difference in population, while a later event could result in a significant change, particularly given that the presence of the barrier asset may encourage population growth in the protected region. We will consider the spatial effects of the developments further in Chapter 8.

environmental and monetary attributes have a more complex relationship. Costs/values increase with population from the low to the base case, but fall again as population rates increase from base to high. In the environmental case, the increase in noise *benefits* (linked to population directly) is sufficient to outweigh the increase in carbon dioxide and air pollution *impacts* (linked to demand). In the monetary case, the operational cost, revenues and tax are all linked to demand, which is quickly constrained by the airport capacity. Here, the value multiplier is greater for the operational cost, causing the monetary value to be slightly lower in the high population case.

Table 7.8 – Individual asset appraisal results with three population growth rates applied

Asset	Discount Rate	Environmental (£bn)	Social (£bn)	Monetary (£bn)	Service (£bn)	Total (£bn)
Road	Low	-0.74	0.00	-1.95	0.00	-2.68
	Base	-0.85	0.00	-1.95	0.00	-2.79
	High	-0.96	0.00	-1.95	0.00	-2.91
Barrier	Low	-0.89	0.34	-1.62	0.29	-1.88
	Base	-0.94	0.34	-1.62	0.29	-1.94
	High	-1.00	0.34	-1.62	0.29	-1.99
Barrage	Low	0.13	0.00	-0.75	0.90	0.27
	Base	0.13	0.00	-0.75	0.90	0.27
	High	0.13	0.00	-0.75	0.90	0.27
Rail	Low	-1.76	0.00	-18.03	0.00	-19.79
	Base	-1.92	0.00	-18.03	0.00	-19.95
	High	-2.09	0.00	-18.03	0.00	-20.13
Airport	Low	-2.03	-3.41	34.81	-41.08	-11.71
	Base	-2.16	-3.64	35.18	-43.65	-14.28
	High	-2.02	-3.66	35.17	-43.78	-14.28

7.5.3 The results of population uncertainty on the portfolio appraisal

Three of the relationships shown in the individual airport asset appraisal (Table 7.8) are reflected in the portfolio appraisal (Table 7.9). The magnitude of the social attribute result increases with population, while the magnitude of the environmental and monetary attribute results increase from the low to the base projection then decrease from the base projection to the high

projection. However, as the portfolio case includes the system effects of the airport and rail infrastructure we can see that the magnitude of change between projections has altered. The changes in the environmental and social attributes are smaller in the portfolio case as more components are added to the indicators, balancing some of the effects. For example, in the social case, while population increases road accidents, it also increases rail use which decreases accidents.

Table 7.9 – Individual asset and portfolio appraisal results for the airport with three population growth rates applied

Asset	Discount Rate	Environmental (£bn)	Social (£bn)	Monetary (£bn)	Service (£bn)	Total (£bn)
Airport (Individual asset)	Low	-2.03	-3.41	34.81	-41.08	-11.71
	Base	-2.16	-3.64	35.18	-43.65	-14.28
	High	-2.02	-3.66	35.17	-43.78	-14.28
Airport (Portfolio)	Low	-0.25	-0.72	37.05	-3.91	32.17
	Base	-0.32	-0.85	37.49	-4.48	31.85
	High	-0.19	-0.86	37.49	-4.40	32.04

In contrast, the difference between the low and base value in the monetary attribute has increased. The additional rail revenues outweigh any detrimental tax losses (due to decreasing petrol duty) magnifying the beneficial monetary effects of the individual airport asset. However, the population increase from the base to the high projection has less effect than the individual case. Here the benefits are limited by the capacity constraints of the airport and the balancing effect of the loss in petrol duty is felt more strongly.

The service attribute, which for the individual asset appraisal showed the typical relationship, in the portfolio case shows the most negative result in the base population projection. Here, again, the capacity constraints of the airport limit the reliability effects of the airport, with the high population case reaching capacity only two years before the base population case. However, this generates greater benefits from increased rail use and decreased road use, along with

additional capacity utilisation benefits from the airport. These outweigh the additional reliability costs of the airport and produce a less negative service result.

Adding the attribute results, the total is the least in the base case, suggesting that the population uncertainty may improve the value of the developments.

7.5.4 The results of population uncertainty on the pathway appraisal

As expected, the results (see Table 7.10-Table 7.13) demonstrate how the capacity constraints of infrastructure services can restrict the effects of uncertainty. The constraint of air traffic demand in the high and base projections (see Figure 7.10) can be seen in the results, with the percentage change between the base and low projections being an order of magnitude larger than that between the base and high projections for those attributes with indicators only dependant on demand (service, social and monetary attributes). The environmental attribute includes indicators reliant on both population directly (noise and water quality) and indirectly through demand (carbon emissions and air quality). The effect of a change in the population projection on the environmental attribute is therefore variable depending on the value and magnitude of the different indicators. However, for most of its pathways (see Table 7.10), the percentage change results are more comparable in magnitude and are of larger magnitude than for the other attributes. This again presents the importance of maintaining segregation between the attribute types, with the already highly uncertain environmental attribute showing a greater sensitivity to system variable change.

Table 7.10 – Base population pathway results for environmental attribute with percentage change for low and high population projections

Pathway Family	Base Result for Environmental Minima (£m)	Change in Environmental Minima		Base Result for Environmental Maxima (£m)	Change in Environmental Maxima	
		Low	High		Low	High
Minor Road	-£2,405.2	-10.9%	11.7%	-£392.5	-13.7%	15.0%
Minor Road, Flood Barrier Only	-£1,094.4	-9.9%	10.4%	-£1,065.8	-10.1%	10.6%
Minor Road, Flood Barrier with Gen	-£990.4	-10.9%	11.5%	-£961.9	-11.2%	11.7%
Minor Road, Flood Barrier with Gen and Road	-£990.4	-10.9%	11.5%	-£961.9	-11.2%	11.7%
Minor Road, Flood Barrier with Gen and Rail	-£2,405.2	-10.9%	11.7%	-£859.0	-12.2%	12.8%
Minor Road with Fully Integrated Barrier	-£2,405.2	-10.9%	11.7%	-£859.0	-12.2%	12.8%
Minor Road with Fully Integrated Barrier and Comm Rail	-£2,274.3	-11.5%	12.4%	-£2,106.0	-12.3%	13.1%
Minor Road with Fully Integrated Barrier and HS Rail	-£2,313.0	-11.3%	12.1%	-£2,136.6	-12.1%	12.9%
Minor Road with Fully Integrated Barrier and Full Rail	-£2,405.2	-10.9%	11.7%	-£2,212.0	-11.7%	12.5%
Major Road	-£4,575.6	-9.6%	4.7%	-£784.9	-13.7%	15.0%
Major Road, Flood Barrier Only	-£2,716.5	-7.5%	3.4%	-£1,429.8	-11.3%	12.0%
Major Road, Flood Barrier with Gen	-£2,612.5	-7.8%	3.5%	-£1,325.8	-12.1%	12.9%
Major Road, Flood Barrier with Gen and Road	-£3,319.4	-8.6%	1.5%	-£1,325.8	-12.1%	12.9%
Major Road, Flood Barrier with Gen and Rail	-£4,575.6	-9.6%	4.7%	-£1,196.3	-13.2%	14.0%
Major Road with Fully Integrated Barrier	-£4,575.6	-9.6%	4.7%	-£1,196.3	-13.2%	14.0%
Major Road with Fully Integrated Barrier and Comm Rail	-£3,195.1	-11.1%	7.4%	-£2,443.4	-12.7%	13.7%
Major Road with Fully Integrated Barrier and HS Rail	-£4,575.6	-9.6%	4.7%	-£2,473.9	-12.6%	13.5%
Major Road with Fully Integrated Barrier and Full Rail	-£3,326.0	-10.7%	7.1%	-£2,549.4	-12.2%	13.1%
Major Road with Airport	-£4,575.6	-9.6%	4.7%	-£2,014.6	-7.5%	1.9%
Major Road, Flood Barrier and Airport	-£2,716.5	-7.5%	3.4%	-£2,716.5	-7.5%	3.4%
Major Road, Flood Barrier with Gen and Airport	-£2,612.5	-7.8%	3.5%	-£2,612.5	-7.8%	3.5%
Major Road, Flood Barrier (Gen and Road) and Airport	-£3,319.4	-8.6%	1.5%	-£2,612.5	-7.8%	3.5%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£4,575.6	-9.6%	4.7%	-£2,536.2	-8.0%	3.6%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£4,575.6	-9.6%	4.7%	-£2,536.2	-8.0%	3.6%

Table 7.11 – Base population pathway results for social attribute with percentage change for low and high population projections

Pathway Family	Base Result for Social Minima (£m)	Change in Social Minima		Base Result for Social Maxima (£m)	Change in Social Maxima	
		Low	High		Low	High
Minor Road	£0.0	0.0%	0.0%	£327.6	0.0%	0.0%
Minor Road, Flood Barrier Only	£327.6	0.0%	0.0%	£327.6	0.0%	0.0%
Minor Road, Flood Barrier with Gen	£327.6	0.0%	0.0%	£327.6	0.0%	0.0%
Minor Road, Flood Barrier with Gen and Road	£327.6	0.0%	0.0%	£327.6	0.0%	0.0%
Minor Road, Flood Barrier with Gen and Rail	£288.4	0.0%	0.0%	£288.4	0.0%	0.0%
Minor Road with Fully Integrated Barrier	£288.4	0.0%	0.0%	£288.4	0.0%	0.0%
Minor Road with Fully Integrated Barrier and Comm Rail	£288.4	0.0%	0.0%	£288.4	0.0%	0.0%
Minor Road with Fully Integrated Barrier and HS Rail	£288.4	0.0%	0.0%	£288.4	0.0%	0.0%
Minor Road with Fully Integrated Barrier and Full Rail	£288.4	0.0%	0.0%	£288.4	0.0%	0.0%
Major Road	-£3,327.8	-6.7%	0.6%	£327.6	0.0%	0.0%
Major Road, Flood Barrier Only	-£1,474.9	-7.5%	0.7%	£327.6	0.0%	0.0%
Major Road, Flood Barrier with Gen	-£1,474.9	-7.5%	0.7%	£327.6	0.0%	0.0%
Major Road, Flood Barrier with Gen and Road	-£3,327.8	-6.7%	0.6%	£327.6	0.0%	0.0%
Major Road, Flood Barrier with Gen and Rail	-£3,327.8	-6.7%	0.6%	£288.4	0.0%	0.0%
Major Road with Fully Integrated Barrier	-£3,327.8	-6.7%	0.6%	£288.4	0.0%	0.0%
Major Road with Fully Integrated Barrier and Comm Rail	-£613.8	-20.1%	2.1%	£288.4	0.0%	0.0%
Major Road with Fully Integrated Barrier and HS Rail	-£3,200.3	-6.8%	0.6%	£288.4	0.0%	0.0%
Major Road with Fully Integrated Barrier and Full Rail	-£613.8	-20.1%	2.1%	£288.4	0.0%	0.0%
Major Road with Airport	-£3,327.8	-6.7%	0.6%	-£117.9	-52.2%	5.3%
Major Road, Flood Barrier and Airport	-£1,474.9	-7.5%	0.7%	-£1,474.9	-7.5%	0.7%
Major Road, Flood Barrier with Gen and Airport	-£1,474.9	-7.5%	0.7%	-£1,474.9	-7.5%	0.7%
Major Road, Flood Barrier (Gen and Road) and Airport	-£3,327.8	-6.7%	0.6%	-£1,474.9	-7.5%	0.7%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£3,327.8	-6.7%	0.6%	-£117.9	-52.2%	5.3%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£3,327.8	-6.7%	0.6%	-£117.9	-52.2%	5.3%

Table 7.12 – Base population pathway results for monetary attribute with percentage change for low and high population projections

Pathway Family	Base Result for Monetary Minima (£m)	Change in Monetary Minima		Base Result for Monetary Maxima (£m)	Change in Monetary Maxima	
		Low	High		Low	High
Minor Road	-£19,723.7	0.0%	0.0%	-£861.8	0.0%	0.0%
Minor Road, Flood Barrier Only	-£1,057.8	0.0%	0.0%	-£861.8	0.0%	0.0%
Minor Road, Flood Barrier with Gen	-£1,706.7	0.0%	0.0%	-£1,510.7	0.0%	0.0%
Minor Road, Flood Barrier with Gen and Road	-£2,099.7	0.0%	0.0%	-£1,903.7	0.0%	0.0%
Minor Road, Flood Barrier with Gen and Rail	-£19,611.4	0.0%	0.0%	-£2,467.9	0.0%	0.0%
Minor Road with Fully Integrated Barrier	-£19,723.7	0.0%	0.0%	-£2,580.2	0.0%	0.0%
Minor Road with Fully Integrated Barrier and Comm Rail	-£15,588.3	0.0%	0.0%	-£13,260.6	0.0%	0.0%
Minor Road with Fully Integrated Barrier and HS Rail	-£13,810.5	0.0%	0.0%	-£11,760.6	0.0%	0.0%
Minor Road with Fully Integrated Barrier and Full Rail	-£17,590.3	0.0%	0.0%	-£14,950.0	0.0%	0.0%
Major Road	-£20,391.2	0.0%	0.0%	£22,867.7	-1.6%	-0.0%
Major Road, Flood Barrier Only	-£1,725.4	0.0%	0.0%	£9,921.3	-2.2%	-0.0%
Major Road, Flood Barrier with Gen	-£2,374.2	0.0%	0.0%	£9,440.3	-2.3%	-0.0%
Major Road, Flood Barrier with Gen and Road	-£2,767.2	0.0%	0.0%	£22,867.7	-1.6%	-0.0%
Major Road, Flood Barrier with Gen and Rail	-£20,279.0	0.0%	0.0%	£22,027.7	-1.7%	-0.0%
Major Road with Fully Integrated Barrier	-£20,391.2	0.0%	0.0%	£21,954.1	-1.7%	-0.0%
Major Road with Fully Integrated Barrier and Comm Rail	-£16,255.8	0.0%	0.0%	£13,557.7	-3.2%	0.0%
Major Road with Fully Integrated Barrier and HS Rail	-£14,478.1	0.0%	0.0%	£13,104.5	-2.9%	-0.0%
Major Road with Fully Integrated Barrier and Full Rail	-£18,257.9	0.0%	0.0%	£11,868.3	-3.7%	0.0%
Major Road with Airport	-£9,582.0	1.8%	0.3%	£19,709.6	-1.8%	-0.0%
Major Road, Flood Barrier and Airport	£8,938.7	-2.4%	-0.0%	£8,938.7	-2.4%	-0.0%
Major Road, Flood Barrier with Gen and Airport	£8,289.8	-2.6%	-0.0%	£8,289.8	-2.6%	-0.0%
Major Road, Flood Barrier (Gen and Road) and Airport	£7,896.8	-2.7%	-0.0%	£19,709.6	-1.8%	-0.0%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£9,469.7	1.8%	0.3%	£18,991.3	-1.9%	-0.0%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£9,582.0	1.8%	0.3%	£18,879.1	-1.9%	-0.0%

Table 7.13 – Base population pathway results for service attribute with percentage change for low and high population projections

Pathway Family	Base Result for Service Minima (£m)	Change in Service Minima		Base Result for Service Maxima (£m)	Change in Service Maxima	
		Low	High		Low	High
Minor Road	£0.0	0.0%	0.0%	£1,035.6	0.0%	0.0%
Minor Road, Flood Barrier Only	£279.4	0.0%	0.0%	£279.4	0.0%	0.0%
Minor Road, Flood Barrier with Gen	£1,035.6	0.0%	0.0%	£1,035.6	0.0%	0.0%
Minor Road, Flood Barrier with Gen and Road	£1,035.6	0.0%	0.0%	£1,035.6	0.0%	0.0%
Minor Road, Flood Barrier with Gen and Rail	£899.1	0.0%	0.0%	£899.1	0.0%	0.0%
Minor Road with Fully Integrated Barrier	£899.1	0.0%	0.0%	£899.1	0.0%	0.0%
Minor Road with Fully Integrated Barrier and Comm Rail	£899.1	0.0%	0.0%	£899.1	0.0%	0.0%
Minor Road with Fully Integrated Barrier and HS Rail	£899.1	0.0%	0.0%	£899.1	0.0%	0.0%
Minor Road with Fully Integrated Barrier and Full Rail	£899.1	0.0%	0.0%	£899.1	0.0%	0.0%
Major Road	-£41,005.2	-5.9%	0.4%	£1,035.6	0.0%	0.0%
Major Road, Flood Barrier Only	-£20,655.9	-5.9%	0.4%	£279.4	0.0%	0.0%
Major Road, Flood Barrier with Gen	-£20,116.3	-6.0%	0.4%	£1,035.6	0.0%	0.0%
Major Road, Flood Barrier with Gen and Road	-£41,005.2	-5.9%	0.4%	£1,035.6	0.0%	0.0%
Major Road, Flood Barrier with Gen and Rail	-£41,005.2	-5.9%	0.4%	£899.1	0.0%	0.0%
Major Road with Fully Integrated Barrier	-£41,005.2	-5.9%	0.4%	£899.1	0.0%	0.0%
Major Road with Fully Integrated Barrier and Comm Rail	-£2,432.9	-20.6%	-0.5%	£899.1	0.0%	0.0%
Major Road with Fully Integrated Barrier and HS Rail	-£40,126.2	-6.0%	0.4%	£899.1	0.0%	0.0%
Major Road with Fully Integrated Barrier and Full Rail	-£2,432.9	-20.6%	-0.5%	£899.1	0.0%	0.0%
Major Road with Airport	-£41,005.2	-5.9%	0.4%	-£830.2	-30.2%	-0.7%
Major Road, Flood Barrier and Airport	-£20,655.9	-5.9%	0.4%	-£20,655.9	-5.9%	0.4%
Major Road, Flood Barrier with Gen and Airport	-£20,116.3	-6.0%	0.4%	-£20,116.3	-6.0%	0.4%
Major Road, Flood Barrier (Gen and Road) and Airport	-£41,005.2	-5.9%	0.4%	-£20,116.3	-6.0%	0.4%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£41,005.2	-5.9%	0.4%	-£830.2	-30.2%	-0.7%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£41,005.2	-5.9%	0.4%	-£830.2	-30.2%	-0.7%

While variation of the population projection does not change all the pathway results, for those it does, most reflect the typical response with increasing population magnifying the cost/impact of the base case. For example, the social attribute minima of the major road pathway family is -£3.3bn in the base case. This is reduced 6.7 per cent in the low population case (improving by £0.2bn to -£3.1bn) and increased 0.6 per cent in the high population case (worsening by £0.02bn to -£3.4bn), see Table 7.11¹⁸. These changes reflect how the increasing population, increases demand for the airports and therefore surface access routes, causing greater numbers of road accidents, while lowering population has the opposite effect. Similar relationships are shown for:

- The environmental attribute for all pathway families, due to the dominance of negative local externalities and their relationship with population through demand (air quality, carbon dioxide) and willingness to pay (air quality, noise, water quality);
- The social attribute maxima for the airport pathway families; here the negative safety effects of the surface access routes¹⁹ overwhelm the beneficial effects of the barrier, creating negative maxima which are related to airport demand;
- The monetary attribute maxima for major road pathways which implement commuter rail, but not the airport; where passenger revenues from the rail and airport assets outweigh any demand related operational cost increases; and
- The service attribute minima for all major road pathway families except those which include commuter rail and the service attribute maxima for airport pathway families excluding commuter rail infrastructure; here increasing population increases congestion on the roads with no or low level uptake of rail to counteract this effect.

¹⁸ Again, a negative percentage change reflects that the result is of a smaller magnitude than the base case and a positive percentage change reflects that the result is of larger magnitude than the base case. The shading is used to represent whether this change improves the pathway result (green) or worsens the pathway result (red).

¹⁹ Additional road accidents.

However, the combination of assets and system effects also produces some cases where the high and low population projection results are either both superior, or both inferior to the base projection. In these cases the separate assets and their system effects work to counterbalance the uncertainty, making the results more stable.

The examples of this behaviour are highlighted in Table 7.12 and Table 7.13. In Table 7.12, monetary attribute results of the high and low population projections are seen to be worse than the base case. While in Table 7.13, the service attribute results of the high and low population projections are seen to be better than the base case. In both examples, the unusual behaviour is due to two factors:

- The capacity constraints of the airport reducing the realisable demand growth in the high population case, making the high and base population results artificially similar; and
- The balancing of positive and negative indicators within the attribute.

In the case of the monetary attribute, the balancing factors are the tax revenues from increasing/decreasing road usage, revenues from the rail and airport assets²⁰ and the operational costs of the airport²¹. The taxes, rail revenues and landing fees are calculated directly from the model based on passenger demand and a projection of current rates and fares. These, therefore plateau at the same value in the base and high population cases as the demand is constrained by capacity. In contrast, the operational costs and 'other' airport revenues²² are estimated based on those given for 2012 within the Thames Hub Vision proposal documentation (Foster+Partners et al., 2011b). These have been projected by calculating a cost/revenue per

²⁰ Note that only half of the revenues are recorded under the monetary attribute, with the other half recorded under the service attribute.

²¹ The operational costs of the rail assets are assumed to be fixed.

²² Revenues other than landing fees, such as that from the restaurants within the airport building.

passenger at the 2012 demand level and multiplying by demand growth. This produces a different result per passenger for each projection, with the final operation cost and 'other' revenue being lower in the low population case and higher in the high population case. While the difference in cost/revenue per passenger is relatively small²³, this difference is realised over the lifetime of the asset and is sufficient to cumulatively change the impact of the increased/decreased population.

In the case of the monetary attribute minima, airport pathways with negative results relate to those which implement all rail assets, maximising the capital cost, but only implement the first phase of the airport, heavily restricting passenger capacity and hence revenue. Here, in the low population case, the lower operational costs compared to the base population projection are outweighed by the decreased revenues and taxes, resulting in a lower pathway result. In the high population case, the increased taxes and revenues are constrained by airport capacity, giving a similar result to the base case. While both the operational costs and the 'other' revenues are also constrained, the operational costs dominate making the final result more negative than the base case.

The monetary attribute minima airport pathways with a positive result relate to those which implement major roads, a barrier and the first stage of the airport. All travel to the airport is therefore by road, resulting in some tax benefits, but revenue benefits are restricted to the airport and the barrage, and are heavily constrained in the former case by capacity. The lower capital costs allow the results to be positive in all population projections; however, again, the decreased taxes and revenues in the low population case and the dominance of the operational costs in the high population case, cause both results to be worse than the base case.

²³ For example the additional revenue per passenger in the high population projection is £0.04 per passenger greater than that of the base case.

The monetary attribute maxima pathways show a similar relationship for all major road families without commuter rail infrastructure. Pathways implement the full airport where possible, minimising other assets and delaying them until the airport can be delivered, thereby minimising their capital costs. All results are positive and display the same balance of operational costs and revenues as described above. The only pathway families which show the expected positive/negative relationship are those where commuter rail is implemented. Here, the monetary results are lower than the 'without rail' pathway families; however, the addition of rail fares allows a slight increase in the high population result, despite reductions in tax earnings from petrol duty.

The service attribute minima for the pathways with commuter rail included (either through the full rail or single rail line alternatives) and the maxima pathways with rail and the airport produce the opposite effect of the monetary attribute, with both low and high population results being more favourable than the base case (see Table 7.13). Here the service attribute is dominated by the negative reliability effects of the airport's surface access demands on the existing road network. As the rail increases the accessibility of the airport, this reduces the demand on the road network and increases utilisation of the rail asset. The total negative service effect per person is therefore smaller in these pathways, allowing the complexity of the other indicator components to show. In particular, half of the 'other' revenue from the airport is recorded within the service attribute (capacity utilised indicator) and works against the reliability impacts of the airport on road network. In the low population case, the decreased reliability impacts on the road network dominate, but in the high population case, where the demand related effects are limited by the airport's capacity constraints, the long-term increased 'other' revenues create a slight improvement over the base case.

Finally, if we compare the results of the population uncertainty to those of the discount rate, we can see that, although the population projection is integral to the calculations and affects indicators both directly and indirectly, the effects of its uncertainty are much smaller. None of the changes are sufficient to change the results from a cost to a benefit (or vice versa) and only eight of the pathway families show changes greater than 15 per cent of their base value.

7.6 Conclusions and Implications

The uncertainty surrounding long-term infrastructure investments is recognised and has been investigated by other authors through scenario, sensitivity and real option analyses; however, all reviews have thus far been from a single sector and often single asset perspective. The purpose of this chapter was to analyse the uncertainty of such investments from a systems perspective. Its aims were to understand:

- The sources of uncertainty within our appraisal methodology;
- Which of these uncertainties have the most significant effects on the pathway results;
and
- How this effect manifests for the pathways and attributes over time.

We have completed these aims, reviewing the model inputs, determining that the discount rate and population growth rate are the most significant uncertainties and performing a sensitivity analysis on each of these factors.

Both types of uncertainty produced different effects in the individual asset case than in the portfolio and pathway cases. This highlights a further limitation of current approaches,

reinforcing the argument for a systems pathway approach and suggesting a systems uncertainty analysis is a worthwhile addition to the methodology.

Our results suggest that the discount rate is the most important uncertainty, with the ability to reverse the result of the appraisal in some cases. The analysis highlighted the importance of the timing of costs and benefits, with large variations in pathway family results depending on the opportunity to delay investment. Therefore our first confirmation is of the value of designing assets flexibly, allowing decisions to be delayed and assets implemented in stages as we better understand the uncertainties. However, more specifically aligned to this work, it confirms the importance of understanding the pathways generated by assets and the flexibility created by these if we are to ensure resilience to uncertainty.

In both sensitivity analyses, unexpected results were created by the system interactions of the pathways. In particular, both analyses produced attribute results that were better in *both* the extreme cases than in the base case. This suggests that it is possible to derive beneficial effects from uncertainty if we understand the system interactions and effects. For example, in the population uncertainty analysis, this result was derived by introducing the commuter rail asset into the major road pathways, reducing the negative effects of the airport and bringing the system effects into balance. Understanding such relationships could therefore help to ensure pathways were resilient to future change. However, such balancing can only be achieved by bringing the costs and impacts into greater alignment. The cost of providing such resilience to uncertainty is therefore that the design cannot be 'optimised' on benefits, potentially producing a worse base case result.

The results also highlight the benefits of the multi-attribute approach, with the segregated attributes showing different dependencies on the two uncertainties investigated. For example,

the environmental attribute, which is already known to be highly uncertain, was found to be more dependent on the population projection than the other attributes. Such segregation also allows the decision maker to observe where balancing effects are occurring and which attributes are driving changes in results, enabling a greater understanding of the system as a whole.

7.7 Next steps:

There are a number of possible extensions to the work conducted within this chapter; however, given the timeframe of this research, not all can be explored herein. Firstly we could investigate more of the uncertainties identified within Section 7.3 or their combination, through sensitivity analysis or one of the more complex uncertainty analyses outlined in Chapter 2. It is unlikely that the effects of all uncertainties and combinations could be rigorously explored²⁴ and more complex analyses would likely make the framework unwieldy for practical application; however, this would give a greater understanding of the system uncertainties and the effects on individual attributes.

Secondly we could explore how the projections have been generated in greater depth. In our analysis of the population uncertainty, two indicator components were noted as producing unusual relationships (airport operating costs and 'other' revenue). These were derived from a single estimate, but projected based on the three different population projections. It would therefore be interesting to explore how the original estimates were made and whether the noted relationships were changed if alternative projection techniques were used.

Thirdly, given the importance of the discount rate and the timing of investments, we could re-run the model for multiple start dates and implementation policies to investigate how this

²⁴ See Marcial Echenique and Partners Ltd (2001) conclusions from the EUNET project.

effects the appraisal results. Again, such an investigation may prove unwieldy for practical application, but would provide useful evidence of the value of delaying until uncertainty was diminished²⁵.

Instead, however, we choose to investigate our current assumption that factors such as economic growth and land use, which make up infrastructure investment landscape, are exogenous to the infrastructure developments made (see Figure 7.4). We have noted the enabling effect of infrastructure throughout this thesis; however, thus far, this has only been in relation to other infrastructure sectors. While many infrastructures are dispersed through a network, providing relatively consistent levels of service (for example utilities), others, such as flood protection and transport have a greater impact in their immediate location. Such developments can therefore skew user behaviour and population dynamics, affecting the benefits and impacts of the development and future developments. Indeed the importance of such factors was noted in Chapter 3, with ‘equity’ and ‘accessibility’ being two of those most commonly used in previous studies and guidance (see Table 3.5). If we wish to incorporate interdependency into the appraisal process and understand the system effects, we must also consider the interactions between infrastructure developments and their environment: We must bring a spatial dimension into the analysis. This will be the focus of the next chapter.

²⁵ The ‘value of information’.

8 Assessing System Feedbacks: An Analysis of the Spatial Interdependency of Infrastructure Developments

8.1 Introduction

We have now completed the systems appraisal methodology outlined in Chapter 3 (see Figure 8.1), building from a common cross-sector single asset appraisal in Chapter 5, through a portfolio analysis in Chapter 6 to a full pathways appraisal and a system uncertainty analysis in Chapters 6 and 7.

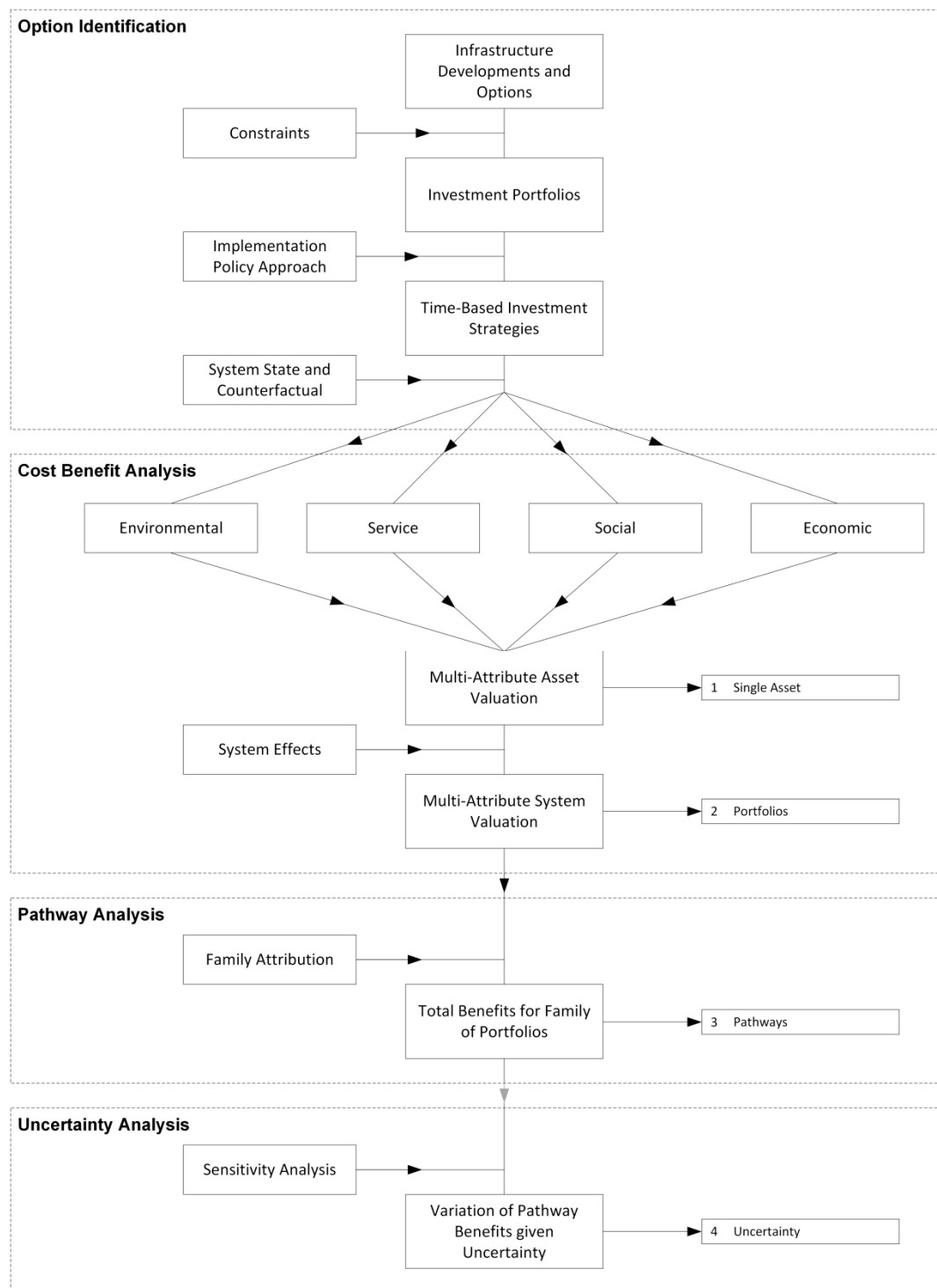
However, if we return to our research proposal in Chapter 1, we had five increments of complexity we wished to explore:

- Assessment against a single attribute vs multi-attribute valuation;
- Investment in individual projects vs investment in groups of projects (portfolios);
- A specified single project/portfolio vs consideration of pathway flexibility;
- Single future projection vs valuation under an uncertain future (sensitivity analysis); and
- Isolated predictions of change vs path dependency and feedback (incorporation of the interdependency between the development and the investment landscape).

The last of these considers the effects of treating system variables, such as population growth and land use change, as exogenous to the development, when many are known to be influenced by existing and prior infrastructure developments¹. We have seen in Chapter 5 that while some infrastructure effects are distributed, others are concentrated in the vicinity of the asset.

¹ For example, transport capacity and accessibility are known to be a key factors in residential and working location decisions (Vickerman, 2008), in turn, the location of residential and retail developments are known to affect transport demand (Breheny et al., 1998).

Figure 8.1 – Outline methodology (Chapters 5 to 7) (adapted from Young and Hall (2015))



The variation in impacts and benefits caused by these local infrastructure assets can promote behaviour change, altering how the effects are experienced and how many people experience them. The investment environment is therefore changed, altering the appraisal value of both the current and future developments in the locality. This has not yet been considered by our

analysis, but will be the focus of this chapter, aiming to provide an example methodology for testing such feedbacks and an exploration of one such feedback.

The objectives of this chapter are therefore to:

- Review the feedbacks of infrastructure investments, determining which of these affect the inputs to the appraisal methodology;
- Ascertain which of these feedbacks has the greatest influence on the appraisal results;
- Extend the appraisal methodology to allow exploration of this key feedback; and
- Provide an example analysis of this feedback, examining how it affects the appraisal results.

We start by reviewing the feedbacks of infrastructure developments on our model system variables, assessing the magnitude of their impacts and their ability to influence the appraisal results. Determining that population growth is the most significant feedback, we explore its effects and how these change depending on proximity to the infrastructure assets. We review spatial models that could be used to incorporate this feedback into the appraisal, finding that recent Land Use Transport Interaction (LUTI) models offer the greatest potential. We use one of these LUTI models (SIMULACRA) to undertake a limited analysis of the population feedback, aiming to demonstrate how one aspect (the employment provided by the Thames Hub Vision airport) could affect population growth projections². We then integrate the LUTI results with the pathways analysis to understand how these changes affect the inherent value, comparing this to the effects of the more general population projection uncertainty (described in Chapter 7).

² Note that we are not able to consider all population feedbacks herein due to the current limitations of the SIMULACRA model and the time limitations of this work. The methodology could, however, be simply extended to consider other population feedbacks, such as those created by changes in accessibility between zones.

8.2 Studying the feedbacks of infrastructure systems

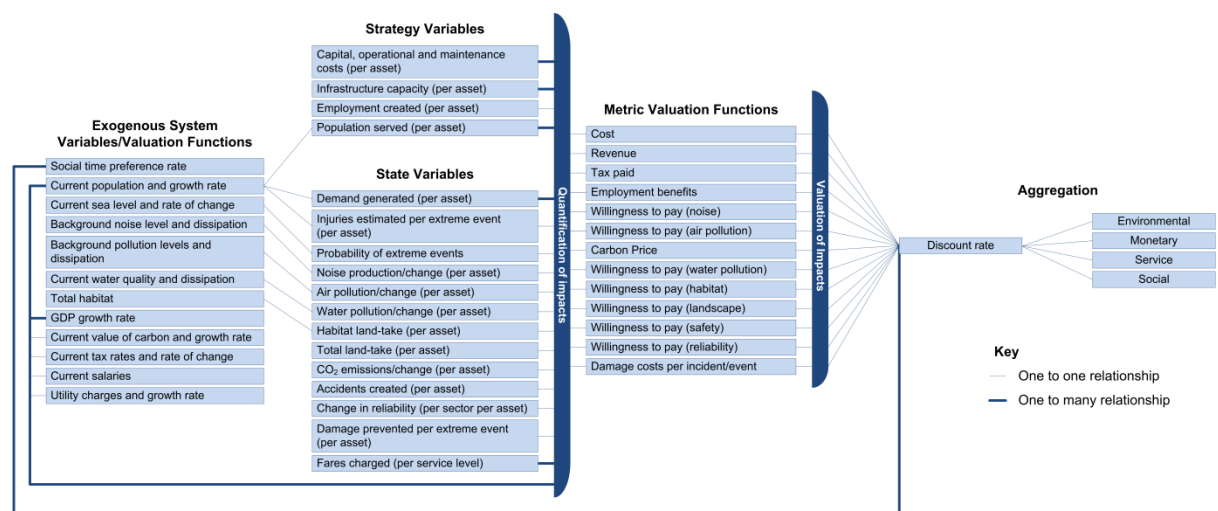
A focus of this thesis has been the interdependencies between infrastructure sectors and assets; however, as a system, they also feedback into the factors that helped define their requirements. They therefore have the ability to impact on the need for future infrastructure services and their value and impact. This process, whereby an effect of an upstream event can impact back on the probability or severity of the initial event, is one of the foci of systems analysis, an approach developed by RAND from the domains of operations research, probability theory, econometrics and game theory (Brady et al., 2012). Through methods such as causal mapping and linear and dynamic programming, the effects of such relationships have been studied since the 1950's (see Forrester (1958)) and are now referred to as 'system dynamics'. Modern computational power has allowed these models to become larger and more intricate, providing the opportunity to study more complex systems and networks.

A recent focus of this effort has been the interdependencies within infrastructure networks, particularly in regard to their failure and vulnerability (see for example, Johansson and Hassel (2010), or Hernandez-Fajardo and Dueñas-Osorio (2013)). However, our focus will remain on how the interdependencies between the networks affect the value and the path dependencies created. In particular how new infrastructures interact with the current system and how feedbacks from these developments affect the benefits and impacts of the current and future system. Over the next sections we will therefore consider how the effects of the infrastructure pathways can feedback into their requirements, how this might affect their value as calculated by the pathway appraisal and how system dynamics or modelling can be used to better understand this relationship.

8.2.1 Feedbacks within our infrastructure model

In Chapter 7 we considered the inputs to our system model (see Figure 8.2). Twelve inputs are assumed to be exogenous to the model. Some of these inputs relate only to current values³, therefore are not affected by the development pathway. However, the others relate to how current values will change over time and can be influenced by the investments made. In Table 8.1 we consider each of these future values, highlighting their potential to be influenced by the four infrastructure attributes identified in Chapter 3 (environmental, monetary, service and social). Where there is the potential for feedbacks, we assess whether this is likely to inhibit or reinforce future developments; hence, whether it will stabilise or magnify impacts.

Figure 8.2 – Model inputs and components



³ Current population, background noise, pollution and water quality and their dissipation rates, total habitat, current carbon prices, taxation rates and salaries.

Table 8.1 – ‘Exogenous’ system variables/valuation functions with the potential to be affected by the infrastructure development pathway⁴

System Variable/ Valuation Function Component	Potential Feedbacks
Population growth rate	As we noted in Chapter 3, infrastructure benefits and impacts are often greater for the local population than for those more removed from the development. This is particularly true for the service and social attributes of transport and flood protection infrastructures, and for environmental externalities more generally. We can therefore expect population growth, where there are local benefits (such as increased accessibility to employment centres) and suppression of population growth where there are local impacts (such as increased noise or reduced air quality). This will magnify the effects of the benefits and constrain the effects of the impacts for both the existing infrastructure assets and any future local developments. The current regional projections of population growth used within the model will not reflect these relationships.
GDP growth rate	Infrastructure developments are seen as investments, producing revenues for investors, employment for the local population and increased taxes for the Treasury. They will therefore have an impact on a country's GDP. However, given that the developments will only be a small component of the current country's industry, these direct effects are likely to be too small to be measured on the national scale and affect GDP. They do, however, denote a change in the region's share of the national economic activity and therefore its attractiveness for companies. This will show through other factors such as the local population growth rate (see above). In contrast, the macro-economic system effects of large infrastructure developments could create substantial changes in GDP. Appraisals have started to consider these factors (Frontier Economics, 2011; HS2 Limited, 2013); however, the relationships are complex (Banister and Berechman, 2003) and not well understood.
Growth/decline in utility charge rates	In the case of perfect market conditions, increased availability of a product would increase competition and decrease its cost. While, infrastructure services are not sold under such perfect market conditions (Beuthe, 2002), one of the aims of the regulators is to ensure competition where this is possible ⁵ . It would therefore be expected that increased infrastructure developments would decrease revenues, thereby constraining future infrastructure investments. Current charge rates have been based on sector projections where available (energy/fuels) to take account of predicted technology change, efficiencies and anticipated competition; however, the remaining rates (transport fares) have been projected based on GDP growth and will not reflect these relationships.
Taxation change	Taxation is specific to the infrastructure sector and sub-sector. For example, taxation is particularly high in the case of road transport; therefore, should developments constrain road use, taxation may be raised elsewhere. However, as it is impossible to know where taxation would be increased (and by how much), the effect on future infrastructure investment is unknown. Furthermore, a single development is unlikely to significantly affect the national taxation received and therefore its feedback effects are likely to be small.

⁴ Noise, pollution and water quality levels will change over time and will be dependent on the infrastructure built. They may, therefore, affect population growth locally (and have been included within this factor's potential feedbacks). They do not, however, affect valuation within the appraisal which only considers original levels. They have therefore been excluded from this table.

⁵ See Chapter 1 for the role of regulators in the UK.

System Variable/ Valuation Function Component	Potential Feedbacks
Carbon value growth rate	Infrastructure is one of the main contributors to current carbon dioxide emissions through its energy use. Should no renewable options be available for energy generation, infrastructure developments will increase current emission rates, potentially increasing carbon prices if a market system is successfully created. This will increase the operational costs of future infrastructure assets, constraining their benefits and hence potential investment.
Rate of sea level change	Sea level change will mainly be dependent on the rate of climate change, which is in turn linked to carbon dioxide levels in the atmosphere. As noted above, infrastructure is a large contributor to current carbon dioxide emission levels, therefore in the absence of renewable alternatives, increased infrastructure will increase carbon dioxide emissions and, through this, the rate of sea level rise, requiring, for example, more flood protection infrastructure to be built. However, the potential for one infrastructure development to affect global sea level rise is minute.
Social time preference rate	The appropriate rate of social time preference is highly debated (see Chapters 2 and 7). While it is possible that the availability and quality of infrastructure services may affect an individual's willingness to prioritise such services for future generations, such relationships have not been sufficiently explored for conclusions to be drawn regarding the scale or direction of such effects.

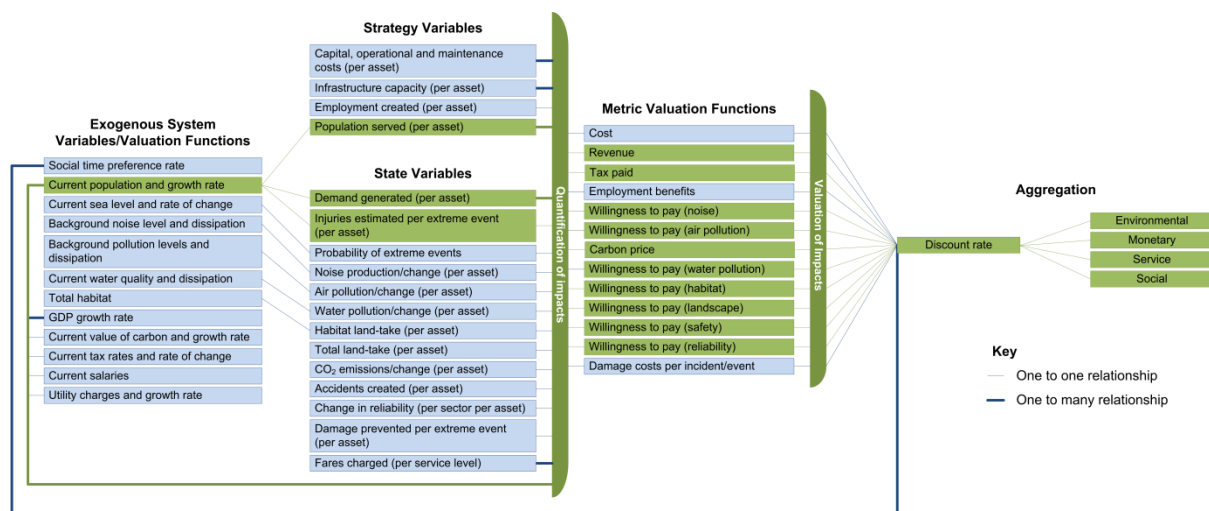
Having reviewed the exogenous variables/valuation functions we can see that each could be affected by the infrastructure attributes. We can split them into four categories based on their responses to these feedbacks:

- Those where feedbacks are not sufficiently understood to enable modelling herein (social time preference and macro-economic GDP impacts);
- Those where impacts are judged against national/global measures and are currently too small to produce measurable feedbacks (taxation, direct effects on GDP and sea level rise);
- Those where feedbacks will produce effects at the regional level and are likely to constrain future development (rate of change of utility charges and carbon costs); and

- Those where feedbacks will produce effects at the regional level and are likely to both constrain *and* enable future development (population growth rate⁶).

Variables in the latter two categories will provide the greatest opportunity to explore the effects of infrastructure developments on the future investment landscape. However, of these three variables, only one (population growth rate) has the potential to affect multiple attributes and assets. Of the other two, utility charge rates and carbon cost feedbacks only affect the monetary and environmental attributes respectively. In contrast, as we saw in Chapter 7, population has the potential to affect all attributes and assets (see Figure 8.3). Furthermore, as noted above, it highlights the effects of a second investment environment feedback, that of increased local economic activity (for example employment) and its ability to attract people to an area. Feedbacks into the population growth rate thus have the potential to significantly impact the appraisal outputs. We will therefore focus on feedbacks between infrastructure investments and local population growth rates in this chapter.

Figure 8.3 – Propagation of population growth rate uncertainty through the model



⁶ As noted in Table 8.1 this is not just affected directly by the impacts of infrastructure development but also how these impacts encourage or discourage commercial industry, affecting the distribution of economic activity within a country, and a region's attractiveness through, for example, employment opportunities.

8.2.2 Feedbacks on local population growth rates

The main function of infrastructure is to provide services to the population. In the UK, many of these services are delivered through national networks to almost all households⁷. While service levels may differ slightly (particularly for the ICT networks), most households receive a sufficiently high level of service that regional migration can be considered independent of investments in these networks⁸. However, some infrastructure investments (particularly transport and flood protection assets) provide a much greater level of service to those living in close proximity. Furthermore, most of the externalities of infrastructure developments will be experienced locally. Infrastructure investments therefore have the potential to encourage and discourage population growth in their proximity.

We can depict this relationship in a causal loop diagram (see Figure 8.4). Here we see that increasing infrastructure investments increases local benefits, attracting population growth. This population growth necessitates additional infrastructure services, hence investments. The new investments will be appraised against a more densely populated context, increasing the number of people who experience the benefits and hence making them more attractive. Furthermore, the existing infrastructure assets will be providing their service to more people, increasing their value. This produces a reinforcing feedback loop. In contrast, those same investments will produce increased local impacts. These will increase the 'costs' of living close to the infrastructure asset and encourage people to live elsewhere⁹. Any reductions in population will reduce the need for further local infrastructure investments and reduce the

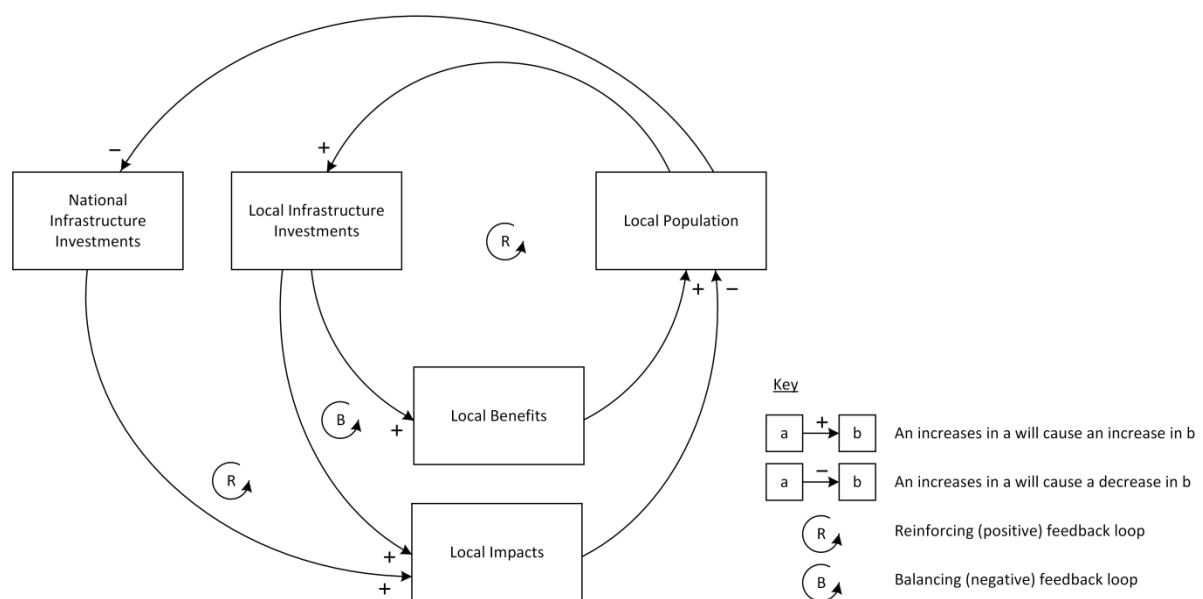
⁷ Clean water and sanitation, electricity and gas supplies, connection to broadband internet and other telecommunications services, and local waste removal services.

⁸ The UK is ranked tenth in the world for infrastructure according to the World Economic Forum (Schwab, 2014). This level of infrastructure service may affect *international* immigration levels; however, as each infrastructure asset will only make a small change to the national service levels and future immigration levels will be highly uncertain, we will assume the effect on international immigration is also sufficiently small to be ignored.

⁹ We recognised this relationship in Chapter 5 through the use of hedonic pricing valuations.

value of the local services already provided (a balancing feedback loop). However, as a reduced population will reduce the number of people who will experience any negative impacts of future infrastructure investments, it may encourage national infrastructure assets (those without additional local benefits) to be built in the locality. This will increase local impacts, further reducing the attractiveness of the area and reinforcing the area as attractive for national infrastructure investments.

Figure 8.4 – Causal loop diagram of infrastructure effects and population



As population projections are produced on a national or regional scale, they do not reflect these intra-regional behaviour-based changes. Yet, as we saw in Chapter 7, such changes in population can strongly affect the appraisal valuation by creating additional demand for services and willingness to pay to avoid negative externalities.

Applying the feedbacks in Figure 8.4 to our appraisal framework, we can classify each of our 15 performance indicators as local, national, or non-spatial effects (see Table 8.2). This confirms that eleven of the fifteen indicators represent local effects. They therefore have the potential to affect the attractiveness of a locality and, through this, its population growth. Of the local effect

indicators, the five environmental indicators and the employment indicator will be relevant to all infrastructure assets. Spatiality is therefore confirmed as a concern for all infrastructure developments. The remaining five indicators will only be important for certain types of infrastructure developments. Local social effects will be limited to more dangerous working conditions (energy or transport infrastructure), encouragement of behaviour change (transport infrastructure¹⁰), or through flood protection. Local services, as we have already stated, are limited to flood protection measures and transport infrastructures.

Table 8.2 – Spatial effect of performance indicators

Attribute	Indicator	Spatial Effect
Environmental	Air quality	Mainly local
	Carbon dioxide emissions	National
	Habitat	Mainly local
	Landscape	Mainly local
	Noise	Mainly local
	Water quality	Mainly local
Monetary	Cost	Stakeholder specific (non-spatial)
	Revenue	Stakeholder specific (non-spatial)
	Tax	Stakeholder specific (non-spatial)
	Employment	Mainly local
Service	Capacity utilised	Local or national*
	Reliability	Local or national*
	Protection	Mainly local*
Social	Safety	Mainly local*
	Security	Mainly local*

* Specific to type of infrastructure: Flood protection and transport assets produce local effects; energy, other water, waste and ICT assets mainly produce national effects

In addition, infrastructure developments are linked to wider economic impacts, particularly agglomeration¹¹. The likelihood of such effects is questioned, particularly in mature economies (Anderson and Lakshmanan, 2007; Banister and Berechman, 2003) and, where they do occur,

¹⁰ For example changes between transport modes with different safety rates.

¹¹ Economies, such a travel time savings and greater productivity caused by the clustering of people and industries (Glaeser, 2011).

the direction of causality¹² is not understood (Mackie et al., 2011). However, the effects are local. Indeed, one of the key concerns of agglomeration is whether benefits are truly national or merely displaced from other regions (see Kline and Moretti (2014)). Taking a regional perspective, however, these indirect benefits will make the area more attractive, increasing population growth and thereby impacting on infrastructure value. While macro-economic effects are not the focus of our appraisal methodology, additional welfare changes created by these effects (such as increased service utilisation or employment) will be captured. These changes can therefore help inform stakeholders of how potential macro-economic effects could change the value of the infrastructure developments.

Having reviewed the impacts of infrastructure developments, of our fifteen direct welfare-based impacts, we have six indicators which are spatially dependant for all infrastructure assets. Five are likely to be negative (environmental indicators) and discourage population growth, while one is likely to be positive (employment) encouraging growth. The remaining five indicators (social and service indicators) are likely to only produce local effects for flood protection or transport assets, but in most cases will produce positive effects. Any wider economic impacts achieved by combining complementary infrastructure developments will also be positive. Each of these indicators has the potential to affect the attractiveness of a locality and thereby skew population dynamics. However, our methodology does not currently capture this detail. If we wish to understand how these benefits and impacts change the investment landscape, we must model them spatially. Therefore, in the next section we review types of model able to capture the spatiality of effects. Focusing on population change, we consider which are most suitable for use within the appraisal framework and for application to a regional case study.

¹² Whether infrastructure investments create agglomeration or whether agglomeration promotes infrastructure investments.

8.3 Incorporating spatial modelling into appraisal

8.3.1 An introduction to spatial models and their current use within infrastructure appraisal

The most common type of spatial model is derived from Lowry's (1964) 'model of metropolis'.

While earlier economic models had already demonstrated important relationships between transport and particular types of land use¹³, they focused on a monocentric city. By combining statistics, probability theory and spatial choice theory, Lowry produced a hybrid model capable of considering a multi-centred city and a more detailed transport network, allowing representation of interactions between areas of the city (Horowitz, 2004). Furthermore, it required fewer assumptions regarding the development of residential and commercial locations (Echenique, 2004), allowing feedbacks between the components to be recognised (Wegener, 2004). Such models will be referred to herein as Land Use Transport Interaction (LUTI) models.

The original LUTI models (see Lowry (1964), for example) consider the organisation of residential developments and commercial activities, with the latter split into those whose location is dependent on the proximity of their customers ('retail sector') and those which are not ('basic sector'). Choice theory is used to determine where employees wish to live¹⁴, which is then calibrated against empirical data. These desires are compared to earnings and affordability of land prices/travel costs to determine residential locations. Retail services, which must locate near their customers, are constrained by these residential locations. Other basic commercial

¹³ Agricultural land organisation (von Thünen, 1826), residential development patterns (Hansen, 1959), and residential and commercial organisation (Alonso, 1960).

¹⁴ For example, assuming a wish to minimise transport cost to their place of employment. The most simple models use a gravity-based relationship to represent this preference, see Waddell and Ulfarsson (2004), while more complex models use maximisation of entropy or random utility (Horowitz, 2004; Echenique, 2004; Wegener, 2004).

activities are only constrained by earnings and land prices. By solving for all relationships and zones, the model generates the spatial organisation of the city at equilibrium conditions. The result is, in most cases, a static output of land use or change in GDP, and does not discern *how* the equilibrium is reached over time, at what time the equilibrium will be reached, or spatial organisation within zones (Horowitz, 2004). Furthermore, as the services within the model can be interdependent, the relationships can quickly grow, requiring multiple zones to be solved simultaneously. As a result, the models can quickly become restricted by available computational power (Horowitz, 2004). The models therefore use a number of simplifying assumptions and limitations (see Horowitz (2004) and Weisbrod and Alstadt (2007)). For example, relationships within the model, such as the individual choice assumptions, are normally kept static, removing the opportunity to consider behaviour change (Vickerman, 2008).

LUTI models are normally applied at the level of a single metropolitan area or region, where the spatial data requirement for validation of the model is still feasible (Weisbrod and Alstadt, 2007). They have historically been used by urban planners to understand travel demand and the effects of transport developments on land use (Vickerman, 2008). However, their use for infrastructure appraisal is limited to a few studies of transport systems at the strategic scale (Department for Transport 2011a)¹⁵. While modern models have been developed to include some dynamics or consider inter-regional impacts of transport on land use (Vickerman, 2008), many of the limitations remain, particularly regarding the resolution of the interactions. This has created a move toward more disaggregated approaches, either through the industry types explored (through Spatial Computational General Equilibrium (SCGE) models), the spatial scale (through Cellular Automata (CA) models), or the elements of the system (through Agent Based Modelling (ABM)) (Batty, 2010).

¹⁵ For example, one such model of London was used to assess the benefits of new light rail lines and the introduction of congestion charging prior to implementation (Echenique, 2004).

SCGE models developed from non-spatial economic models of national economies. These CGE models use a country's national accounts data to examine the economic relationships between market sectors and the effects that may occur following changes in national policy. By adding a spatial component, the interactions between different areas of a country (or different countries) can also be considered. Such SCGE offer advantages over LUTI models, providing a greater resolution of the market sectors of the economy and allowing for imperfect markets between them (Vickerman, 2007). They can therefore provide separate results for the different transportation modes or industry sectors. Equilibrium is found through simultaneous solution of all relationships, ensuring the result is valid for all markets without double counting (Weisbrod and Alstadt, 2007). Consumer utility is also included and can reflect preferences for individual or differentiated goods (Vickerman, 2008). This inclusion of utility allows SCGE to estimate welfare change directly through the equivalent variation in income (Vickerman, 2007); however, it undermines the validity of some of the integral spatial interaction assumptions (see Vickerman (2008)). SCGE also require significantly more data and greater computational effort than LUTI models, strongly limiting the number of zones that can be considered. Applications have therefore tended to focus on the inter-regional, national or international scale, considering transformational developments, thought to have significant impacts outside of the transport domain, where the additional time and computational effort can be justified (Weisbrod and Alstadt, 2007; Vickerman, 2008). For example a SCGE was used by the Airports Commission in the UK to investigate the macro-economic benefits of increasing airport capacity in the South East (PwC, 2014)¹⁶.

CA and ABM models emerged in the 1980's (Waddell and Ulfarsson, 2004) and provided the opportunity to understand behaviour in much greater detail than either LUTI or SCGE models.

¹⁶ Three schemes were considered: (i) a second runway at Gatwick airport; (ii) an additional North West runway at Heathrow airport; and (iii) an extended northern runway at Heathrow airport.

CA models consider a grid of cells whose individual state is dependent on the surrounding cells (Wegener, 2004). The resulting cell patterns are considered over time to understand the complex dynamics produced by different cell relationships. Their use for urban modelling has mostly concentrated on urban growth or land use change where, with the addition of random noise, they have been made to closely resemble real city behaviour (Batty and Xie, 1994).

ABMs are a more flexible and complex form of this type of model, considering the behaviour and state of individual 'agents' rather than cells. These agents interact with each other, but are not necessarily fixed spatially. They can therefore be dependent on fixed inputs, other specific agents, nearby agents, and/or the general behaviour of all agents. These relationships can be assigned individually or to groups of agents, allowing the model to represent the different priorities or responses of entities in the real world. Open source tools have rapidly increased the uptake of such models, for example, MATSim (Multi-Agent Transport Simulation) has been used to create large scale traffic models of over 50 cities across the globe including London (see EUNIOA Consortium (2012)).

Both CA and ABM offer a greater level of resolution than LUTI or SCGE models. Furthermore, they provide the opportunity to explore system behaviour and emergent effects. However, they have little or no recognition of real transport networks, their cost to users (time and financial) or land prices (Batty, 2009). In addition, their reliance on modelling the relational rules between cells or agents requires an understanding of (and appropriate data for) each of these relationships. The more complex the system, the more rules that are required to model it and the greater its data requirement. For infrastructure systems it is unlikely that all the rules and behaviours could be derived (Weijnen and Bouwmans, 2004), perhaps explaining why their use for operational planning or policy decisions has been limited to date (Waddell and Ulfarsson, 2004).

From the above discussion we can conclude that LUTI models are most appropriate for our early stage appraisal, having the lowest data requirements, and being focused on the regional scale. They also provide the most comprehensive representation of the transport system, one of the two infrastructure sectors known to produce strong local impacts. Furthermore, they particularly focus on employment, one of the six indicators classified as having local spatial effects for all sectors in Section 8.2.2. We will therefore focus on this type of model. In the next section we review existing LUTI models of the London region and their potential for exploring the feedbacks of the Thames Hub Vision case study.

8.3.2 Recent applications of LUTI models to the London region

Given the high land prices, density and transport requirements of the London region, it has been modelled many times. These include four recent LUTI based models, which were available for use by the author. Each of these is summarised in Table 8.3.

Table 8.3 – Available LUTI models for the London region

Model	Description
Tyndall Cities (see Dawson et al. (2009); Hall et al. (2009))	The Tyndall Cities (also referred to as 'Engineering Cities') model focused on the Greater London region (33 boroughs and a population of approximately 8 million people) with extension along the Thames Estuary. The project aimed to provide an integrated assessment of the effects of sea level rise on this region over the next 50-100 years. Employment was predicted in aggregate, with growth driven by a regional input-output model. Population was generated through a LUTI model, with land use predicted by an urban development model for each 100m ² of land. Population and employment were allocated using the gravity based method, according to the 'attractiveness' ¹⁷ of each zone. These locations were then used to predict transport flows, constrained by total cost ¹⁸ and calibrated to ensure average cost was conserved. Transport was disaggregated into four modes (private car, rail, light rail and bus), allowing developments in each mode to be explored individually.

¹⁷ Linked to their interconnection with other zones and the priorities of the develop paradigm ('baseline', 'centralisation', 'eastern axis' or 'suburbanisation').

¹⁸ The model used a complete representation of the urban transport network to calculate the cost of travel between every Census ward, where cost of travel included journey time, fares, congestion charging, fuel consumption, waiting time and time taken to access, overcrowding and safety.

Model	Description
ARCADIA (Adaptation and Resilience in Cities – Analysis and Decision-making using Integrated Assessments) (see ARCADIA, (2012); Batty et al. (2013); Batty (2013))	This project extended the Tyndall Cities model to the commuting area of London ¹⁹ . It explored the vulnerability of the metropolitan area to climate change (floods, draughts and storms) and the potential economic impacts of different future scenarios. Employment was disaggregated into ten sectors, with land use investigated under three future planning scenarios (business as usual, decarbonisation and deregulation ²⁰). These, in turn, drove the LUTI population location model (based on entropy maximisation) which was disaggregated into 50m ² sub-zones via a CA based model. The Tyndall Cities transport model was extended to include the expanded case study area, with mode disaggregation kept to four groups, allowing the investigation of the effects of modal switching ²¹ . Furthermore, transport demand was generated dynamically, allowing the model to produce estimations of employment and population at snapshots in time rather than the equilibrium results.
SIMULACRA (SIMulating Urban Landuse As Commercial and Residential Activities) (see Batty et al. (2013))	SIMULACRA is a framework connecting a collection of highly disaggregate models of the residential, transport, retail and other commercial sectors of the Outer Metropolitan Area of London ²² . It builds on the Tyndall Cities and ARCADIA models; however, its flexibility and efficiency make it more capable of rapidly testing different scenarios, of encapsulating much higher spatial resolution, or of including more disaggregation in the land use sectors. Current tests use two modes of transport (public and private), five employment types and five household types; however, these can be further aggregated (to reduce run times) or disaggregated (to improve resolution) as necessary. The simplest SIMULACRA model calculates residential locations based on total employment and the costs of travel and land. It then computes retail requirements and employment based on these population densities and finally basic (referred to as 'internal') commercial employment from total and retail employment. Growth is constrained by available space. The model is still being developed, but has been calibrated using existing land use and transport capacities, with current studies focused on how single points of increased employment could affect land use.
ReVISIONS (Regional Visions of Integrated Sustainable Infrastructure Optimised for Neighbourhoods) (see ReVISIONS (2012); Echenique et al. (2011))	The ReVISIONS project considered whether spatially planning infrastructure and buildings together could improve their sustainability and economic competitiveness. A case study was conducted on the wider South East of England with 192 spatial zones. A LUTI model was built using an extended input-output table to disaggregate residential and commercial types ²³ . It allowed estimation of residential/commercial demands through a specifically designed social accounting matrix, which incorporated the price-elasticity of demand. Location was then distributed based on random utility theory, including the disutility of production areas. The resulting spatial demands were to be used to predict energy, water and waste demands, under four spatial development policies ('trend', 'compact city', 'structured expansion' and 'market-led dispersal') applied over a 50 year period. Different infrastructure developments were then tested against the spatial demands to find out which combinations were most sustainable.

¹⁹ Defined as all Census wards with greater than 10 per cent of their population commuting to central London (a total of 633 wards).

²⁰ Where planning laws are relaxed to allow greater development.

²¹ See Batty (2013) for an investigation of the effects of doubling road costs on the use of the remaining modes and on residential location choices.

²² Including 1767 Census wards and a population of approximately 14 million people.

²³ Commercial activities were split into seven sectors based on the UK Standard Industrial Classification 1992.

Three of the models (Tyndall Cities, ARCADIA and SIMULACRA) are related, having been developed over time by the same team, but with each having a different focus. The first two models (Tyndall Cities and ARCADIA) were developed to investigate climate change effects and therefore have a temporal component that could help integrate the models with the time-based analysis herein. However, both models require significant computational effort due to their size and disaggregation of residence/commercial types. They are therefore most appropriate for analysis of a limited number of discrete future scenarios. SIMULACRA, while allowing greater spatial disaggregation, is more flexible and efficient. The disaggregation of residential and commercial land use can be adapted to the needs of the model, allowing its complexity to be reduced or increased as necessary. It therefore has the potential to test many different scenarios (or developments) to aid stakeholder understanding. However, it only produces the equilibrium condition, with no information on when this equilibrium will be reached.

The ReVISIONS model uses random utility (rather than gravity or entropy maximisation) to distribute demand and therefore residential locations. As behaviour is based on utility rather than cost it directly reflects changes in welfare, therefore the model should integrate well with the welfare based cost benefit appraisal. It also incorporates social accounting techniques to model price-elastic demands, giving the opportunity to predict behaviour change. However, while the model considers far fewer zones than either the ARCADIA or SIMULACRA models, its complexity makes it computationally expensive. Again, it is therefore more appropriate for analysis of a limited number of detailed scenarios than exploring multiple potential developments.

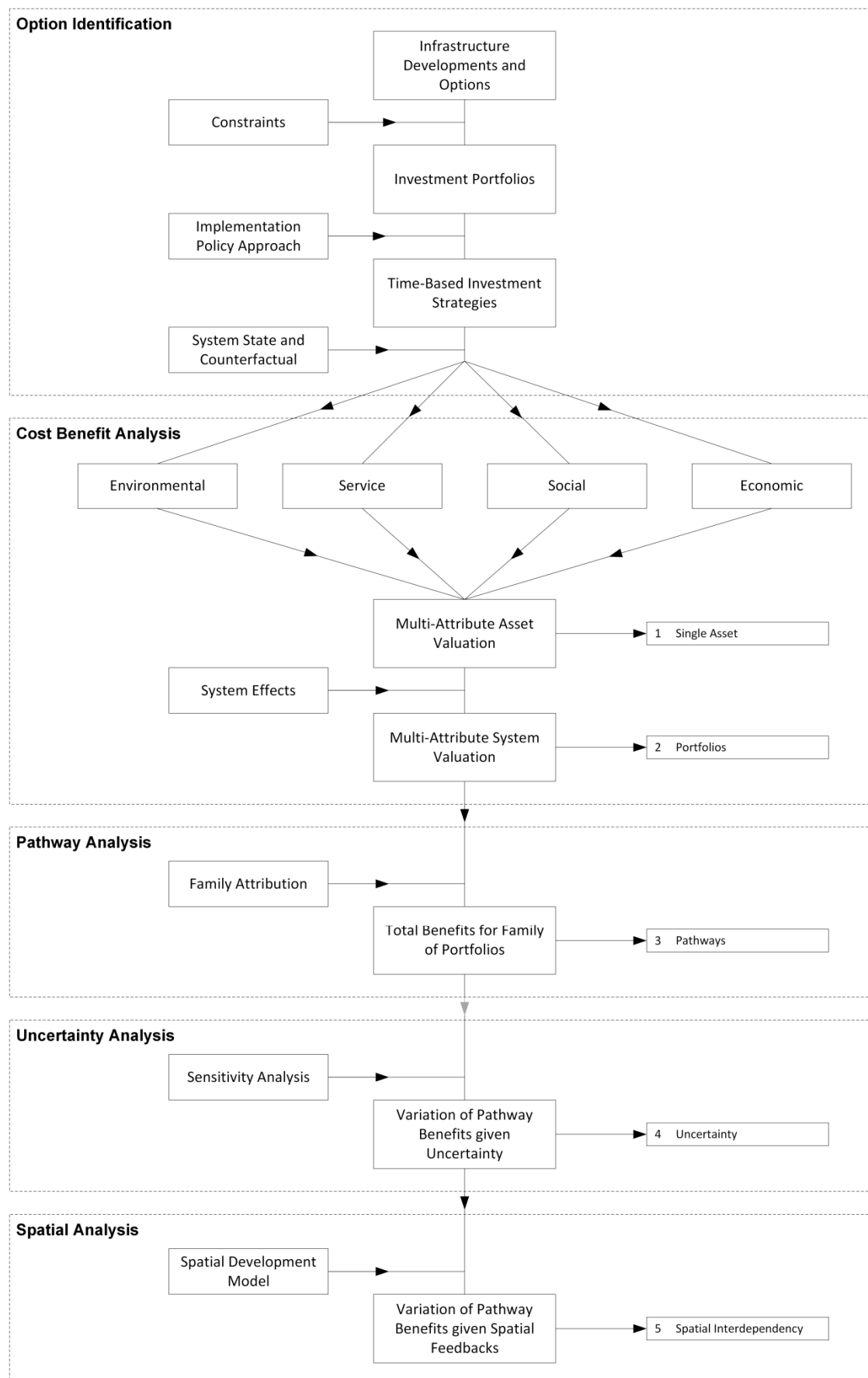
The SIMULACRA model appears to be the best model for application to our appraisal framework. Firstly it offers the greatest flexibility to adapt to the limited data likely to be available at the strategic appraisal stage for which our methodology is designed. Secondly it is the most efficient

of the models, allowing investigation of multiple potential developments rather than a few specific scenarios. In addition, it models far more zones than the other three models, providing a higher spatial resolution with which to investigate the spatiality of effects. However, as the model only produces equilibrium conditions, its integration with the time-based pathway appraisal model must be carefully considered. Over the next sections we therefore provide a walkthrough of how these two elements can be integrated and, furthermore, how they can be used to provide an understanding of one of the spatial population feedbacks and its effects on the appraisal valuation.

8.4 Using the SIMULACRA model to investigate the spatial population feedbacks within the case study

If we wish to understand the effect of feedbacks on the pathway appraisal valuation, we must add a final stage to our appraisal methodology, using a spatial development model to understand this interdependency (see Figure 8.5). In the next two sections we demonstrate how these feedbacks could be examined, by considering a single feedback (population) and applying it to our appraisal methodology. LUTI models have already been determined to provide an appropriate modelling framework to examine this feedback, specifically tracking the changing economic activities and accessibility produced by an infrastructure development and using these to derive population change. We will therefore integrate the outputs of one such model (SIMULACRA) with our pathways analysis. While we have noted a number of feedbacks between developments and population, to restrict the complexity of this undertaking, we will examine just one within this chapter. We will therefore follow a similar method to that used in Chapter 7, determining a key variable and estimating its effects on the system as a whole. We will use this variable to demonstrate the methodology before suggesting extensions for further application.

Figure 8.5 – Full appraisal methodology (adapted from Young and Hall (2015))



8.4.1 Choice of key variable and input into the SIMULACRA model

While the SIMULACRA model is still under development, sufficient progress has been made to allow point source additions to employment levels. As we noted in Section 8.2.2, employment is one of the six currently recorded indicators to create feedbacks for all infrastructure assets. It also plays a particularly important role in the derivation of transport demand (Headicar, 2009), the main infrastructure sector within our case study and one of the two sectors identified to have strong local effects. Furthermore, indirect employment through productivity gains is a possible effect of agglomeration. By considering the employment effects of the development we can therefore explore both the direct feedback effects of the developments and their indirect effects, should they create agglomeration economies. While employment only represents one population feedback of the developments, we will use it herein as an example of how the methodology could be applied to other feedbacks.

Within our case study, by far the most significant employment benefits are realised by development of the airport asset²⁴, creating an additional 28,000 jobs over the expanded Heathrow case (Foster+Partners et al., 2011b). In addition, the proposal suggests that the development as a whole could create an additional 100,000 indirect jobs in the region.

Taking the proposal employment estimates as a starting point, the SIMULACRA project team derived three additional employment levels:

- An additional 25,000 employees (only direct employment produced);

²⁴ It has been assumed that the rail orbital will create approximately 1,500 jobs (in line with HS2 predictions (RAC Foundation 2013)), that the generation barrage will create 25 jobs (in line with other tidal generation (Shankleman 2013)), that the barrier will provide employment equivalent to the current Thames Barrier (no net gain), and the road assets will not generate employment.

- An additional 50,000 employees (indirect employment generated to the same level as the direct employment); and
- An additional 100,000 employees (indirect employment generated to three times the level of the direct employment).

These were added to the SIMULACRA model with their source set as the Hoo Peninsula (the location for the Thames Hub Vision airport). The model was then run separately for each employment level, deriving the equilibrium spatial population effects for each (as described in the next section).

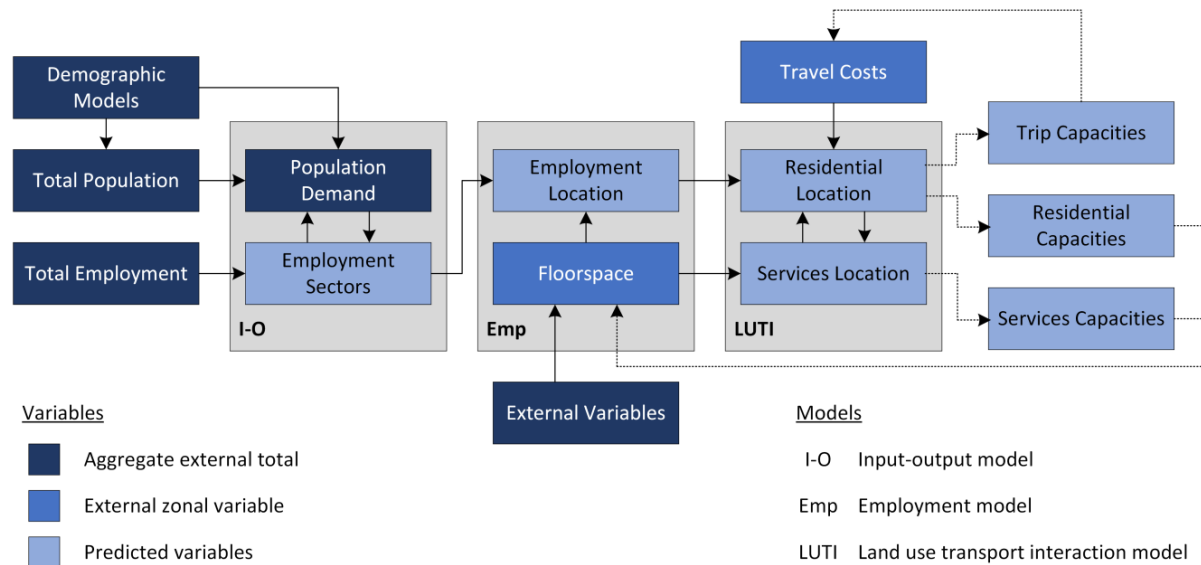
8.4.2 Consideration of point source employment growth using the SIMULACRA model

The structure of the SIMULACRA model is described in Batty et al. (2013). This is summarised in Figure 8.6. The model has three location components: residential, retail employment (industries that must be located near population sources) and internal employment (industries not dependent on population). It first calculates employment and industry locations. It then uses these to calculate trips from workplaces to residential locations, based on the available residential land area and restricted by average incomes, average house prices in different zones and the cost of travel between them²⁵. Population is calculated for each residential zone based its commuter trips (number of employees) and household size. The residential population capacity of each zone is limited, triggering further iteration of the first two steps of the model with appropriate weightings until conditions are met. Once residential populations have been calculated, retail locations are generated in a similar manner, considering available industrial

²⁵ Regression models have been used to derive monies spent on housing and travel within the zones. It is then assumed that the more closely a person's available money for transport and housing matches that calculated for a given location, the greater the probability of them choosing to live there.

floorspace and travel costs. This is used to derive trips between residences and retail locations and hence spatial retail employment. Employment in other local industries is based on the zone's total commercial floorspace and its accessibility to commercial activities.

Figure 8.6 – SIMULACRA model structure (Batty et al., 2013)



Aggregate external data was taken from the 2005 UK Census, along with data from the Office for National Statistics (employment) and the Valuation Office Agency (housing prices) for the same year. While the goodness of fit of the model outputs reflect its 'in-development' status, the current results are considered generally acceptable and sufficiently accurate to produce useful results (Batty et al., 2013).

As noted above, population is driven by employment levels (normally derived from the input-output model). The addition of a given number of employees at a set location (in the employment model) therefore causes the population of the total region to increase. The LUTI model distributes these employees and their households between the possible residential locations, taking account of the additional commuter travel produced by the employees and its effects on transport costs between the various model zones. It then outputs the equilibrium spatial distribution for the new level of employment/population.

The commuter travel demands calculated by the SIMULACRA model could not previously be estimated by the pathways model as the residential location of employees was unknown. However, given the capacity of the airport, commuter journeys were estimated to be only a small proportion of the travel effects²⁶. If, however, indirect employment grew to the levels predicted in the Thames Hub Vision proposal, these journeys would become more significant. While we will limit the current analysis to the direct population effects of employment, further exploration of the effects of commuter travel (for example, additional emissions and reliability effects) would be a worthwhile extension once the SIMULACRA model has been further developed.

8.4.3 Conversion of the SIMULACRA outputs for inclusion within the pathways analysis

The SIMULACRA model produces equilibrium population results for the Census Area Statistics (CAS) ward zones against a 2005 year baseline. The data was translated into the additional population per zone by subtracting the results of a baseline with no additional employment ('no-employment scenario'). These zonal populations were then disaggregated into Lower layer Super Output Area (LSOA) zones (as used in the 2011 census), by attributing each to a CAS, calculating its average population density and multiplying by the area of the LSOA. LSOAs were originally defined to have comparable population sizes²⁷, therefore will be used herein to analyse the changes in population between the employment scenarios and the no-employment case. For inclusion within the pathways analysis, the LSOA populations will then be aggregated into Local Authority (LA) zones. The results of spatially limiting and disaggregating the data are shown in Table 8.4.

²⁶ Average daily passenger numbers are predicted to be over 14 times the number of direct employees.

²⁷ LSOAs have a population of between 1,000 and 3,000 residents with an average of approximately 1,500 residents (population as recorded in 2011).

Table 8.4 – Population growth under each employment scenario

Zonal Disaggregation	Additional Population		
	25,000 Employee Scenario	50,000 Employee Scenario	100,000 Employee Scenario
CAS Wards (SIMULACRA area)	25,000	50,000	100,000
CAS Wards (Clipped to case study area)	25,833	50,798	100,737
LSOA Zones/LA Zones (Disaggregated by zone area)	25,833	50,789	100,737

Clipping the study area from that included with the SIMULACRA model to that within the pathways analysis produces an additional increase in population of approximately 800 people. This reflects the regional population dynamics noted earlier when discussing the potential for agglomeration. The increased employment has made the study area more attractive, creating additional population growth at the expense of the surrounding regions. This highlights the importance of the spatial area considered by the LUTI model and its interactions with surrounding areas. For a national perspective, the model would need to record this migration to allow any detrimental effects on other regions to be considered. Disaggregation of the results into LSOA zones and then aggregation into LA zones does not cause further changes to the population.

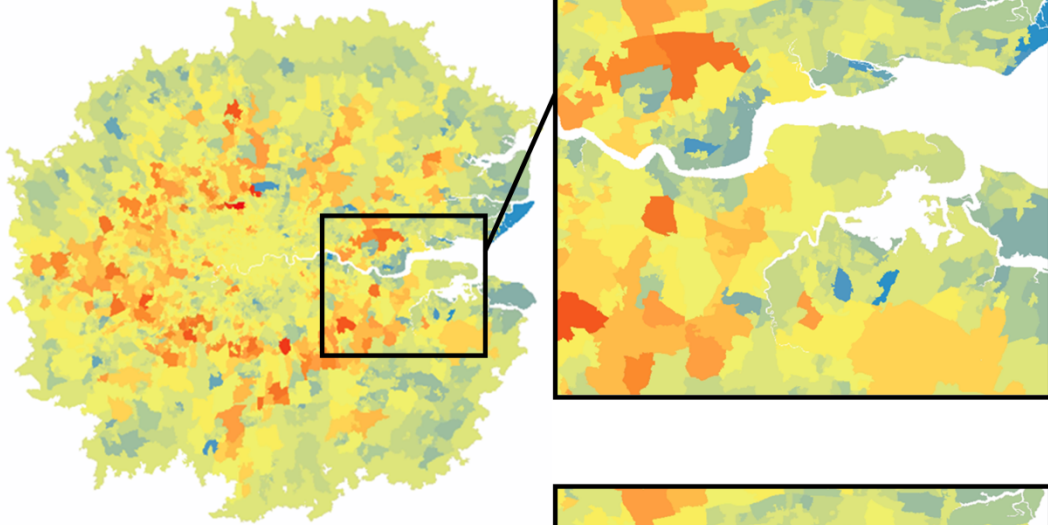
8.4.4 Review of the SIMULACRA outputs: The spatial population effects of increased employment

The effect of the increased employment on the LSOA populations is shown in Figure 8.7²⁸. Population change varies from Rochford 010B in East London (-3,960 to -3,966 depending on employment scenario) to Barnet 007A in North London (4,969 to 4,903 depending on employment scenario).

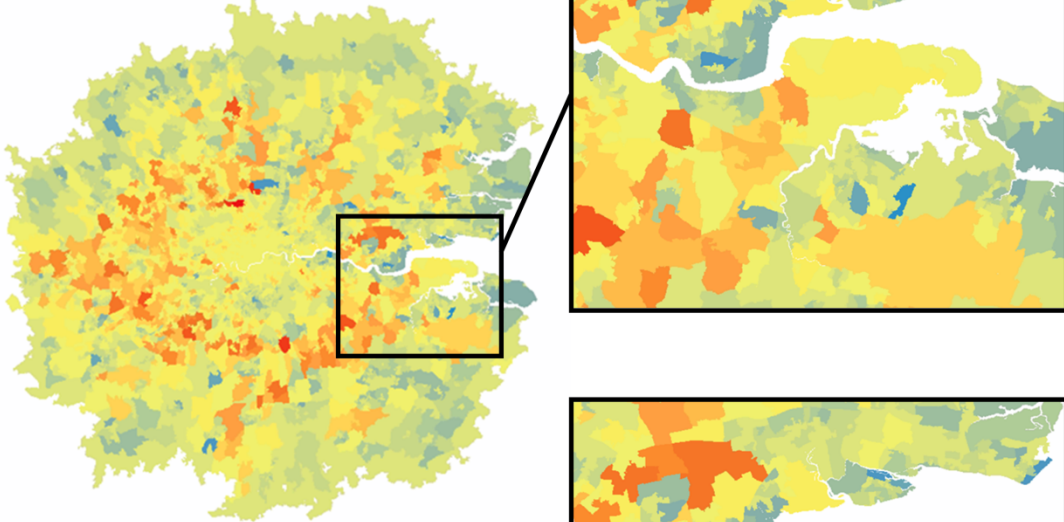
²⁸ Blue shading represents a decrease in population, while red shading represents an increase.

Figure 8.7 – SIMULACRA population outputs (Hoo Peninsula area magnified)

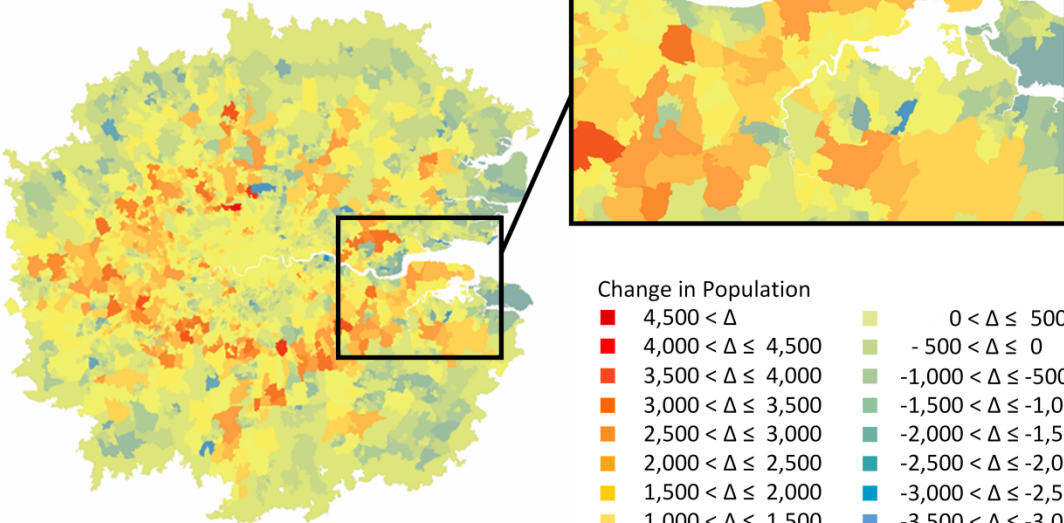
a) Population Change: 0 - 25,000 Employees



b) Population Change: 0 - 50,000 Employees



c) Population Change: 0 - 100,000 Employees



Change in Population

4,500 < Δ	0 < Δ ≤ 500
4,000 < Δ ≤ 4,500	- 500 < Δ ≤ 0
3,500 < Δ ≤ 4,000	-1,000 < Δ ≤ -500
3,000 < Δ ≤ 3,500	-1,500 < Δ ≤ -1,000
2,500 < Δ ≤ 3,000	-2,000 < Δ ≤ -1,500
2,000 < Δ ≤ 2,500	-2,500 < Δ ≤ -2,000
1,500 < Δ ≤ 2,000	-3,000 < Δ ≤ -2,500
1,000 < Δ ≤ 1,500	-3,500 < Δ ≤ -3,000
500 < Δ ≤ 1,000	Δ ≤ -3,500

The results can be seen to be very stable, with little difference between the 25,000 and 100,000 employee scenarios. However, as noted by Batty et al. (2013), the effects are much wider than the area surrounding the employment increase. Population increases are mostly found in the central regions, spreading out to the west and south west. The largest increases circle Greater London, where zones provide reasonable commuting times to central London and access to the M25 motorway, but lower land prices than the more central zones. In contrast, population decreases are mainly in the outer most regions of the study area, with large population decreases shown in the most eastern zones.

It could be expected that an increased input of employment would either make an area more attractive or less attractive than the base case, with the magnitude of employment simply magnifying the impacts. However, this is not always the case. For 107 of the LSOA zones, some levels of employment growth cause a population decline while others cause population growth. Where these swings do occur, many are very small, for example, 46 of the results have a swing of less than 50 people²⁹. The smallest of these swings are likely to be purely due to the iterative nature of the model, creating slightly different solutions in each scenario. Slightly larger changes may also reflect the interactions between a location's attractiveness, its population and the costs of travel. For example, as a location becomes more attractive it becomes more populated. Travel modes then become more congested and the zone's attractiveness decreases in contrast to less populated neighbouring areas. This causes some of the zone's population to move to the neighbouring zones, converting a population increase into a population decrease.

The remaining 61 LSOAs have population swings of more than 50 people. These LSOAs are contained within four LAs: 50 are in the Medway LA (the location of the airport); four are in each

²⁹ A change of less than 5 per cent of the minimum LSOA population between the 25,000 and 100,000 employee scenarios.

of the Swale and Gravesham LAs (the east and west neighbouring LAs); and three are in the Dartford LA (the next neighbouring LA to the west). The most significant changes in population dynamics are therefore limited to the immediate vicinity of the airport. In each case, the 25,000 employee scenario causes a decrease in population compared to the base case, while the 100,000 employee scenario creates population growth. The population generated in the 50,000 employee scenario is always between that of the other two cases and, in most cases, (44 of the 61 cases) reflects a population decrease from the base case. The initial migration away from these zones does not reflect the increased attractiveness that should be caused by the increased employment, and indeed is shown in the 100,000 employee scenario. This is because the increased travel caused by employment initially increases travel costs in the region, making it less attractive for those commuting to other zones. As employment levels within the zone become more significant its attractiveness increases, drawing the population back.

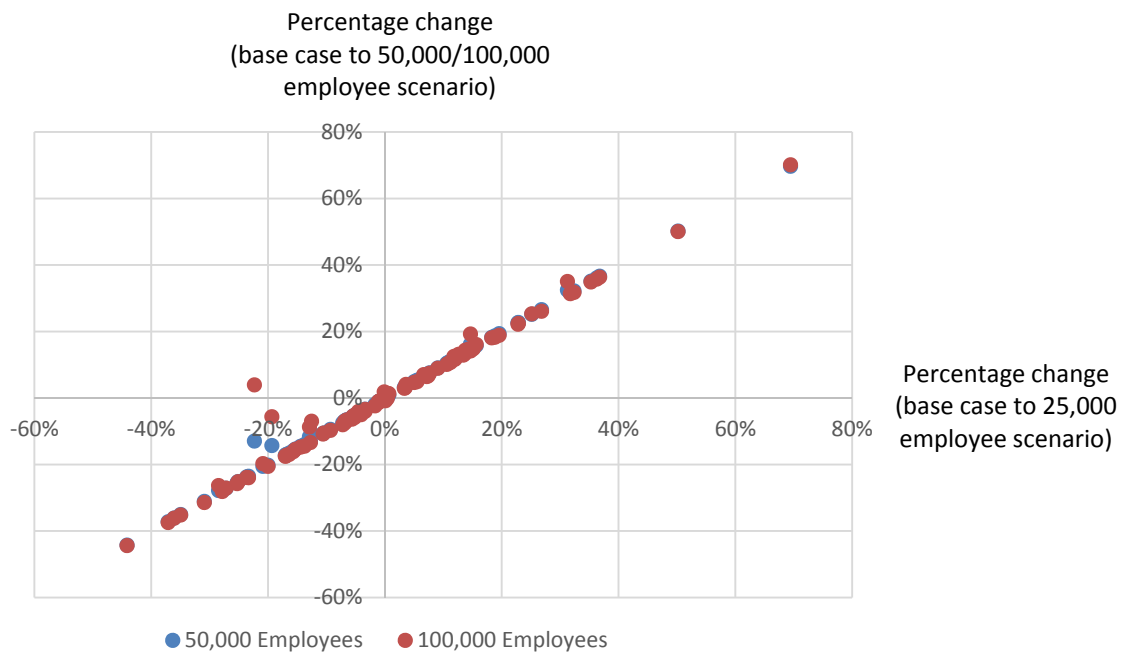
A further 203 LSOA zones show a second inconsistency with the predicted response. Here the population does not simply increase with employment, either first increasing then decreasing (42 LSOAs) or vice versa (161 LSOAs). In the latter case none of the swings are greater than 1 per cent of the minimum LSOA population. Indeed, the maximum swing is only 6 people. However, in the former case, 27 LSOAs show a swing of 1 per cent or greater with a single LSOA (Barnet 007C) showing a swing in excess of 5 per cent (94 people swing). Again, the very small (less than 1 per cent) changes are likely to be due to the iterative nature of the model. However, for the larger swings (particularly Barnet 007C) it appears that the dynamics have changed. Here, the zone attracts additional population as the employment increases to 25,000 and 50,000, but loses this (and more) as the employment increases to 100,000. We can conclude that when employment is first increased by 25,000 and again to 50,000, the zone is attractive. However, when the employment is again increased to 100,000 the zone becomes less attractive than either case. This is again due to the cost of travel and the importance of the east London

employment source. As the employment source becomes more important, the high levels of congestion and/or limited routes to this location make the Barnet LA far less attractive than local LAs such as Medway, Swale, Gravesham and Dartford. The Barnet LA therefore loses population to these local LAs.

These two diversions from expected behaviour demonstrate the iterative nature of the model. However, if we compare the percentage change in population caused by the scenarios, we can see that the effect of these diversions is small and the results are indeed as stable as they appear in Figure 8.7. Figure 8.8 shows this relationship, plotting the percentage population change in the 50,000 and 100,000 employee scenarios against that of the 25,000 employee scenario³⁰. Only two of the 50,000 employee scenario results and three of the 100,000 employee scenario results vary from those of the 25,000 employee scenario by more than 5 per cent. These are Medway and Gravesham (the location of the airport and the neighbouring LA, applicable in both scenarios) and Maidstone to the south east of London (applicable in the 100,000 employee scenario). Therefore, while changes in local benefit and cost may be experienced throughout the region for the 25,000 employee scenario, the effects of further increasing employment to 50,000 or 100,000 (that is, the effects of indirect employment) are likely to be limited to these three LAs.

³⁰ Growth or decline at equilibrium against the population recorded by the UK Census in 2011.

Figure 8.8 – SIMULACRA population outputs: Comparison of 25,000 employee scenario population change with population change of 50,000 and 100,000 employee scenarios



Having explored the spatial effects of increasing employment, we will use the results in two ways. Firstly, we will compare the LSOA population changes against the assets within the case study, to determine how the change could affect their individual values. Secondly we will include the changes within the pathway model (aggregating to LA zones), considering the resultant effects on the two appraisal performance metrics which are directly valued by residential population (noise and water quality). We will then compare this uncertainty to that derived in Chapter 7. We will present the results of these analyses in Section 8.5; however, we must first determine how to combine the equilibrium results of the SIMULACRA model with the time based data of the pathways model.

8.4.5 Integration of the spatial population results with the appraisal model

The population results in Section 8.4.4 represent the population change at the unknown date when equilibrium is reached. However, we can assume that, as the employment is generated

(directly or indirectly) by the airport, the airport is present at this time. The equilibrium date must therefore be after the airport's minimum construction time. Furthermore, since the Thames Hub Vision airport requires an additional 28,000 employees to operate, these people must be able to commute to the airport by the time it is opened³¹.

Referring to our constraints and prerequisites in Appendix A, we can conclude that the equilibrium date is either during or after 2028 (the airports earliest operational date) and that the population generated by the need for an additional 28,000 employees, must be in place by this year. Therefore, to simplify the analysis and magnify the effects of the changes in population, we choose to implement the additional population for all scenarios in the year 2028.

Since the SIMULACRA population projections will only occur in pathways where there is a requirement for the additional employees, our analyses will be limited to the airport pathways. To further highlight any differences, the 'do minimum' Heathrow expansion (see Chapter 4) will be assumed to induce no population feedbacks and hence will use the results generated in the prior pathways analyses.

8.5 Results and analysis

8.5.1 Infrastructure service results

If we compare the spatial results discussed in Section 8.4.4 with the location of the Thames Hub Vision assets, we can determine how the additional employment will affect the services provided by the infrastructure elements. In Table 8.5 we present the population changes in the LSOAs intersected by the road and commuter rail stations, and those bordering the estuary

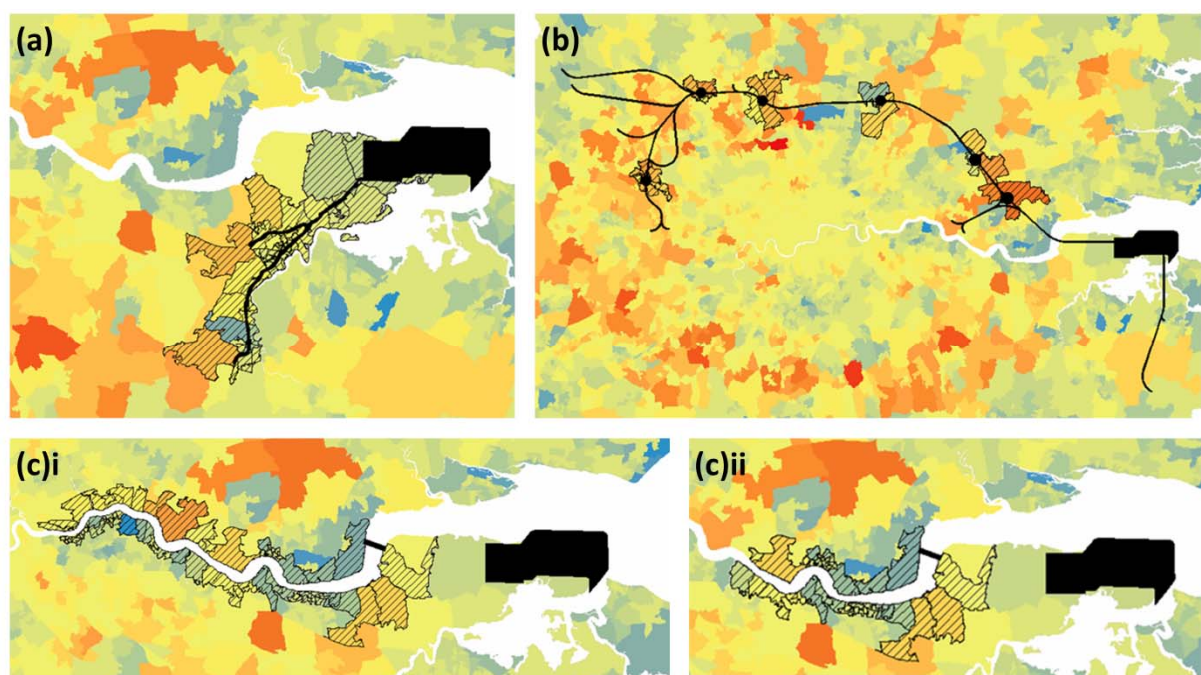
³¹ Note these people may not remain in these locations if further employment is generated.

between the current/'do minimum' barrier (see Chapter 4) and the Thames Hub Vision barrier (see hashed regions in Figure 8.9).

Table 8.5 – SIMULACRA predicted population change for LSOAs in proximity to the Thames Hub Vision assets

Asset	25,000 Employee Scenario	50,000 Employee Scenario	100,000 Employee Scenario
(a) Road	-2,887	6,362	17,076
(b) Commuter Rail Stations	21,347	21,444	21,656
(c)i. Barrier (compared to Greenwich Barrier)	-22,954	-20,463	-16,775
(c)ii. Barrier (compared to Long Reach Barrier)	-15,136	-12,761	-9,437

Figure 8.9 – LSOAs included within Table 8.5 results (shown for the 25,000 employee case)



8.5.2 Demand for the Thames Hub Vision road and rail assets

It must be remembered that the transport costs within the SIMULACRA model reflect existing transport assets. The population changes predicted are therefore those that would occur if the airport employment was created with no additional surface access developments. The development of the Thames Hub Vision road and rail assets would work to lower these transport

costs for neighbouring LSOAs and make them more attractive for both the residential population and population reliant industries. The population of the hashed LSOAs in Figure 8.9(a) and (b) are therefore likely to be lower than if the effects of the road and rail assets were included. Despite this, we can infer how the predicted changes in population would affect inherent demand for the Thames Hub Vision assets.

The results suggest that there will initially be less demand for the road asset with a total reduction of 2,887 people in the LSOAs through which the road runs. This represents a 5 per cent reduction compared to the no-employment case. However, as we have noted above, provision of greater transport links in this area may affect this result, making the area more attractive than that shown in the SIMULACRA results. For the other two scenarios the situation is reversed, with an increase in population in these LSOAs equivalent to 11 and 30 per cent of the no-employment population levels (50,000 and 100,000 employee scenarios respectively). In contrast, the residential populations of the LSOAs in the immediate vicinity of the rail stations are significantly increased by the 25,000 employee scenario, rising 21,347 (39 per cent) over the no-employment case. However, further doubling or quadrupling the employment increase has little effect, with the 50,000 employee scenario increasing population by a further 97 people (a 0.4 per cent increase over the 25,000 employee scenario), and the 100,000 employee scenario increasing population by a further 212 people (a 1 per cent increase over the 50,000 employee case).

As noted in Chapter 5, the road asset would need to save travellers approximately 3,500 hours per day to have a 1:1 Benefit Cost Ratio (BCR). This was deemed unlikely given that surrounding roads have daily traffic counts of only 6,000 to 20,000 vehicles (Department for Transport, 2012). The population reductions shown in the 25,000 employee scenario suggest that the potential of reaching a positive BCR would be decreased; however, all 25,000 employees must

reach the airport and unless there is a suitable rail connection, they must use the road network. The creation of 25,000 jobs (and 25,000 return journeys) will therefore significantly improve the utilisation of the road asset. Indeed, should all 25,000 employees access the airport by road, each would only need to save 4.2 minutes per journey to reach the 1:1 BCR.

The provision of the rail asset undermines this result, providing a secondary means of access to the airport. Furthermore, in the 25,000 employee case, much of the population growth is centred around LSOAs in proximity to the commuter stations, making rail access more attractive. Given the high percentage of commuters in London who chose to travel by rail³² and the proposed active traffic management approach of the airport, it is likely that many of the employees would chose to make use of the rail asset. The 25,000 single journeys per day required to create a 1:1 BCR for the rail infrastructure (see Chapter 5), therefore seems likely to be met in all three of the employment scenarios (see Table 8.6)³³. Indeed, the stability of population growth in these areas despite further increases in employment, suggests that the existing transport network has become congested, raising transport costs and making the areas less attractive for accessing the Hoo Peninsula. This further supports the supposition that the rail asset would provide benefit. The addition of the rail asset would alleviate some of this congestion and therefore could change the 50,000 and 100,000 population results.

Table 8.6 – Potential demand for rail and road assets from employment generated by airport

	25,000 Employee Scenario	50,000 Employee Scenario	100,000 Employee Scenario
Rail Asset			
Additional population in proximity to stations	21,347	21,444	21,656
Average commuters	16,864	16,941	17,108
Single journeys	33,728	33,882	34,216

³² 79 per cent (London Transport Data 2012).

³³ Note this is still a low BCR and would not normally be sufficient to encourage investment.

	25,000 Employee Scenario	50,000 Employee Scenario	100,000 Employee Scenario
Road Asset			
Remaining employees	8,136	33,059	82,892
Required time saving ³⁴ (mins)	25.8	6.4	2.5

To estimate the employment-generated road demand when the rail asset is present we subtract the rail demand in Table 8.6 from the total employees. Dividing the results by the time saving necessary to achieve a 1:1 BCR we find the required time saving per journey (see Table 8.6). In the 25,000 employee case, a 1:1 BCR is unlikely to be realised requiring savings of over 25 minutes per journey. However, the 6.4 minute and 2.5 minute savings per journey required by the 50,000 and 100,000 employee scenarios are much more likely to be realised. We can therefore conclude that while the rail asset appears worthwhile in all scenarios, the road asset is only beneficial in the absence of the rail asset or if 50,000 or more jobs are generated.

Furthermore, unless the employees travelling by road live in the direct vicinity of the airport, their effects on the reliability of other roads and their creation of additional emissions could outweigh any beneficial effects of the road asset even under the 50,000 and 100,000 employee scenarios. Exploration of these additional effects would be a useful extension to the work once the SIMULACRA model is further developed.

8.5.3 Protection from the Thames Hub Vision barrier

The Thames Hub vision barrier is further east than either the existing Greenwich (Figure 8.9(c)i) or proposed Long Reach³⁵ barriers (Figure 8.9(c)ii), protecting more people and assets.

However, the SIMULACRA results suggest that population along the banks of the eastern end of the Thames Estuary will decline, reducing this benefit. The single asset result for the barrier

³⁴ To reach a BCR of 1:1.

³⁵ Assumed to be implemented in 2070 in accordance with current Environment Agency plans (Environment Agency, 2009).

(-£1.94bn, see Chapter 5), is therefore likely to get worse as the £0.34bn security benefit is reduced.

However, as noted above, the effects of new transport assets are not included within the SIMULACRA transport costs. The effects of the Thames Hub Vision river crossing (barrier) and Lower Thames Crossing are therefore not taken into account when calculating the population distribution. These crossings would substantially decrease transport costs between the north and south banks of the River Thames making the surrounding areas more attractive. While the transport benefits would be shared between the two crossings, throughout this thesis we have attributed them to the Lower Thames Crossing, which is likely to be implemented first. The barrier does not therefore generate transport service benefits, but would create benefits from any population increases that resulted from the greater accessibility provided. Again, inclusion of the Thames Hub Vision and 'do minimum' transport assets (see Chapter 4) within the SIMULACRA model would be a useful and informative next step in this analysis, once the model has been further developed.

8.5.4 Environmental effects of the single/portfolio assets

As noted earlier, two of our appraisal performance metrics (noise and water quality) rely directly on the residential population in proximity to the assets. We can therefore quantify the effects of the SIMULACRA population predictions on these factors by using the appraisal methodology. As both metrics are environmental indicators, we can consider the effects of the population feedbacks by looking at this attribute (see Table 8.7). We discuss these results below.

Table 8.7 – Effects of the SIMULACRA model population predictions on the total environmental attribute

Asset	Total Environmental Result (2010 prices, £bn)			
	No Employment	25,000 Employees	50,000 Employees	100,000 Employees
Road	-0.85	-0.76	-0.79	-0.85
Barrier	-0.94	-0.93	-0.93	-0.93
Full Rail	-1.92	-1.95	-1.96	-1.98
Airport (single asset)	-2.16	-2.15	-2.16	-2.17
Airport (portfolio)	-0.32	-0.31	-0.32	-0.32

In most cases the SIMULACRA population predictions produce a change in the environmental attribute of less than 5 per cent. This is despite the fact that the noise and water quality impacts were an order of magnitude larger than the other environmental effects for the road, rail and barrier assets (see Chapter 5). It therefore shows that the population changes generated by the employment scenarios are relatively small compared to the baseline population projections.

The exception is the road asset, for which the population decreases reduce the noise impacts by 10.2 per cent (£86.6m) in the 25,000 employee scenario and 6.4 per cent (£54.3m) in the 50,000 employee scenario. The positive effect seen in the 50,000 employee scenario is perhaps surprising, given the population increase noted in the LSOAs neighbouring the road (see Table 8.5). However, as noted in Section 8.4.3, the appraisal model uses the aggregated LA population results which show a decrease in population in the 50,000 employee scenario for the LAs in the vicinity of the road asset. The increases in the LSOA populations generated by the 100,000 employee scenario are sufficient to overwhelm any decreases elsewhere in the LA and produce an increase overall. The noise effect of the road asset is therefore greater (more negative) in this scenario, producing a total environmental result that is £4.2m lower than the no-employment result.

As airport noise affects similar LAs to the road asset, reductions are also seen for the first two employment scenarios for the airport asset, with an increase in the 100,000 employee scenario

(both single asset and portfolio). However, here the magnitude of the change is much smaller, increasing the environmental total of the airport by £9.1m in the 25,000 employee case and £5.3m in the 50,000 employee case, then decreasing by £1.5 in the 100,000 scenario³⁶.

The noise effects of the rail network are dispersed over a much wider area. By following the M25 motorway, the rail route follows areas with a high level of connectivity and therefore a low travel cost. This makes the LAs more attractive, drawing population and resulting in population increases in all three employment scenarios. The negative effects of rail noise are therefore greater in each of the three employment scenarios. The change in the total environmental effect, however remains small, varying from a 1.7 per cent change (£31.8m) in the 25,000 employee scenario to 3.0 per cent change (£58.1m) in the 100,000 employee scenario.

In contrast, the population between the existing Thames Barrier/proposed Long Reach barrier and the Thames Hub Vision barrier reduces in all cases. The value of the potential reduction in water quality is therefore reduced in all scenarios. However, again the changes in value are relatively small varying from £8.0m in the 100,000 employee case (a 0.9 per cent change) to £12.1m in the 25,000 employee scenario (a 1.3 per cent change).

8.5.5 Effects on the environmental results of the pathways analysis

Putting the SIMULACRA projections into the pathways analysis, we can consider the significance of changes in total environmental value in comparison to those generated by the more general population uncertainty (see Chapter 7). We present the results of the updated pathways analysis in Table 8.8 to Table 8.11. Note that only the airport pathways are presented as the airport asset needs to be present for the employment to be created.

³⁶ The magnitude of these changes are the same for both the single asset and portfolio cases.

Table 8.8 – Base population pathway results for no-employment scenario environmental attribute with percentage change for low and high population projections (see Chapter 7)

Pathway Family	Base Result for Environmental Minima (£m)	Change in Environmental Minima		Base Result for Environmental Maxima (£m)	Change in Environmental Maxima	
		Low	High		Low	High
Major Road with Airport	-£4,575.6	-9.6%	4.7%	-£2,014.6	-7.5%	1.9%
Major Road, Flood Barrier and Airport	-£2,716.5	-7.5%	3.4%	-£2,716.5	-7.5%	3.4%
Major Road, Flood Barrier with Gen and Airport	-£2,612.5	-7.8%	3.5%	-£2,612.5	-7.8%	3.5%
Major Road, Flood Barrier (Gen and Road) and Airport	-£3,319.4	-8.6%	1.5%	-£2,612.5	-7.8%	3.5%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£4,575.6	-9.6%	4.7%	-£2,536.2	-8.0%	3.6%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£4,575.6	-9.6%	4.7%	-£2,536.2	-8.0%	3.6%

Table 8.9 – Base population pathway results for 25,000 employee scenario environmental attribute with percentage change for low and high population projections

Pathway Family	Base Result for Environmental Minima (£m)	Change in Environmental Minima		Base Result for Environmental Maxima (£m)	Change in Environmental Maxima	
		Low	High		Low	High
Major Road with Airport	-£4,500.2	-9.8%	4.8%	-£1,922.4	-7.8%	1.9%
Major Road, Flood Barrier and Airport	-£2,612.3	-7.8%	3.5%	-£2,612.3	-7.8%	3.5%
Major Road, Flood Barrier with Gen and Airport	-£2,508.3	-8.2%	3.7%	-£2,508.3	-8.2%	3.7%
Major Road, Flood Barrier (Gen and Road) and Airport	-£3,212.2	-8.9%	1.5%	-£2,508.3	-8.2%	3.7%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£4,500.2	-9.8%	4.8%	-£2,432.0	-8.3%	3.7%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£4,500.2	-9.8%	4.8%	-£2,432.0	-8.3%	3.7%

Table 8.10 – Base population pathway results for 50,000 employee scenario environmental attribute with percentage change for low and high population projections

Pathway Family	Base Result for Environmental Minima (£m)	Change in Environmental Minima		Base Result for Environmental Maxima (£m)	Change in Environmental Maxima	
		Low	High		Low	High
Major Road with Airport	-£4,546.6	-9.7%	4.8%	-£1,957.1	-7.7%	1.9%
Major Road, Flood Barrier and Airport	-£2,648.2	-7.7%	3.5%	-£2,648.2	-7.7%	3.5%
Major Road, Flood Barrier with Gen and Airport	-£2,544.3	-8.0%	3.6%	-£2,544.3	-8.0%	3.6%
Major Road, Flood Barrier (Gen and Road) and Airport	-£3,249.4	-8.8%	1.5%	-£2,544.3	-8.0%	3.6%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£4,546.6	-9.7%	4.8%	-£2,468.0	-8.2%	3.7%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£4,546.6	-9.7%	4.8%	-£2,468.0	-8.2%	3.7%

Table 8.11 – Base population pathway results for 100,000 employee scenario environmental attribute with percentage change for low and high population projections

Pathway Family	Base Result for Environmental Minima (£m)	Change in Environmental Minima		Base Result for Environmental Maxima (£m)	Change in Environmental Maxima	
		Low	High		Low	High
Major Road with Airport	-£4,631.3	-9.5%	4.7%	-£2,019.8	-7.4%	1.9%
Major Road, Flood Barrier and Airport	-£2,713.6	-7.5%	3.4%	-£2,713.6	-7.5%	3.4%
Major Road, Flood Barrier with Gen and Airport	-£2,609.7	-7.8%	3.5%	-£2,609.7	-7.8%	3.5%
Major Road, Flood Barrier (Gen and Road) and Airport	-£3,317.0	-8.7%	1.5%	-£2,609.7	-7.8%	3.5%
Major Road, Flood Barrier (Gen and Rail) and Airport	-£4,631.3	-9.5%	4.7%	-£2,533.4	-8.0%	3.6%
Major Road, Flood Barrier (Fully Integrated) and Airport	-£4,631.3	-9.5%	4.7%	-£2,533.4	-8.0%	3.6%

Comparing the no-employment results (Table 8.8) with those of the 25,000 employee scenario (Table 8.9), we see that all pathway family minima and maxima improve becoming less negative. This reflects the dominance of the road, barrier and airport reductions over the rail asset increases. The variation in total environmental value in the base case is between £75.4m and £107.2m in line with the assets included within the pathway and the single asset results described above. However, this change represents less than a 5 per cent change in total environmental value in all cases, between one tenth and half the effect of the more general population uncertainties described in Chapter 7. Furthermore, while the range in values between the low and high population projections increases for all pathway families, the variation in the percentage change is less than 0.5 per cent in all cases.

In the 100,000 employee scenario (Table 8.11) we expect to see environmental value decrease as population increases. However, as the change in value for the road and airport asset are now much smaller than in the 25,000 scenario, the beneficial effects of the barrier dominate in some cases causing a small benefit of up to £2.9m. In cases where the rail is present, this dominates the result creating negative effects of up to -£55.7m. These results represent only a small change in the total environmental result (-0.1 to 1.2 per cent), with even smaller changes in the range for the low and high population predictions (maximum of 0.1 per cent change). The feedbacks therefore represent less than one tenth the effect of the population uncertainty discussed in Chapter 7, with seven of the pathway results being less than 1 per cent of this uncertainty.

The 50,000 employee scenario results (Table 8.10) fall between those of the 25,000 and 100,000 employee scenarios. Small growths in the population of the LSOAs surrounding the airport and road assets are dominated by the population reductions elsewhere in the LA. This reduction in the LA population affects the road, airport and barrier values and causes their beneficial results

to dominate the slight increase in environmental costs from the rail stations³⁷. All pathways show positive changes to the total environmental value (varying from £29.0 to £70.0m depending on the assets present). This represents a maximum change of 2.9 per cent from the no-employment scenario results. Variations in the low and high population ranges are again very small, with a maximum change of 0.2 per cent in any case.

8.5.6 Comparing the additional value of the spatial analysis with the effort required

Given the limited effects of the spatial analysis on the pathway results, we must question whether it is a worthwhile addition to the methodology. Considering the single feedback of population (employment) assessed herein, the additional effort required to undertake this analysis would be difficult to justify. Most of the pathway range is produced by the sensitivity analysis undertaken in Chapter 7. This analysis only requires re-running the appraisal model for the bounds of population, while the spatial analysis requires integration with another model, which may not exist for the region under consideration. Furthermore, the model is not likely to be within the skill-set of our stakeholders, limiting the practicality of the overall methodology. Drawing on the limited results herein, the addition of a spatial analysis is therefore likely to remain optional, being potentially useful where transport effects dominate and can be analysed using existing models. However, the full effects of the feedbacks need further assessment, after which this conclusion should be revisited.

³⁷ The population of the LAs in proximity to the rail asset is only slightly increased from the 25,000 employment scenario as their attractiveness is reduced by the increased transport costs caused by the previous population growth.

8.6 Conclusions

Spatial models are already considered a useful complement to CBA appraisals for transport investments (Vickerman, 2007)³⁸; however, are not used for appraisals in the other sectors. In this chapter we have considered whether such an extension could be useful, aiming to explore our final increment of complexity: the effects of interdependencies between infrastructure assets and the investment landscape. We therefore undertook to qualitatively review the feedbacks between infrastructure developments and their investment landscape and examine one such feedback to demonstrate an appropriate extension to the appraisal methodology.

We proposed four objectives in meeting our aim, and have delivered each of these in turn. First we reviewed the inputs and effects of infrastructure investments, determining that the population feedbacks were likely to have the greatest influence on the appraisal results. We analysed potential models that could be used to include this feedback within the appraisal methodology, finding LUTI models to be the most appropriate at the regional scale and for considering the relationships between infrastructure, where people choose to live and the local economy. Within this set, the SIMULACRA model was found to offer the greatest granularity and flexibility for early appraisal studies. Furthermore, it provide the opportunity to explore the effects of employment, one of the six performance metrics noted to produce population feedbacks in all infrastructure cases and one of the few metrics able to capture some of value of macro-economic effects.

Our final objective was to determine the effects of this feedback on the appraisal results, incorporating the SIMULACRA results into our model and testing on the Thames Hub Vision case

³⁸ Indeed with the strong links between transport and land use, some authors suggest testing proposed transport schemes against current/wanted spatial dynamics at their inception, with those that fail not being considered further (see Headicar (2009), for example).

study. Our results suggest that airport generated employment could create significant demand for the road and/or rail assets and be sufficient to result in a positive BCR for these investments. However, where both assets are present they compete for this demand. In the lowest employment scenario, population growth is seen near the rail assets, while population is reduced near the road assets. This suggests that employee travel to the airport is likely to be predominantly by rail, undermining the case for the road investment. Furthermore, the consistency of the population levels near the rail assets despite further increases in employment, suggests that transport has become congested and that additional infrastructure (such as the rail orbital) would be valued. This congestion, however, makes areas close to the airport asset more attractive, increasing demand for local roads. Therefore in the higher employment scenarios it is possible that both the road and rail assets would have positive BCRs, although the emissions and congestion caused by increased road use would need to be further explored. As the SIMULACRA model develops it should be possible to alter the transport costs to reflect the Thames Hub Vision and 'do minimum' assets (see Chapter 4) and therefore test these conclusions further.

The population projections also allowed the noise and water quality impacts of the assets to be reassessed. While these indicators represented the majority of the environmental costs for the road, barrier and rail asset, the results of the feedbacks were found to be small in comparison to that created by the general uncertainty of the population projections (see Chapter 7), particularly in the 100,000 employee scenario. This result undermines the value of the additional effort required in undertaking the spatial assessment. However, the translation of the SIMULACRA results for the pathway analysis highlighted two important factors for the consideration of the spatial model. Firstly, in reducing the scope of the model, we created an increase in total population. This shows the movement of people from neighbouring regions and therefore a benefit to the case study region at the cost of another region. Such movements

could undermine the business case for infrastructure assets in other regions. It would therefore be important to consider such population movements in a more national assessment of infrastructure investments. The second aspect of the model was the spatial resolution, here we saw different results for the assets under the 50,000 employee scenario depending on whether the LSOA or LA zoning was used. As increased model resolution increases the computation expense of the model, we must decide on the most suitable level of resolution given the uncertainty of the results and the intricacies of the scenarios. The benefit of models such as SIMULACRA is that the spatial resolution can be varied, allowing the model efficiency to be increased when lower levels of resolution are sufficient. In addition to the further review of the employee transport effects suggested above, it would therefore also be valuable to consider the results from local and national perspectives, moving up and down the appraisal hierarchy outlined in Chapter 1.

9 Conclusions and Implications: The Information Gain of Appraising Infrastructure as a Systems of Systems

9.1 Introduction

In Chapter 1 we concluded that current infrastructure appraisal, while highly developed in some sectors, was oversimplified. In particular, it lacked a consideration of the system of system interactions and that this hid much of the value of infrastructure investments. Furthermore, that this, and the relatively short-term nature of the appraisals, obscured some of the long-term impacts of the developments and therefore the system's resilience to change. We posited the hypothesis that:

There is more scope for achieving robust outcomes in the long-term, if the interdependencies between infrastructure networks are taken into account; in contrast to the situation that exists at present where each network is addressed largely in isolation.

The focus of this thesis has been to investigate this hypothesis, aiming to:

Develop and demonstrate a practical decision making methodology for multi-sector infrastructure investment, which is robust to future uncertainties and takes account of the system's interdependency.

The requirements of this aim were investigated in Chapter 1, through a review of recent studies into appraisal best practice and advances in decision making under deep uncertainty. From these insights we developed two objectives necessary for achieving our aim, specifically:

- To develop a common appraisal framework that delivers a more complete valuation of infrastructure developments, capturing the multiple stakeholder perspectives and resources required, but also the cross-sector and systems effects created by the system as a whole; and
- To develop a policy level multi-sector decision-support tool focused on ensuring solutions are robust to future change by considering how future infrastructure investments are enabled and constrained by the decisions made, the potential total value of the system and the uncertainty of the results.

After reviewing current methodologies and frameworks (see Chapter 2), we found that none currently captured pathway and system effects over the long-term, therefore determining that a new combined approach would be necessary. However, that the complexity of this new methodology would need to be constrained if it was to remain usable and maintainable by stakeholders. Furthermore, that a new decision-support tool would need to be created if the results were to be translated into a form that was comprehensible by stakeholders. Given our aim, this decision-support tool should emphasise the flexibility provided by developments, as well as their intrinsic and system value. In Chapter 3, we defined such a framework, methodology and toolset, building on current appraisal methods (which would be familiar to stakeholders), but also real options, portfolio analysis and pathways analysis.

After choosing a suitable case study (Chapter 4) and refining our valuation methodologies (Chapter 5), the appraisal methodology was applied in five incremental stages of complexity. These were:

- Assessment against a single attribute vs multi-attribute valuation;
- Investment in individual projects vs investment in groups of projects (portfolios);

- A specified single project/portfolio vs consideration of pathway flexibility;
- Single future projection vs valuation under an uncertain future (sensitivity analysis); and
- Isolated predictions of change vs path dependency and feedback (incorporation of the interdependency between the development and the investment landscape).

Through use of these five increments, relevant to all decisions under deep uncertainty, we aimed to derive the benefit of the additional effort necessitated by a more complex methodology and the change in perspective each level provided. We have outlined the results of these studies in Chapters 5 to 8, but now bring the conclusions together in this chapter to consider whether our aim and objectives have been achieved and whether our hypothesis was valid.

9.2 Thesis summary and validity of hypothesis

9.2.1 Delivery of thesis objectives

The first objective of this thesis was:

To develop a common appraisal framework that delivers a more complete valuation of infrastructure developments, capturing the multiple stakeholder perspectives and resources required, but also the cross-sector and systems effects created by the system as a whole.

This common appraisal framework was developed in Chapter 3. To ensure that the different stakeholder perspectives were reflected by the results, performance metrics were developed under four attributes, with this multi-attribute segmentation maintained throughout the analysis. The four attributes focused on stakeholder priorities (environmental, monetary,

service and social), rather than specific stakeholder groups. For example, the monetary attribute indicates the financial viability of the development; however, it includes benefits to the operator (revenues), to the population (employment) and to the Treasury (taxes and employment). This aimed to focus stakeholder discussion on the purposes (and priorities) of the developments without creating barriers between the different groups. Furthermore, as full tailoring of the results would need to reflect the different valuations the groups would apply to the different metrics, it would work against the common approach necessitated for the system analyses. The segregations also reflected the uncertainty of the valuations, allowing more uncertain results (environment and social) to remain visible despite their low initial valuations.

The methodology was first tested in Chapter 5. Appraisals equivalent to current single sector analyses were produced for each of the case study assets, proving the methodology capable of recording the key performance factors¹ for each of the sectors (water, energy and road, rail and air transport modes). Of the resources for infrastructure development identified in Chapter 3, three² were recorded directly through the performance indicators and were therefore present in these single asset assessments. By calculating use of these resource metrics in a common way and summing across the developments, we can provide a simplified systems perspective on resource requirements. This would be very difficult to achieve through the current sector-siloed methodologies due to their different assumptions and valuation methodologies. However, we noted three shortcomings of such single asset approaches³, which would affect the accuracy of the appraisal:

¹ See Chapter 5, Section 5.2.1.

² Financial, impact ('finite' resources, defined in Chapter 6, Section 6.2.2, such as those which are naturally or legislatively limited, for example carbon dioxide emissions) and operational (functional resources such as people/skills, electricity or water).

³ See Chapter 6, Section 6.2.1.

- Assets may only be possible when developed together, or may be mutually exclusive; therefore the choice may be between a sum of effects or none of the effects;
- The assets are inherently coupled, therefore the valuations may not be entirely separable, but may assume the presence or absence of other infrastructure assets; and
- The valuations may not be a simple summation of those for each asset, but rather there may be system effects in addition to those ascertained by the individual appraisals.

To ensure a more complete valuation of the developments, it was therefore necessary to capture the constraints and prerequisites, cross sector effects (such as the use and presumed availability of resources) and system impacts (such as efficiencies, connectivity and aggregation) of the developments as a system. By understanding these interdependencies we recognised a further resource (the spatial requirements of the developments) and more fully captured the effects of the original three. This included the competition between assets (affecting their financial resources), cross sector effects (such as increased demand, changing the financial and operation resources of other assets) and the systems effects (such as efficiencies, reducing, for example, their impact resources). These system effects were found to be significant for the case study, being sufficient to reverse the result of the airport appraisal.

Having developed a common system appraisal methodology, we moved to our second objective, namely:

To develop a policy level multi-sector decision-support tool focused on ensuring solutions are robust to future change by considering how future infrastructure investments are enabled and constrained by the decisions made, the potential total value of the system and the uncertainty of the results.

As noted above, the appraisal methodology was already cross-sectoral and, having been based on the welfare economics approaches used within the sectors, was inherently focused on the policy level decision maker. However, we also wished for the tool to ensure solutions were robust to future change. We therefore needed a temporal analysis of the developments, including the different possible implementation timings and the uncertainty created over the period.

Our identification of development prerequisites and constraints allowed us to create potential development pathways, capturing how investments were enabled or constrained by prior developments. These pathways could be valued as a whole, including their cross-sector and system effects, negating the need to attribute such effects to a single asset, as would be required by current appraisal approaches. Furthermore, by recording the system values, the results highlighted the potential to use groups of assets to balance impacts and benefits between stakeholders/attributes or over time. By varying the groups in which our assets were implemented and our implementation policy⁴ we developed an array of different development pathways reflecting different future approaches. However, this also provided a large decision space to be navigated by the decision maker⁵, strengthening the need for a decision-support tool.

By grouping these pathways into families, we explored which initial investments gave the greatest opportunities for each of the attributes, which had the greatest risks and which provided stability. We therefore captured the flexibility and robustness provided by each pathway family. Families whose total value did not reach required benefit thresholds (or exceeded impact constraints) could be eliminated, reducing the decision space and allowing it to

⁴ Earliest implementation data and delay between implementation groups, see Chapter 3, Section 3.5.

⁵ In the case study, 77 possible portfolios were developed with 644 implementations for each set of inputs (for example population projection) and implementation policy.

be more easily navigated by the decision maker. Finally, by including all the results of the pathway family as ‘ranges’ of opportunity/impact, the methodology captured the uncertainty of the pathway and highlighted this to the decision maker. Further uncertainties were introduced into these opportunity ranges, allowing exploration of how key attributes (see Chapter 7) and feedbacks (see Chapter 8) affected the results.

9.2.2 Delivery of thesis aim

The objectives were derived from the aim of the thesis:

To develop and demonstrate a practical decision making methodology for multi-sector infrastructure investment, which is robust to future uncertainties and takes account of the system’s interdependency.

Therefore, by completing both objectives, most of the aim has been achieved; however, this has been at the cost of increasing the complexity of the methodology. The effects of this increase in complexity (the additional analytical time and effort required), were considered in Chapter 2 (Section 2.6) and were minimised where possible⁶. However, if the methodology is to be ‘practical’ as required by our aim, it must remain suitable for stakeholder use and maintenance, and the additional effort required by the complexity must be deemed worthwhile. We therefore implemented the methodology in five increments of complexity, assessing the additional effort and information gain provided by each as they were implemented (Chapters 5 to 8). We summarise the conclusions below.

⁶ For example, through the use of a simple, high-level cost benefit analysis grouped into only four attributes and a flexibility based approach to deep uncertainty, rather than through the consideration of vast arrays of possible futures.

The first increment was to take a multi-attribute perspective. This has been revisited throughout the thesis with three key benefits found. Firstly it represents the different stakeholder viewpoints and, as noted above, maintains this focus despite the environmental and social attributes holding a far lower value than the monetary or service attributes. It therefore provides information on which stakeholder priorities are, and are not, met by the development. Secondly, it splits the indicators by the valuation approaches. While all monetary and most service performance indicators can be valued through the markets, the environmental and social performance indicators cannot. These must therefore be valued through ‘shadow pricing’ methods⁷ which have a much higher level of uncertainty attached to their valuations (see Chapter 5, Section 5.7). The non-market indicators also include finite resources for which the marginal change assumptions of Cost Benefit Analysis (CBA) can be invalidated, making their valuation even more uncertain (see Chapter 6, Section 6.2.2). Thirdly, it more clearly displays the effects of uncertainty, revealing balancing effects between attributes and if any attributes are more strongly affected by a given uncertainty. For example, the large changes in the monetary and service attributes of the airport (single asset assessment) under variation of the discount rate are hidden in its total appraisal valuation due to their opposing nature (see Chapter 7, Section 7.4.3) and the environmental attribute pathway results were found to be far more susceptible to changes in population projection than the other attributes in almost all cases (see Chapter 7, Section 7.5.4). These changes, which as noted earlier represent changes in stakeholder priorities, would only be captured by a multi-attribute perspective.

Given that a multi-attribute approach only requires keeping our results disaggregated, the additional effort required in this increment is mainly that in analysing the results and considering their implications. This is already done in the sector specific analyses, indeed, our choice of only

⁷ Deriving individual willingness to pay/accept either by directly asking people about their preferences or by considering their current behaviour.

four attributes (made to limit the additional effort created by this increment), is less complex than some of the sector approaches. This level of aggregation was found to have the beneficial effect of amalgamating the six small environmental indicator results, bringing their scale into closer alignment with the other attributes and therefore making them more visible (see Chapter 5, Section 5.7.6). It does, however, hide some of the intricacies of the appraisal, obscuring the indicators included and their individual magnitude. As one of the methods for reducing the decision space is to compare the outputs to thresholds, and these are more likely to be available for the individual indicators (for example maximum carbon dioxide emissions) it is necessary to retain the ability to disaggregate the attributes for more detailed analysis. The four attribute approach therefore provides significantly more information than a single Benefit Cost Ratio (BCR) without a significant increase in effort and should be maintained along with the ability to further disaggregate the attributes if necessary.

The second increment was to consider the developments as integrated, interacting elements rather than standalone assets whose costs and benefits could simply be summed. This required the prerequisites and constraints of each asset to be assessed, along with their potential cross-sector and system effects. This is a significant undertaking. Should the methodology be used to bring together the national and sector plans for a region, this stage would require interviews with all sector stakeholders and potentially cross-sectoral workshops to identify all the resource requirements of the proposed assets. However, for the case study, the information gained by this process led to a significant change in the benefits recorded. This was sufficient to change the appraisal result for the airport (see Chapter 6, Section 6.3) from a net negative of -£14.3bn to a net positive result of £31.9bn. This increment was therefore judged to be fundamentally important if we wish to more correctly value our assets as part of the existing and changing infrastructure system of systems. To not do so undermines our ability to make appropriate decisions about how to use our resources. Furthermore, by understanding how the assets are

reliant on each other, we can inform infrastructure operators of the opportunities and risks of these dependencies, encouraging ongoing engagement between these groups. This increment should also therefore be maintained.

The third increment of complexity required introducing time into the analysis, considering how the infrastructure assets enable or constrain future developments and therefore the flexibility they create. Here, the prerequisites and constraints needed to create potential development portfolios (groups of investments) had already been identified at the previous increment of complexity. Therefore the additional effort for this increment was in setting these portfolios against different implementation groupings and timings (referred to as 'strategies') and analysing the large quantity of data produced. To allow this analysis, the results were aggregated into 'pathway families' based on their common infrastructure asset(s), displaying only the range of costs and benefits that the common asset could achieve depending on the strategy taken. Flexibility was then considered by tracing alternative development decisions and comparing the difference in opportunity or risk shown by their ranges of results. The value in this stage is therefore twofold. Firstly, it provides a greater understanding of the effects of the assets as part of a developing system over time, particularly their ability to enable future developments, a factor which is lost in current appraisals. This was found to be particularly significant for early investments. Taking the case study road developments for example, while the direct effects of the two alternative developments considered were quite similar, their pathway effects were substantially different⁸ and up to an order of magnitude larger (see Chapter 6, Section 6.5.1). Secondly, it provides the framework to navigate the decision space created by the more complex, but more complete, appraisal developed in our second and third increments. It focuses attention on the costs and benefits of the system as a whole, allowing

⁸ For example, the monetary maximum for the major road pathway family is over 20 times that of the minor road pathway family.

stakeholders to examine which opportunities are most important and should be kept open. Furthermore, it allows these effects to be traced to key relationships or assumptions to identify which should be monitored and when the decisions should be reviewed. This increment was therefore deemed necessary for managing the developing system over the long-term and dealing with the deep uncertainty inherent in these decisions. The additional effort required is restricted to the development of a reusable algorithm and this increment should therefore be maintained.

Our fourth increment focused on capturing how uncertainty affected the system appraisal results, assessing two key variables through a sensitivity analysis of each. The additional work was therefore limited to running the model for two bounding values for each variable and comparing these to the pathway results. The effects of the uncertainties were found to be significant, particularly in the case of the discount rate, which caused a reversal of some of the attribute results (see Chapter 7, Section 7.4.4). However, they were also found to be different for the single asset appraisals and the systems analyses. For example, the total portfolio result was found to be far more sensitive to changes in discount rate than the single asset result (see Chapter 7, Section 7.4.3). This again suggests the importance of a systems perspective rather than the current asset or sector specific focus, if we are to make appropriate appraisal decisions, reinforcing our reasons for maintaining increment 2.

The specific variables chosen highlighted the balance of impacts and benefits over time (discount rate) and the effects of current capacity constraints (population projection). They would therefore provide useful information for any infrastructure project. In addition, both sensitivity analyses highlighted interdependencies and common assumptions within the attributes, that created balancing effects in the results. For example, the reduced sensitivity in the single asset case (as noted above) was due to the opposing effects of the monetary and

service attributes. In the single asset case both attributes are strongly dependant on air passenger numbers, balancing the results despite the change in discount rate (see Chapter 7, Section 7.4.3). However, in the systems case, the service attribute is partially decoupled from passenger numbers due to the availability of rail services. The effect of varying the discount rate is therefore much greater⁹. These balancing effects allow indicators that are less affected by the sensitivity variable to dominate¹⁰. In both sensitivity analyses such effects produced attribute results that were better in both extreme cases than the base projection. Such results could be seen as advantageous, being resilient to the uncertainty. However, as they rely on costs and benefits being in balance, the predicted benefit cost ratio is likely to be low, making them appear less valuable. This increment of complexity therefore also presents the trade-offs between resilience and optimal performance under expected conditions.

From a decision-support perspective, the sensitivity analysis highlights whether variables affect multiple indicators and/or have the potential to cause compound errors. Furthermore, it identifies which variables or attributes cause the greatest uncertainties¹¹. This informs the monitoring process, providing additional variables that should be tracked and used to initiate pathway reviews if progress is not according to the projections made. As the effort required to gain these insights is limited and similar to that already conducted within the sectors, this was deemed practical, therefore this increment should also be maintained.

The final increment introduced the feedbacks between the developments and the investment landscape and was explored through a Land Use Transport Interaction (LUTI) model. The

⁹ Over five times larger in the portfolio case than in the single asset case.

¹⁰ Indicator components not reliant on population (such as 'other' airport revenues in our model) and those which either happen very early/very late in the time period and therefore are less affected by discounting, or which allow assets to be implemented at different times, for example to take early advantage of benefits and delay costs.

¹¹ For example the service minima for the airport pathways under the Stern discount rate (see Chapter 7, Section 7.4.4).

development of such models is a complex undertaking requiring specialist knowledge and significant effort. It is not likely to fit within the skillset of stakeholders or the timeframe given to make appraisal decisions and was not, therefore, included within the initially proposed framework. However, where existing models are already available, these can provide a spatial analysis of population change given specified changes in employment (all sectors) or accessibility (transport only). This, in turn, can be used to further test the uncertainty of the appraisal results, for example whether the induced population changes support or undermine previous investments.

A limited analysis of this increment was conducted in Chapter 8, through a review of a single feedback: the effects of employment on the case study. The employment growth modelled represented a very ambitious target for any development, doubling and then doubling again the estimated change in employment from the airport (25,000 to 100,000 employees). Despite these large changes in employment, the percentage change in population from the low to high employment scenario remained less than 5 per cent in all but three zones¹², limiting the effects on the system. Results for the individual assets, showed that this population change would be unlikely to reverse any appraisal decisions¹³ (see Chapter 8, Sections 8.5.2 and 8.5.3). Similarly, the effects on the pathway environmental minima and maxima (noise and water quality) were found to be of the order of 5 per cent or less, less than half that of the population uncertainty results (fourth increment). Furthermore, the effects on the environmental pathway ranges were less than 0.5 per cent in either direction.

¹² This is due to the feedbacks of the system, making initially attractive zones less attractive as they become more populated and therefore more congested.

¹³ While the rail development may become positive, the BCR would remain very low. Similarly, the road asset would not have a positive BCR unless significant indirect employment was induced and the barrier would become more negative as its affected population (and hence security benefit) was reduced.

Further exploration of other feedbacks (such as the accessibility effects of the employment growth or that created directly by the proposed transport developments) is necessary. However, drawing on the single analysis conducted, the observed effects of the employment feedback are limited compared to those of the population sensitivity analysis. Furthermore, the analysis requires significant additional effort. This increment is therefore likely to remain as an optional analysis. It may still be useful where transport effects dominate and can be analysed using existing models. However, for non-transport dominated systems, the sensitivity analyses undertaken as part of the fourth increment of complexity, will capture most of the uncertainty created by feedbacks with the investment landscape.

From the above discussion we can conclude that we have indeed delivered the thesis aim, developing and demonstrating a decision making methodology for multi-sector infrastructure investment, through our two objectives. The ‘practicality’ of this methodology has been investigated in the discussion above, with the conclusion that the first four increments offer significant additional information without requiring excessive additional effort. These increments deliver an understanding of the interdependencies and uncertainties of the appraised system and therefore provide the final element of the aim, the focus on robustness.

9.2.3 The validity of our hypothesis

Having completed our aim we can consider whether our hypothesis has been validated. Our hypothesis was that:

There is more scope for achieving robust outcomes in the long-term, if the interdependencies between infrastructure networks are taken into account; in contrast to the situation that exists at present where each network is addressed largely in isolation.

From our discussion in Section 9.2.2, we can conclude that current infrastructure appraisal is incomplete. Interdependencies have been shown to lead to additional value, through enabling future developments and system effects. In our case study, these effects were sufficient to reverse the appraisal result, suggesting that by taking these factors into account we can indeed make more informed decisions about our infrastructure. In addition, the interdependencies put cross-sector stresses on the system and can constrain future developments, undermining or negating their value. By placing developments into pathways we can consider both the opportunities and constraints created by a particular development and trace their effects for the system as a whole. We can compare the flexibility and uncertainty of these pathways helping us to make decisions which can adapt as uncertainty is diminished. Furthermore, by understanding the system dependencies and uncertainties, we can be more aware of factors which must be tracked to inform our decisions or trigger reviews of the current plan.

Such an analysis has heretofore been impossible due to the differing assumptions, performance criteria and valuation approaches taken by the sectors. By developing a common appraisal methodology, this work provides the fundamental step in achieving a systems approach. In addition, it provides a demonstration of how both current uncertainty methods and the more embryonic pathways methods can be extended to allow application in this context. While the methods applied align with current appraisal guidance, by focusing on the interdependencies between the networks, we have created a methodology that allows more informed decisions and provides a plan of action that is flexible and can be actively adapted to changing conditions. Both these benefits provide additional information to the decision maker about the long-term resilience of their decisions. This information would not be available through sector specific analyses and therefore, by including interdependencies, we can indeed provide more scope for making robust decisions.

9.3 Limitations of the proposed methodology

While the research herein achieved its aim and allowed the hypothesis to be validated, it is still limited by the approach taken and the analysis possible within the available time constraints. We must consider these limitations before we can conclude the research contributions made. We discussed the former of these limitations when the constituent methodologies were first considered in Chapter 2 and the latter as we implemented the five increments of complexity. In the discussion below, we therefore draw together the most significant of these limitations and note the additional information that any users should be made aware of when applying the methodology.

The most significant limitations lie with the methodology itself, particularly the use of CBA as the foundation of valuation. CBA is a controversial technique and its legitimacy for valuing non-market effects, long-term, non-marginal changes¹⁴, low probability high consequence events and/or investments with macroeconomic or distributional effects¹⁵, is simply not accepted by some authors. This not only affects the accuracy and uncertainty of the results, but also significantly reduces the potential to consider the more structural effects of infrastructure on regional and national growth, one of the primary purposes of such investments in mature economies. Where the method is accepted, further uncertainties regarding the summation of coupled or interrelated indicator values, the spatiality of benefits, and how societal values may change over time¹⁶, further undermine the valuations produced. Despite these uncertainties, there is a tendency to take CBA results as unbiased evidence, with their quantified results taken as a 'truth'. Headicar (2009, p349) notes this in his review of the Department for Transport WebTAG methodology:

¹⁴ Those including limited resources/planetary boundaries.

¹⁵ See Beuthe (2002).

¹⁶ See Daly (1992) and Frischmann (2012).

“Although its requirements are devised to be as 'fair' and soundly based as possible within their own terms, they nevertheless represent conventions rather than absolute truths. These inevitably cut across different 'views of the world' likely to be held by other groups seeking to influence transport decision-making and impose their own, implicitly superior, legitimacy. In this we are not talking about differences in objective or policy which are acknowledged to reflect value judgements but about the power of technically derived 'evidence' and its presentation being treated as value-free when inevitably it is not.”

By developing a methodology that can be used across sectors, we further legitimise the results and extend this perspective. Furthermore, by using an extended timeframe we increase uncertainties, requiring projections of climate change, economic growth and technological advancement that cannot be substantiated.

CBA is, however, the dominant methodology used within infrastructure sector appraisals. We therefore chose to build the methodology on this technique to ensure it was useable and understandable by the stakeholder community. It will still be important to communicate the limitations of the underlying approach to all users, and we have continually highlighted the uncertainties of the technique throughout this thesis. In addition, we have created attributes which segregate indicators with different valuation uncertainties and displayed the smaller, more uncertain results on a different scale to ensure they are not dwarfed by the other attributes. Furthermore, we present the results as ranges to further emphasise the uncertainties surrounding variable projections and implementation timings. While the underlying concerns surrounding CBA have not therefore been removed, we believe that the methodology does encourage consideration of the uncertainties produced.

Our valuations will also be affected by our choice of indicators and attributes. Our indicators were chosen based on an analysis of existing approaches (see Chapter 3, Section 3.3.3) focusing on those with cross-sector importance. However, we have excluded factors of emerging importance such as quality of service and macroeconomic effects, which are not sufficiently

understood to value as part of a CBA. Our exclusion of these factors unintentionally diminishes their importance for decision making. To include such factors they may need to be considered qualitatively, or be included at different levels of the appraisal hierarchy (see Chapter 1, Section 1.4.2) where they may be easier to quantify. Undertaking appraisals at different levels will allow indicators with sector specific¹⁷, national, or international importance to be highlighted. It must be remembered that the methodology described herein is not intended to replace these appraisals, but to allow regional issues to be considered alongside these priorities. Our aggregation of indicators into attributes helps ensure that the smaller, more uncertain values are still recognised and simplifies the information presented to the decision maker. However, it also obscures which indicators have been measured. It will therefore be necessary to convey what indicators have been included within the analysis, and how they have been valued, to the decision maker, both so that they may take advantage of disaggregating the attributes if useful for decision making¹⁸ and so they are aware of what is not included in the analysis.

Finally the methodology is limited by its intended function; that is, early stage strategic appraisal where there is limited data on the proposed developments. For example, it would be expected that transport developments would induce demand, yet we have not included these in the results¹⁹, instead focusing on the systems demand created. The induced demand would work to validate the transport developments, but would also create negative externalities in the form of pollution, noise and accidents. The absence of such data will therefore make the results less accurate and must again be conveyed to the decision maker. This is particularly important where information is available for some sectors, but not others, as the results may then be biased towards assets with greater benefit/less impact related data.

¹⁷ For example, the peak effects of noise for transport developments.

¹⁸ For example, to apply indicator thresholds, such as limits to emissions.

¹⁹ An analysis of the demand required to produce a positive BCR is, however, provided in Chapter 5 (Section 5.7.1) and reviewed in Chapter 8 (Section 8.5.2).

In addition to the limitations of the methodology itself, time constraints have limited our analysis of the methodology, its versatility, the uncertainty of its valuations and its appropriateness for decision making. In particular, limitations surround our:

- Use of a single deviant²⁰ and hypothetical²¹ case study;
- Consideration of only single variable uncertainties and not how the uncertainty is affected by interactions between these variables;
- Consideration of only the employment feedbacks of the system with its investment landscape; and
- Lack of engagement with policy level decision makers in order to gauge the benefits of the decision-support tool.

The first of these limitations affects the commonality of the results; indeed the Thames Hub Vision is exceptional in size, level of investment and focus on system benefits. The conclusions drawn about the level of system effects or magnitude of uncertainty cannot therefore be directly applied to other projects. While more common, simpler case studies could have been chosen these would have provided less information regarding the ability of the methodology to capture value for different sectors or for system effects (see Chapter 4, Section 4.2.1). The Thames Hub Vision was therefore considered the greatest test for the methodology.

Our sensitivity analyses in Chapter 7 only depict the uncertainty created by single variables, but do not consider the interactions between the system variables. By undertaking the analysis in

²⁰ See Flyvbjerg (2006).

²¹ The benefits and limitations of ex post and ex ante projects were discussed in Chapter 4 (Section 4.2.1). Given the need to define long-term alternative pathways and the counterfactual case, the data available for ex post cases was not found to offer significant advantage. Indeed, those with the greatest data were the most removed from current technologies, and socio-technical concerns. The case was therefore not chosen based on this criteria.

this way we more closely examined how uncertainties can compound through different indicators and over time. However some of the uncertainty bounds may not be correct. Other authors have explored how such interactions affect the possible future environment of single assets and have shown them to reduce the range and probability of certain results (see, for example, de Neufville and Scholtes' (2011) worked example for a new car park). Such analyses have not been conducted for multi-sector infrastructure systems and without this understanding the results created can be questioned. However, should the conclusions of the single sector analyses hold, such interdependencies would reduce the uncertainty of the results, suggesting the uncertainty bounds herein would encapsulate these results.

In addition, the sensitivity analysis of feedbacks with the investment landscape has been limited to the potential employment effects. This should be expanded (following appropriate developments of the SIMULACRA model) to consider both the transport effects²² of the employment and the transport and population effects of the developments within the proposal, before final drawing conclusions on the scale of effects compared to the more general sensitivity analyses in Chapter 7 and therefore the benefits of such analysis for transport/other sector investments.

Finally, while the decision-support tool has been designed for policy level decision makers, it has not been tested against this set of stakeholders. The methodology has, however, been based on existing methods to aid in the comprehension of results. Presentation of the work has received favourable comments from stakeholders within HM Treasury and Environment Agency; however, it would be useful to test how the results were perceived and interpreted by both policy makers and the wider infrastructure community. As noted in Chapter 1, infrastructure decisions are made in a multi-actor context. Each of these actors will have an individual set of

²² Air quality, carbon dioxide emissions, noise, tax, reliability, capacity utilised and safety.

values and priorities, which cannot all be represented in a single CBA. The aim of decision support tools, such as that developed herein, is therefore to encourage a more universal understanding of the trade-offs created by a development, acknowledging the uncertainties in the valuation and thereby enabling a more structured debate between stakeholders. I would propose that this was conducted in two stages, first presenting the results to each stakeholder individually, to explain the developments, options, uncertainties and limitations, allowing them to draw their own conclusions and suggest any concerns. These responses should then be gathered and used to outline a structured stakeholder debate on the developments, with the aim of agreeing on objectives necessary to reduce the decision space (threshold requirements) and which initial enabling infrastructures should be considered further. The remaining options could then be considered in more depth by sector specific appraisal methods, while the pathways could be compared to national priorities. At a more granular level, the methodology should also be presented to the appraisal practitioner community to discuss its usability and their thoughts for improvement.

9.4 Research contributions

Despite the limitations outlined in Section 9.3, the work herein has extended the literatures of both infrastructure appraisal and decision making under deep uncertainty. For the former, it has provided a common strategic methodology through which all sectors can be appraised, allowing decision makers to understand the total system resources required and, where necessary, strategically prioritise investment across sectors. Furthermore, this has created the opportunity to combine assets into portfolios, removing the need to attribute effects to single assets and instead focusing on the benefits of the system as a whole. This provides a more complete valuation of infrastructure investments, capturing not only their inherent value, but also their

cross-sector demands and efficiencies, emergent system effects and their ability to constrain or enable future development.

The latter provides perhaps the most important contribution, combining the work of real options 'in' projects and adaptation pathways to create an understanding of the opportunity value provided by the system of infrastructure systems over the long-term. This has allowed us to build a decision-support tool that highlights the uncertainty of the decisions and, drawing on the recommendations of other authors, focuses attention on discussion of trade-offs between stakeholder groups (Weaver et al., 2013), maintaining flexibility or 'opportunity' (de Neufville and Scholtes, 2011), and promoting the tracking and review of decisions to ensure benefits are realised (Collingridge, 1981). Furthermore, it allows us to navigate the decision space, through creating a plan of infrastructure developments that can be adapted in response to change and a list of key assumptions/variables that must be tracked and reviewed to ensure that the value is realised.

Additional contributions have been made through:

- Literature reviews of:
 - o Current appraisal methods and how these have been extended to consider deep uncertainty;
 - o The interdependencies of existing and proposed infrastructure projects; and
 - o Indicators used to measure the performance of infrastructure.

- Development of:
 - o A set infrastructure performance indicators, that encapsulate the main costs and benefits of infrastructure assets at the regional level and that can be consistently applied across the infrastructure sectors;
 - o The key constraints of infrastructure development at the appraisal stage and an algorithm to create potential pathways of infrastructure developments from this information;

- Analysis of the additional information provided by adding increments of complexity to appraisal alongside the effort required, therefore:
 - o The additional understanding of uncertainty and trade-offs provided by taking a multi-attribute approach;
 - o The additional value captured through systems effects and efficiencies if a portfolio approach is taken;
 - o The additional value captured through enablement, flexibility and changing implementation timings if a pathways approach is taken;
 - o How the uncertainty of key variables can build over the analysis, how this affects the uncertainty of the appraisal result and the benefits received by different stakeholder groups; furthermore, how this uncertainty can be reduced (robustness improved) if the costs and benefits are brought into greater alignment; and
 - o How a key feedback between the developments and the investment landscape further affects this level of uncertainty, undermining or strengthening the value derived from prior and future developments.

9.5 Implications for UK infrastructure development

This research began in late 2011 amid a wave of interest from UK Government Agencies in the economic benefits of infrastructure and the vulnerabilities and opportunities created by its interdependencies. While many cycles of political interest are short lived, infrastructure has proven to be an exception. Indeed the Agencies have commissioned many studies of their own in the intervening period, some of which are drawn upon in this work. Furthermore, with greater industry and Governmental interest and with increasing technological improvements²³, more data has become available to the academic community allowing modelling and tracking of infrastructure as a system of systems. Each of these studies have confirmed the significance of impacts of infrastructure interdependencies, supporting the supposition that formed the foundation of this work: that omitting system interdependencies will “at best limit the validity of analyses and at worse lead to bad or inappropriate policies” (Rinaldi, 2004, p1). This work is just one piece in this exploration of infrastructure systems and fully supports these conclusions, finding, as we have noted above, that the interdependencies lead to costs/constraints and benefits/opportunities that are not visible from a single project or single sector perspective. The methodology helps bring infrastructure appraisal into greater alignment with this body of work, particularly those studies which focus on infrastructure sustainability and resilience, by moving the emphasis to the long-term, acknowledging the uncertainty involved and looking for opportunities.

As part of the wider research into infrastructure systems, this work therefore provides an opportunity to review current infrastructure plans to ascertain whether they are possible as a complete system, the total resources required and whether their opportunities align with wider

²³ Such as remote sensing and increased use of Building Information Models.

goals. Furthermore, to determine whether national plans²⁴, are attractive to regions and to provide sector plans with a greater understanding of their interdependencies. Where there are misalignments in the plans, the common appraisal framework provides a means to prioritise projects across sectors. On a smaller scale, the work provides a methodology for assessing the growing number of projects that deal with multi-sector investments/coordinated delivery of utilities (see Chapter 4, Sections 4.3.2 and 4.3.3).

Finally, our analysis of infrastructure performance metrics (see Chapter 3, Section 3.3.3) and the data issues of appraising historical projects (see Chapter 4, Section 4.3.1), provides insights for how we should track the performance of infrastructure. This work is feeding into a review of Infrastructure UK's performance metrics, aiming to ensure that they provide a consistent data resource over the long-term, that remains useful despite any shifts that may occur in societal values over this time.

9.6 Future work

The limitations discussed in Section 9.3 point to three avenues for direct extension of the research herein:

- Application of the methodology to further case studies, or extension of the current case study to consider more potential developments in the region. In particular it would be interesting to investigate smaller (more common) developments, complementary assets, or alternatives which seem less optimal in the short-term but which provide greater flexibility;

²⁴ Such as the UK Infrastructure Timeline (Engineering the Future, 2013), or ITRC Work Stream 1 strategies (Hall et al., 2012a).

- Application of a multi-variable sensitivity analysis, to understand the interdependencies between uncertainties and how they compound or balance each other over time or through the portfolio of assets; and
- Presentation of the methodology and decision-support tool to stakeholders and discussion of whether the methodology is sufficiently familiar to be used, maintained and trusted²⁵; furthermore, whether it sufficiently represents their different perspectives.

Each of these extensions would make the methodology more complex and time consuming analytically. It may not, therefore, be appropriate to add them to the methodology if it is to remain usable and maintainable by stakeholders. However, by using the incremental process applied herein, the information gain could be considered against this increase in analytic effort. Furthermore, the understanding provided by such extensions, may be able to be considered in more abstract forms, either through an increase in uncertainty, or through a more qualitative awareness of the issues created.

In addition, both decision making under deep uncertainty and systems analysis of infrastructure are highly active areas for research. More fully integrating the work in this thesis with our developing understanding in these two areas could therefore provide significant benefit. In particular:

- Further integration with the SIMULACRA model as it is developed; firstly, to input the proposed transport developments to see how this affects population distributions and

²⁵ Weaver et al. (2013, p42) note that if information is to be used for decision making/support it has to be perceived as “credible, salient and legitimate: i.e., scientifically and technically accurate in its evidence and arguments, but also relevant to the needs of the decision makers and having been produced in a way that is unbiased and respectful of their divergent perspectives and values”.

secondly to consider the transport journeys created by employment, the implications of this demand on the four appraisal attributes and the effects on the pathway values;

- Further consideration of the macro-economic interactions of infrastructure investments, their structural effects on regional economic growth and how such factors could be integrated into the methodology;
- Comparison of the results with the current and future outputs of parallel projects looking at different scales²⁶ and bringing these together to further understand and define the appraisal hierarchy discussed in Chapter 1; and
- Consideration of the vulnerability and tipping points²⁷ of pathway families developed herein using an ensemble of possible futures (drawing on methods such as Adaptation Pathways and Dynamic Adaptive Policy Pathways (see Haasnoot et al. (2013)), for example linking economic growth and population models, including more extreme economic futures such as decline or no-growth, or exploring the effects of different potential technological changes on projections.

²⁶ For example, iBUILD (2015b) at the local level, ITRC (2015) at the national level and ICIF (2015) at the international level.

²⁷ Points that cause a shift the preferred decision path.

10 References

- Ackerman, F., 2007. Debating climate economics: The Stern review vs. its critics. A report to Friends of the Earth - UK. Available online at: <http://sei-us.org/publications/id/108>; accessed 28/02/2012: Friends of the Earth.
- Ackerman, F., 2008. Critique of cost-benefit analysis, and alternative approaches to decision-making. A report to Friends of the Earth England, Wales and Northern Ireland. Available online at: http://www.foe.co.uk/resource/reports/policy_appraisal.pdf; accessed 16/10/2013: Friends of the Earth.
- Ackerman, F., and Heinzerling, L., 2004. Assessing natural resources: Price vs. value. *Renewable Resources Journal*, 22(3), pp. 16-21.
- Adamowicz, W., Louviere, J., and Williams, M., 1994. Combining revealed and stated preference methods for valuing environmental amenities. *Journal of Environmental Economics and Management*, 26(3), pp. 271-292.
- AEA Technology Environment, 2005. Damages per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas. AEAT/ED51014/CAFE CBA damage costs. Available online at: http://ec.europa.eu/environment/archives/cafe/activities/pdf/cafe_cba_externalities.pdf; accessed 12/08/2014: European Commission.
- Airports Commission, 2013. Airports Commission: Interim report. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/271231/airports-commission-interim-report.pdf; accessed 10/02/2014: The Stationary Office.
- Airports Commission, 2014a. Airports Commission: Appraisal framework consultation. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/271679/airports-framework-consultation.pdf; accessed 18/01/2014: Airports Commission.
- Airports Commission, 2014b. Introductory note: Inner Thames Estuary feasibility studies. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/271658/airports-intro-note.pdf; accessed 31/05/2014: Airports Commission.
- Airports Commission, 2014c. Inner Thames Estuary airport: Summary and decision paper. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/349518/decision-and-summary.pdf; accessed 16/03/2013: The Stationary Office
- Airports Commission, 2015. Final report. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/440316/airports-commission-final-report.pdf; accessed 16/03/2016: The Stationary Office
- Airports Council International, 2014. Annual world airport traffic report: Passenger traffic 2013. Available online at: <http://www.aci.aero/Data-Centre/Annual-Traffic-Data/Passengers/2013-final>; accessed 18/03/2015: ACI.
- Alhadidi, B., Alzyoud, F., El-Khairi, A., and Zakarneh, E., 2013. A comparison study of common routing protocols used in wireless ad-hoc networks. *Research Journal of Applied Sciences, Engineering and Technology*, 5(12), pp. 3287-3293.
- Alonso, W., 1960. A theory of the urban land market. *Papers in Regional Science*, 6(1), pp. 149-157.

- AMEC, 2014a. Heathrow's north-west runway air quality assessment. Available online at: <http://your.heathrow.com/wp-content/uploads/2014/07/02-Heathrow-3RNW-Air-Quality-Assessment.pdf>; accessed 24/11/2014: Heathrow Airport Limited.
- AMEC, 2014b. Heathrow's north-west runway carbon footprint assessment. Available online at: <http://your.heathrow.com/wp-content/uploads/2014/07/04-Heathrow-3RNW-Carbon-Footprint-Assessment.pdf>; accessed 18/12/2014: Heathrow Airport Limited.
- Anderson, W.P. and Lakshmanan, T.R., 2007. Infrastructure and productivity: What are the underlying mechanisms? In: C. Karlsson, W.P. Anderson, B. Johansson and K. Kobayashi, eds, *The management and measurement of infrastructure: Performance, efficiency and innovation*. Cheltenham: Edward Elgar, pp. 147-162.
- Andersson, H., and Treich, N., 2011. The value of a statistical life. In: A. de Palma, R. Lindsey, E. Quinet and R. Vickerman, eds, *A handbook of transport economics*. Cheltenham: Edward Elgar, pp. 396-424.
- Ansar, A., 2010. 'New departures' in infrastructure provision: An ongoing evolution away from physical assets to user needs. DPhil thesis. University of Oxford.
- Ansar, A., 2014. Does infrastructure contribute to economic growth? Micro-level evidence from transportation projects in China, *The future of national infrastructure systems and economic prosperity conference*, Cambridge, 27-28/03/2014.
- Apostolakis, G.E., and Lemon, D.M., 2005. A screening methodology for the identification and ranking of infrastructure vulnerabilities due to terrorism. *Risk Analysis*, 25(2), pp. 361-376.
- Armitt, J., 2013. The Armitt review: An independent review of long term infrastructure planning commissioned for Labour's Policy Review. Available online at: <http://www.armittreview.org/>; accessed 06/03/2015: Labour Party.
- Arrow, K.J., 1950. A difficulty in the concept of social welfare. *The Journal of Political Economy*, 58(4), pp. 328-346.
- Arslanalp, S., Bornhorst, F., and Gupta, S., 2011. Investing in growth. *Finance and Development*, 48(1), pp. 34-37.
- Ashuri, B., Lu, J., and Hamed, K., 2011. A real options framework to evaluate investments in toll road projects delivered under the two-phase development strategy. *Built Environment Project and Asset Management*, 1(1), pp. 14-31.
- Atkinson, S.E., and Halvorsen, R., 1990. The valuation of risks to life: Evidence from the market for automobiles. *The review of economics and statistics*, 72(1), pp. 133-136.
- Audit Scotland, 2015. Commonwealth Games 2014: Third report. Available online at: http://www.audit-scotland.gov.uk/docs/central/2015/nr_150312_commonwealth_games_third.rtf; accessed 15/07/2015: Audit Scotland.
- Baker, R., Chilton, S., Jones-Lee, M., and Metcalf, H., 2008. Valuing lives equally: Defensible premise or unwarranted compromise? *Journal of Risk and Uncertainty*, 36(2), pp. 125-138.
- Banister, D., 2008. The sustainable mobility paradigm. *Transport Policy*, 15(2), pp. 73-80.
- Banister, D. and Berechman, J., 2003. *Transport investment and economic development*. Taylor and Francis e-Library edn. London: UCL Press.
- Bateman, I.J., Lovett, A.A., and Brainard, J.S., 2003. *Applied environmental economics: A GIS approach to cost-benefit analysis*. Cambridge, UK: Cambridge University Press.

- Bateman, I.J., Day, B.H., and Lake, I., 2004. The valuation of transport-related noise in Birmingham - Technical report to the Department for Transport. Norwich: University of East Anglia.
- Bateman, I.J., Day, B.H., Georgiou, S., and Lake, I., 2006. The aggregation of environmental benefit values: Welfare measures, distance decay and total WTP. *Ecological Economics*, 60(2), pp. 450-460.
- Bateman, I.J., Abson, D., Beaumont, N., Darnell, A., Fezzi, C., Hanley, N., Kontoleon, A., Maddison, D., Morling, P., Morris, J., Mourato, S., Pascual, U., Perino, G., Sen, A., Tinch, D., Turner, K., and Valatin, G., 2011. Chapter 22: Economic values from ecosystems. The UK national ecosystem assessment technical report. Cambridge: UNEP-WCMC, pp. 1067-1152.
- Bates, J., Polak, J., Jones, P., and Cook, A., 2001. The valuation of reliability for personal travel. *Transportation Research Part E: Logistics and Transportation Review*, 37(2-3), pp. 191-229.
- Batty, M., 2009. Urban modeling. In: N. Thrift and R. Kitchin, eds, *International Encyclopedia of Human Geography*. Oxford: Elsevier, pp. 51-58.
- Batty, M., 2010. Anticipating future complexity: Are systems such as cities getting more complex? Podcast. Available online at: <http://podcasts.ox.ac.uk/anticipating-future-complexity-are-systems-such-cities-getting-more-complex>; accessed 15/09/2015: University of Oxford.
- Batty, M. and Xie, Y., 1994. From cells to cities. *Environment and Planning B: Planning and Design*, 21(7), pp. 31-48.
- Batty, M., Vargas, C., Smith, D., Serras, J., Reades, J. and Johansson, A., 2013. SIMULACRA: Fast land-use-transportation models for the rapid assessment of urban futures. *Environment and Planning B: Planning and Design*, 40(6), pp. 987-1002.
- Beuthe, M., 2002. Transport evaluation methods: From cost-benefit analysis to multicriteria analysis and the decision framework. In: L. Giorgi, A.D. Pearman, and Interdisciplinary Centre for Comparative Research in the Social Sciences, eds, *Project and policy evaluation in transport*. Aldershot: Ashgate, pp. 209-241.
- Bharadwaj, A.S., 2000. A resource-based perspective on information technology capability and firm performance: An empirical investigation. *MIS Quarterly: Management Information Systems*, 24(1), pp. 169-193.
- Bhargava, M., Dubelaar, C., and Ramaswami, S., 1994. Reconciling diverse measures of performance: A conceptual framework and test of a methodology. *Journal of Business Research*, 31, pp. 235-246.
- Bickel, P., Arampatzis, G., Burgess, A., Esposito, R., Fagiani, P., Friedrich, R., Hunt, A., Jonkhoff, W., Kelly, C., Laird, J., Lieb, C., Navrud, S., Odgaard, T., Ricci, A., Rustenburg, M., Sieber, N., Tavasszy, L., and Trædal, Y., 2006. HEATCO: Developing harmonised European approaches for transport costing and project assessment. Deliverable 7: Final technical report. Available online at: <http://heatco.ier.uni-stuttgart.de/deliverables.html>; accessed 23/03/2012: HEATCO.
- Birol, E., Koundouri, P., and Kountouris, Y., 2008. Using the choice experiment method to inform river management in Poland: Flood risk reduction versus habitat conservation in the Upper Silesia region. In: E. Birol, and P. Koundouri, eds, *Choice experiments informing environmental policy: A European perspective*. Cheltenham, UK: Edward Elgar, pp. 271-291.
- Bishop, K., 1992. Assessing the benefits of community forests: An evaluation of the recreational use benefits of two urban fringe woodlands. *Journal of Environmental Planning and Management*, 35(1), pp. 63-76.

- Booth, R., 2012. Risk planning for interdependencies: From theory to practice. *Proceedings of the ICE - Municipal Engineer*, 165(2), pp. 85-92.
- Borison, A., 2003. Real Options Analysis: Where are the Emperor's Clothes? 7th Annual Real Options Conference, Washington D.C., 10-12/06/2003, Available online at: <http://www.realoptions.org/papers2003/borison.doc>; accessed 05/09/2013: Real Options Group.
- Bowker, J.M., and Didychuk, D.D., 1994. Estimation of the nonmarket benefits of agricultural land retention in eastern Canada. *Agricultural and Resource Economics Review*, 23(2), pp. 218-225.
- Brady, T., and Davies, A., 2014. Governing complex infrastructure developments: Learning from successful megaprojects, P. Campbell and P. Perez, eds. In: *Proceedings of the International Symposium of Next Generation Infrastructure*, 1-4 October 2013, SMART Infrastructure Facility, University of Wollongong, Australia.
- Brady, T., Davies, A. and Nightingale, P., 2012. Dealing with uncertainty in complex projects: Revisiting Klein and Meckling. *International Journal of Managing Projects in Business*, 5(4), pp. 718-736.
- Bristol Temple Quarter Enterprise Zone, 2013. About the zone. Available online at: <http://www.bristoltemplequarter.com/about-the-zone/>; accessed 16/07/2015: Bristol City.
- Broome, J., 2008. The ethics of climate change. *Scientific American*, 298(6), pp. 96-102.
- Buldyrev, S.V., Parshani, R., Paul, G., Stanley, H.E., and Havlin, S., 2010. Catastrophic cascade of failures in interdependent networks. *Nature*, 464(7291), pp. 1025-1028.
- Butcher, L., 2015. Roads: Strategic road network (SRN). SN1448. Available online at: <http://researchbriefings.files.parliament.uk/documents/SN01448/SN01448.pdf>; accessed 14/07/2015: UK Parliament.
- Byers, E.A., Hall, J., and Amezaga, J.M., 2014. Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, 25(2014), pp. 16-30.
- Cabinet Office, 2012. National risk register of civil emergencies: 2012 edition. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/211858/CO_NationalRiskRegister_2012_acc.pdf; accessed 28/11/2013: Cabinet Office.
- Çalhan, A., and Çeken, C., 2013. Artificial neural network based vertical handoff algorithm for reducing handoff latency. *Wireless Personal Communications*, 71(4), pp. 2399-2415.
- Carhart, N., 2014. Investigation into the development of a framework for the identification and appraisal of infrastructure interdependencies with application to critical UK infrastructure: Case study report for Infrastructure UK - Identification of high-level infrastructure interdependencies for the Lower Thames Crossing. Available online at: <http://www.icif.ac.uk/networks/123/portfolio.html#t44>; accessed 10/06/2015: International Centre for Infrastructure Futures.
- Carlsson, F., Johansson-Stenman, O., and Martinsson, P., 2004. Is transport safety more valuable in the air? *Journal of Risk and Uncertainty*, 28(2), pp. 147-163.
- Carson, R.T., and Groves, T., 2007. Incentive and informational properties of preference questions. *Environmental and Resource Economics*, 37(1), pp. 181-210.
- CBI and KPMG, 2011. Making the right connections, CBI/KPMG Infrastructure Survey 2011. Available online at: <http://www.cbi.org.uk/media/1052324/2011.09-cbi-kpmg-infrastructure-report.pdf>; accessed 16/10/2013: CBI.

Center for Chemical Process Safety, 2009. Appendix A: Understanding and using F-N diagrams. Guidelines for developing quantitative safety risk criteria. Hoboken, New Jersey: John Wiley & Sons, Inc., pp. 109-117.

CH2M HILL, 2013. Urban Programs news: Urban Programs group helps develop enterprise zone in Bristol, UK. Internal news article. Company intranet: CH2M HILL.

CH2M HILL, 2014a. Transport Market news: Panama Canal team connects over partner's passion for painting. Internal news article. Company intranet: CH2M HILL.

CH2M HILL, 2014b. Europe News: CH2M HILL named as delivery partner for Thames Estuary Asset Management 2100 flood defence programme. Internal news article. Company intranet: CH2M HILL.

Chung, S.H., Byrd, T.A., Lewis, B.R., and Ford, F.N., 2005. An empirical study of the relationships between IT infrastructure flexibility, mass customization, and business performance. Data Base for Advances in Information Systems, 36(3), pp. 26-41.

Civil Aviation Authority, 2003. Heathrow passenger survey - Travel mode, origin and destination data. Personal communication.

Civil Aviation Authority, 2008. Economic Regulation of Heathrow and Gatwick Airports: CAA decision. Available online at: http://www.caa.co.uk/docs/5/ergdocs/heathrowgatwickdecision_mar08.pdf; accessed 04/09/2012: Civil Aviation Authority.

Civil Aviation Authority, 2012. Summary of activity at reporting airports. Available online at: http://www.caa.co.uk/docs/80/airport_data/2012Annual/Table_02_2_Summary_Of_Activity_at_UK_Airports_2012.pdf; accessed 21/02/2014: Civil Aviation Authority.

Civil Aviation Authority, 2013. Aviation trends: Quarter 1, 2013. Available online at: <http://www.caa.co.uk/default.aspx?catid=1279&pagetype=90&pageid=9793>; accessed 29/07/2013: Civil Aviation Authority.

Clifford, M., 2013. Article 208: World's first wave-powered desalination plant to be developed. Available online at: <http://www.technology4change.com/article.jsp?id=208#.VYP-1U3bJaQ>; accessed 19/06/2015: Technology 4 Change.

Coastal Protection and Restoration Authority of Louisiana, 2012. Louisiana's comprehensive master plan for a sustainable coast: Committed to our coast. Available online at: http://issuu.com/coastalmasterplan/docs/coastal_master_plan-v2; accessed 12/01/15: State of Louisiana.

Collingridge, D., 1981. The social control of technology. Milton Keynes, England: Open University Press.

Commonwealth Games Federation, 2014. Glasgow 2014 XX Commonwealth Games: Post-games report. Available online at: <http://www.thecgf.com/games/2014/G2014-Official-Post-Games-Report.pdf>; accessed 15/07/2015: Commonwealth Games Federation.

Copeland, T., and Tufano, P., 2004. A real-world way to manage real options. Harvard Business Review, 82(3), pp. 90-99.

Council for Science and Technology, 2009. A national infrastructure for the 21st century. London: Stationary Office.

Crossrail Ltd, 2014. Crossrail in numbers. Available online at: <http://www.crossrail.co.uk/benefits/crossrail-in-numbers>; accessed 15/07/2015: Crossrail.

Daly, H.E., 1992. From empty-world economics to full-world economics: Recognising an historical turning point in economic development. In: R. Goodland, H.E. Daly and S.E. Serafy, eds, Population, technology and lifestyle: The transition to sustainability. Washington D.C.: Island Press, pp. 23-37.

Daly, H.E., and Farley, J.C., 2011. Ecological economics: Principles and applications. 2nd edn. Washington, D.C.: Island Press.

Dawson, R.J., Ball, T., Werritty, J., Werritty, A., Hall, J.W. and Roche, N., 2011. Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change. *Global Environmental Change*, 21(2), pp. 628-646.

Dawson, D. A., Purnell, P., Roelich, K., Busch, J., and Steinberger, J. K., 2014. Low carbon technology performance vs infrastructure vulnerability: Analysis through the local and global properties space. *Environmental Science and Technology*, 48(21), pp. 12970-12977.

de Kluizenaar, Y., Passchier-Verneer, W., and Miedema, H.M.E., 2001. Adverse effects of noise exposure on health: A state of the art summary. 2001.171, Project number 41046. Available online at: <http://publications.tno.nl/publication/100057/Q1oIVb/kluizenaar-2001-adverse.pdf>; accessed 08/08/2014: TNO.

de Laleu, V., 2009. La Rance tidal power plant: 40 year operation feedback, lessons learnt, 2009 British Hydropower Association annual conference: Empowering our potential, Liverpool, 14-15/10/2009.

de Neufville, R., and Scholtes, S., 2011. Flexibility in engineering design. Cambridge, Massachusetts; London, England: MIT Press.

de Neufville, R., de Weck, O., Frey, D., Hastings, D., Larson, R., Simchi-Levi, D., Oye, K., Weigel, A., and Welsch, R., 2004. Engineering systems monograph: Uncertainty management for engineering systems planning and design, Engineering Systems Symposium, MIT, Cambridge, MA, March 2004, available online: <http://esd.mit.edu/symposium/pdfs/monograph/uncertainty.pdf>; accessed 28/11/2013.

de Neufville, R., Scholtes, S., and Wang, T., 2006. Real options by spreadsheet: Parking garage case example. *Journal of Infrastructure Systems*, 12(2), pp. 107-111.

de Weck, O., de Neufville, R., and Chaize, M., 2004. Staged deployment of communications satellite constellations in low earth orbit. *Journal of Aerospace Computing, Information and Communication*, 1(4), pp. 119-136.

Delucchi, M., and McCubbin, D., 2011. External costs of transport in the United States. In: A. de Palma, R. Lindsey, E. Quinet and R. Vickerman, eds, A handbook of transport economics. Cheltenham: Edward Elgar, pp. 341-368.

Department for Environment Food and Rural Affairs, 2006. Flood and coastal defence appraisal guidance: Supplementary note to Operating Authorities - Climate change impacts. Available online at:

<http://archive.defra.gov.uk/environment/flooding/documents/policy/guidance/fcdpag/fcd3climate.pdf>; accessed 20/02/2014: Department for Environment Food and Rural Affairs.

Department for Environment Food and Rural Affairs, 2007. An introductory guide to valuing ecosystem services. Available online at:

http://ec.europa.eu/environment/nature/biodiversity/economics/pdf/valuing_ecosystems.pdf; accessed 04/03/2014: Department for Environment Food and Rural Affairs.

Department for Environment Food and Rural Affairs. 2009. Appraisal of flood and coastal erosion risk management: A Defra policy statement. PB13278. Available online at:

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69419/pb13278-erosion-manage-090619.pdf; accessed 28/11/2013: Department for Environment Food and Rural Affairs.

Department for Environment Food and Rural Affairs, 2011. Climate resilient infrastructure: Preparing for a changing climate. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69269/climate-resilient-infrastructure-full.pdf; accessed 04/03/2014: Department for Environment Food and Rural Affairs.

Department for Environment Food and Rural Affairs, 2012a. UK climate change risk assessment. Available online at: <http://www.defra.gov.uk/publications/files/pb13698-climate-risk-assessment.pdf>; accessed 16/10/2013: Department for Environment Food and Rural Affairs.

Department for Environment Food and Rural Affairs, 2012b. Interactive monitoring networks (air pollution). Available online at: <http://uk-air.defra.gov.uk/interactive-map>; accessed 10/09/2012: Department for Environment Food and Rural Affairs.

Department for Environment Food and Rural Affairs, 2012c. Noise mapping England. Available online at: <http://services.defra.gov.uk/wps/portal/noise>; accessed 08/09/2012: Department for Environment Food and Rural Affairs.

Department for Transport, 2011a. Transport analysis guidance - WebTAG. Available online at: <http://www.dft.gov.uk/webtag/>; accessed 18/04/2013: Department for Transport.

Department for Transport, 2011b. UK aviation forecasts. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4503/uk-aviation-forecasts.pdf; accessed 21/02/2014: Department for Transport.

Department for Transport, 2011c. Casualties caused by aviation accidents: United Kingdom, 2000-2010. Table AVI0401 (TSGB0214). Available online at: <http://www.dft.gov.uk/statistics/series/aviation/>; accessed 07/11/2013: Department for Transport.

Department for Transport, 2012. Traffic counts. Available online at: <http://www.dft.gov.uk/traffic-counts/download.php>; accessed 20/02/2013: Department for Transport.

Department for Transport, 2013. Passenger casualty rates by mode: 2003-2012. Table RAS53001. Available online at: <https://www.gov.uk/government/publications/reported-road-casualties-great-britain-annual-report-2012>; accessed 07/11/2013: Department for Transport.

Department of Energy and Climate Change, 2010. Severn tidal power feasibility study: Conclusions and summary report. 10D/808. Available online at: <https://www.gov.uk/government/publications/1-severn-tidal-power-feasibility-study-conclusions-and-summary-report>; accessed 16/07/2015: Department of Energy and Climate Change.

Department of Energy and Climate Change, 2011. Digest of United Kingdom energy statistics. London: Department of Energy and Climate Change.

Dimitriou, H.T., Ward, E.J., and Wright, P.G., 2013. Mega transport projects — Beyond the 'iron triangle': Findings from the OMEGA research programme. *Progress in Planning*, 86, pp. 1-43.

Dobbs, R., Pohl, H., Lin, D., Mischke, J., Garemo, N., Hexter, J., Matzinger, S., Palter, R., and Nanavatty, R., 2013. Infrastructure productivity: How to save \$1 trillion a year. Available online at: www.mckinsey.com/insights/mgi/research/urbanization/infrastructure_productivity; accessed 11/11/2013: McKinsey Global Institute.

- Doganis, R., 1992. *The Airport Business*. London: Routledge.
- Dwight, R.H., Fernandez, L.M., Baker, D.B., Semenza, J.C., and Olson, B.H., 2005. Estimating the economic burden from illnesses associated with recreational coastal water pollution - A case study in Orange County, California. *Journal of environmental management*, 76(2), pp. 95-103.
- E.ON, 2010. UK press releases: E.ON's Grain CHP plant generates first electricity. Available online at: <http://pressreleases.eon-uk.com/blogs/eonukpressreleases/archive/2010/07/01/1569.aspx>; accessed 24/02/2012: E.ON.
- Echenique, M., 2004. Econometric models of land use and transportation. In: D.A. Hensher, K.J. Button, K.E. Haynes and P.R. Stopher, eds, *Handbook of transport geography and spatial systems*. Handbooks in transport Volume 5. Kidlington, Oxford: Elsevier, pp. 185-202.
- Égert, B., Kozlu, T., and Sutherland, D., 2009. *Infrastructure and growth: Empirical evidence*. OECD Economics Department Working Papers, No. 685. Paris: OECD Publishing.
- Element Energy, 2010. *Electric vehicles in the UK and Republic of Ireland: Greenhouse gas emission reductions and infrastructure needs - Final report for WWF UK*. Available online at: http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/05/EVs-in-the-UK-and-ROI_final-report_10.12.10.pdf; accessed 18/03/2015: Element Energy.
- Elkington, J., 1997. *Cannibals with forks: The triple bottom line of 21st century business*. Oxford: Capstone.
- Engineering and Interdependency Expert Group, 2011. *Assessing and reporting on systemic risks and opportunities in infrastructure*: Prepared for Infrastructure UK. Unpublished report.
- Engineering the Future, 2013. *Infrastructure Timelines Report*. Available online at: http://www.engineeringthefuture.co.uk/government/pdf/EtF_Infrastructure_Interdependencies_Report.pdf; accessed 18 June 2013: Engineering the Future.
- Englin, J., and Cameron, T.A., 1996. Augmenting travel cost models with contingent behavior data. *Environmental and Resource Economics*, 7(2), pp. 133-147.
- English Nature, 2006. *Coastal squeeze, saltmarsh loss and Special Protection Areas*. English Nature Research Reports 710. Available online at: <http://publications.naturalengland.org.uk/file/75004>; accessed 13/05/2014: Natural England.
- Entec, 2004. *Study into the environmental impacts of increasing the supply of housing in the UK: Final report*. London: Department for Environment Food and Rural Affairs.
- Environment Agency, 2003. *Benefits in the PR04 environment programme: Findings of an Environment Agency seminar, January 2003*. Available online: http://www.environment-agency.gov.uk/static/documents/Business/oxfordreportv2_563124.pdf; accessed 28/11/2013: Environment Agency.
- Environment Agency, 2007. *The costs of the 2007 floods in England*. SC070039/R1. Available online at: <http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/scho1109brja-e-e.pdf>; accessed 28/11/2013: Environment Agency.
- Environment Agency, 2009. *TE2100 Phase 3ii Plan technical report appendix H3ii: Appraisal in TE2100*. Project Report: Environment Agency.
- Environment Agency, 2013. *Water appraisal guidance; assessing costs and benefits for river basin management planning*. Available online at: <http://www.ecrr.org/Portals/27/Publications/Water%20Appraisal%20Guidance.pdf>; accessed 14/07/2015: Environment Agency.

- Ergas, H., 2009. In defence of cost-benefit analysis. *Agenda*, 16(3), pp. 31-40.
- EU, 2001. Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants. OJ L 309 of 27.11.2001.
- EU, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing directives 2001/77/EC and 2003/30/EC. OJ L 140/16.
- EUNOIA Consortium, 2012. D6.1 Case study 1: A travel demand model for London. Available online at: http://www.eunoia-project.eu/media/uploads/deliverables/EUNOIA_D6.1_Case_Study_London_Ed_1_12Jan2015.pdf; accessed 23/03/2016: EUNOIA Consortium
- European Commission, 2002. Guide to cost-benefit analysis of investment projects. Available online at: http://ec.europa.eu/regional_policy/sources/docgener/guides/cost/guide02_en.pdf; accessed 07/03/2014: Evaluation Unit DG Regional Policy European Commission.
- European Commission, 2007. Guidance document on Article 6(4) of the 'Habitats Directive' 92/43/EEC - Clarification of the concepts of: Alternative solutions, imperative reasons of overriding public interest, compensatory measures, overall coherence, opinion of the Commission. Available online at: http://ec.europa.eu/environment/nature/natura2000/management/docs/art6/guidance_art6_4_en.pdf; accessed 25/04/2014: European Commission.
- European Commission, 2012a. Eurostat energy main tables. Available online at: <http://ec.europa.eu/eurostat/web/energy/data/main-tables>; accessed 08/12/2012: European Commission.
- European Commission, 2012b. Eurostat information society main tables. Available online at: <http://ec.europa.eu/eurostat/web/information-society/data/main-tables>; accessed 08/12/2012: European Commission.
- European Commission, 2012c. Eurostat transport main tables. Available online at: <http://ec.europa.eu/eurostat/web/transport/data/main-tables>; accessed 08/12/2012: European Commission.
- Farrow, S., 2004. Using risk assessment, benefit-cost analysis, and real options to implement a precautionary principle. *Risk Analysis*, 24(3), pp. 727-735.
- Fernandes, B., Cunha, J., and Ferreira, P., 2011. The use of real options approach in energy sector investments. *Renewable and Sustainable Energy Reviews*, 15(9), pp. 4491-4497.
- Fernández-Sánchez, G., and Rodríguez-López, F., 2010. A methodology to identify sustainability indicators in construction project management—Application to infrastructure projects in Spain. *Ecological Indicators*, 10(6), pp. 1193-1201.
- Flyvbjerg, B., 2006. Five misunderstandings about case-study research. *Qualitative inquiry*, 12(2), pp. 219-245.
- Flyvbjerg, B., 2007. Policy and planning for large-infrastructure projects: Problems, causes and cures. *Environment and Planning B: Planning and Design*, 34, pp. 578-597.
- Flyvbjerg, B., 2009. Survival of the unfittest: Why the worst infrastructure gets built—and what we can do about it. *Oxford Review of Economic Policy*, 25(3), pp. 344-367.
- Flyvbjerg, B., 2011. Case study. In: N.K. Denzin and Y.S. Lincoln, eds, *The Sage handbook of qualitative research*. 4th edn. Thousand Oaks, California: Sage, pp. 301-316.

Flyvbjerg, B., and COWI, 2004. The British Department for Transport: Procedures for dealing with optimism bias in transport planning guidance document. 58924, Issue 1. London: Department for Transport.

Flyvbjerg, B., Holm, M.S., and Buhl, S., 2002. Underestimating costs in public works projects: Error or lie? *Journal of the American Planning Association*, 68(3), pp. 279-295.

Flyvbjerg, B., Bruzelius, N., and Rothengatter, W., 2003. *Megaprojects and risk: An anatomy of ambition*. Cambridge: Cambridge University Press.

Ford, D.N., Lander, D.M., and Voyer, J.J., 2002. A real options approach to valuing strategic flexibility in uncertain construction projects. *Construction Management & Economics*, 20(4), pp. 343-351.

Forrester, J.W., 1958. Industrial dynamics: A major breakthrough for decision makers. *Harvard Business Review*, 36(4), pp. 37-66.

Foster+Partners, Halcrow and Volterra, 2011a. *Thames Hub: An integrated vision for Britain*.

Available online at:

<http://www.fosterandpartners.com/ThamesHub/data/reports/Thames%20Hub%20Vision%202011.pdf>; accessed 24/02/2014: Foster+Partners.

Foster+Partners, Halcrow, and Volterra, 2011b. *Thames Hub: An integrated vision for Britain - Technical Annexes*. Personal Communication: Halcrow.

Foster+Partners, 2013. *Thames hub airport: Outline proposal to the Airports Commission*. Personal Communication: Foster_Partners.

French, S., 1986. *Decision theory: An introduction to the mathematics of rationality*. Chichester, England: Ellis Horwood; New York: Halsted Press.

Friedrich, R., and Quinet, E., 2011. External costs of transport in Europe. In: A. de Palma, R. Lindsey, E. Quinet and R. Vickerman, eds, *A handbook of transport economics*. Cheltenham: Edward Elgar, pp. 369-395.

Frischmann, B.M., 2012. *Infrastructure: The social value of shared resources*. Oxford; New York: Oxford University Press Inc.

Frontier Economics, 2011. *Connecting for growth: The role of Britain's hub airport in economic recovery, a report prepared for Heathrow*. Available online at: <http://www.frontier-economics.com/documents/2011/09/connecting-for-growth-frontier-report.pdf>; accessed 03/09/2014: Frontier Economics.

Frontier Economics, 2012. *Systematic risks and opportunities in UK infrastructure: A report prepared for HM Treasury and Infrastructure UK*. Available online at: <http://www.frontier-economics.com/europe/en/publications/389/>; accessed 16/10/2013: Frontier Economics.

Frontier Economics, 2013. *The economics of climate resilience: Appraising flood management initiatives - A case study, a report prepared for Defra and the Devolved Administrations*. CA0401. Available online at: http://randd.defra.gov.uk/Document.aspx?Document=11234_CA0401-ECRAppraisingfloodmanagementinitiatives-acasestudy.pdf; accessed 16/10/2013: Department for Environment Food and Rural Affairs.

Frost, M.W., and Ison, S.G., 2007. Comparison of Noise Impacts from Urban Transport. *Proceedings of the Institution of Civil Engineers, Transport*, 160(4), pp. 165-172.

Gärling, T., and Axhausen, K.W., 2003. Introduction: Habitual travel choice. *Transportation*, 30(1), pp. 1-11.

- Geels, F.W., 2012. A socio-technical analysis of low-carbon transitions: Introducing the multi-level perspective into transport studies. *Journal of Transport Geography*, 24(0), pp. 471-482.
- Georgiou, S., Bateman, I., Cole, M., and Hadley, D., 2000. Contingent ranking and valuation of river water quality improvements: Testing for scope sensitivity, ordering and distance delay effects. GEC-2000-18. Available online at: <http://www.cserge.ac.uk/publications/cserge-working-paper/gec-2000-18-contingent-ranking-and-valuation-river-water-quality-i>; accessed 14/08/2013: CSERGE.
- Gesner, G., and Jardim, J., 1998. Bridge within a bridge. *Civil Engineering*, 68(10), pp. 44-47.
- Gillen, D., and Lall, A., 1997. Developing measures of airport productivity and performance: An application of data envelopment analysis. *Transportation Research Part E: Logistics and Transportation Review*, 33(4), pp. 261-273.
- Glaeser, E.L., 2011. *Triumph of the city*. London: Macmillan.
- Gollier, C., and Treich, N. 2003. Decision-making under scientific uncertainty: The economics of the precautionary principle. *Journal of Risk and Uncertainty*, 27(1), pp. 77-103.
- Golub, A., Narita, D., and Schmidt, M.G.W., 2011. Uncertainty in integrated assessment models of climate change: Alternative analytical approaches. FEEM Note di lavoro, 2011.002. Available online at: <http://www.feem.it/getpage.aspx?id=3728&sez=Publications&padre=73>; accessed 17/12/2015: Fondazione Eni Enrico Mattei
- Grace, E., and Pearson, M., 2013. DP World London Gateway. *Evolution Magazine*, Winter 2013, pp. 2-7.
- Grant-Muller, S., MacKie, P., Nellthorp, J., and Pearman, A., 2001. Economic appraisal of European transport projects: The state-of-the-art revisited. *Transport Reviews*, 21(2), pp. 237-261.
- Great Britain, 2008. *Climate Change Act 2008*. London: The Stationery Office.
- Groves, D.G., Fischbach, J.R., Bloom, E., Knopman, D., and Keefe, R., 2013. Adapting to a changing Colorado River: Making future water deliveries more reliable through robust management strategies. ISBN: 978-0-8330-8179-7. Available online at: http://www.rand.org/pubs/research_reports/RR242.html; accessed 15/01/2015: RAND.
- Guo, X., and Jiang, T., 2010. Study on IT infrastructure investment appraisal based on real-option theory, International conference on challenges in environmental science and computer engineering, Wuhan, China, 6-7/03/2010, vol 2: IEEE, pp. 158-161.
- Guthrie, P. and Konaris, T., 2012. Infrastructure and resilience: Commissioned review. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/286993/12-1310-infrastructure-and-resilience.pdf; accessed 19/03/2015: Foresight Government Office for Science.
- Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E., and van Deursen, W.P.A., 2012. Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change*, 115(3-4), pp. 795-819.
- Haasnoot, M., Kwakkel, J.H., Walker, W.E., and ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 23(2), pp. 485-498.
- Haimes, Y.Y., Li, D., and Tulsiani, V., 1990. Multiobjective decision-tree analysis. *Risk Analysis*, 10(1), pp. 111-129.

- Haimes, Y.Y., Horowitz, B.M., Lambert, J.H., Santos, J.R., Crowther, K.G., and Lian, C., 2005. Inoperability input-output model (IIM) for interdependent infrastructure sectors: Case study. *Journal of Infrastructure Systems*, 11, pp. 80.
- Halcrow Group Limited, 2013. Swindon Borough Council DaSTS Swindon transport strategy study. Phase 1 Report. Available online at: http://www.southwest-ra.gov.uk/media/SWRA/RFA2%202008/Swindon_Final_Phase_1_Report.pdf; accessed 31/05/2015: Halcrow Group Ltd.
- Hall, J.W., Le Masurier, J.W., Baker-Langman, E.A., Davis, J.P., and Taylor, C.A., 2004. A decision-support methodology for performance-based asset management. *Civil Engineering and Environmental Systems*, 21(1), pp. 51-75.
- Hall, J.W., Henriques, J.J., Hickford, A.J., and Nicholls, R.J., 2012a. A fast track analysis of strategies for infrastructure provision in Great Britain: Technical report. Oxford: Environmental Change Institute, University of Oxford.
- Hall, J.W., Lempert, R.J., Keller, K., Hackbarth, A., Mijere, C., and McInerney, D.J., 2012b. Robust climate policies under uncertainty: A comparison of robust decision making and info-gap methods. *Risk Analysis*, 32(10) pp.1657-1672.
- Hall, J.W., Barr, S., Thacker, S., and Pant, R., 2014. ITRC infrastructure criticality hotspot analysis: Public briefing document. Available online at: <http://www.itrc.org.uk/wordpress/wp-content/PDFs/ITRC-hotspots-summary.pdf>; accessed 18/03/2015: Infrastructure Transitions Research Consortium.
- Hallegatte, S., Shah, A., Lempert, R., Brown, C., and Gill, S., 2012. Investment decision making under deep uncertainty - Application to climate change. Policy research working paper 6193. Available online at: <http://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-6193>; accessed 03/03/2015: World Bank.
- Hammit, J.K., 2007. Valuing changes in mortality risk: Lives saved versus life years saved. *Review of Environmental Economics and Policy*, 1(2), pp. 228-240.
- Hanley, N., 1991. The valuation of environmental effects. Stage 2, final report. Edinburgh: Scottish Office Industry Department.
- Hanley, N., and Barbier, E., 2009. Pricing nature: Cost-benefit analysis and environmental policy. Cheltenham: Edward Elgar.
- Hanley, N., and Knight, J., 1992. Valuing the environment: Recent UK experience and an application to green belt land. *Journal of Environmental Planning and Management*, 35(2), pp. 145-160.
- Hanley, N., and Spash, C., 1993. Lowland Heaths. In: N. Hanley and C. Spash, eds, *Cost-benefit analysis and the environment*. Cheltenham: Edward Elgar, pp. 211-219.
- Hanley, N., Schlöpfer, F., and Spurgeon, J., 2003. Aggregating the benefits of environmental improvements: Distance-decay functions for use and non-use values. *Journal of environmental management*, 68(3), pp. 297-304.
- Hansen, W.G., 1959. How accessibility shapes land use. *Journal of the American Institute of Planners*, 25(2), pp. 73-76.
- Hartwig, R.P., and Wilkinson, C., 2012. Terrorism risk: A continuing threat - Impacts for property/caualty insurers. Available online at: http://www.lockton.com/Resource_/PageResource/MKT/iii%20Terrorism%20Risk%20February%2013.pdf; accessed 07/11/2013: Insurance Information Institute.

Hayashi, Y., and Morisugi, H., 2000. International comparison of background concept and methodology of transportation project appraisal. *Transport Policy*, 7(1), pp. 73-88.

Headicar, P., 2009. *Transport policy and planning in Great Britain*. London: Routledge.

Health and Safety Executive, 2012. Reported injuries to employees and the self-employed in Great Britain, by detailed industry and severity of injury. Available online at: <http://www.hse.gov.uk/statistics/tables/ridind.xls>; accessed 06/09/2013: Health and Safety Executive.

HEATCO, 2006. Developing harmonised European approaches for transport costing and project assessment. Analysis of existing practice (UK). Available online at: <http://heatco.ier.uni-stuttgart.de/deliverables.html>; accessed 15/12/2015: HEATCO.

Heathrow Airport Limited, 2012. Towards a sustainable Heathrow. Available online at: http://www.heathrowairport.com/static/HeathrowAboutUs/Downloads/PDF/Sustainability/2012_sustainability_summary_report.pdf; accessed 14/03/2014: Heathrow Airport Limited.

Heathrow Airport Limited, 2013. Airports Commission: Long-term hub capacity options. Available online at: http://www.heathrowairport.com/static/HeathrowAboutUs/Downloads/PDF/long-term-hub-capacity-options_LHR.pdf; accessed 17/04/2014: Heathrow Airport Limited.

Heathrow Express, 2014. Heathrow Express website: Facts and figures. Available online at: <https://www.heathrowexpress.com/about-heathrow-express/facts-figures>; accessed 17/06/2015.

Herder, P.M., De Joode, J., Ligtoet, A., Schenk, S., and Taneja, P., 2011. Buying real options – Valuing uncertainty in infrastructure planning. *Futures*, Special Issue: Flexible infrastructures, 43(9), pp. 961-969.

Hermans, E., Brijs, T., Wets, G., and Vanhoof, K., 2009. Benchmarking road safety: Lessons to learn from a data envelopment analysis. *Accident Analysis and Prevention*, 41(1), pp. 174-182.

Hernandez-Fajardo, I., Dueñas-Osorio, L., 2013. Probabilistic study of cascading failures in complex interdependent lifeline systems. *Reliability Engineering and System Safety*, 111, pp. 260-272.

Hickman, R., Saxena, S., Banister, D., and Ashiru, O. 2012. Examining transport futures with scenario analysis and MCA. *Transportation Research Part A: Policy and Practice*, 46(3), pp. 560-575.

Highways Agency, 2014. Green light for Greater Manchester smart motorway as work gets underway. Available online at: <https://www.gov.uk/government/news/green-light-for-greater-manchester-smart-motorway-as-work-gets-underway>; accessed 14/07/2015: UK Government.

Highways England, 2015. Lower Thames Crossing. Available online at: <http://www.highways.gov.uk/roads/road-projects/lower-thames-crossing/>; accessed 15/07/2015: Highways England.

HM Revenue and Customs, 2013. HMRC website. Available online at: <http://www.hmrc.gov.uk/>; accessed 01/12/2013: HM Revenue and Customs.

HM Treasury, 2003. The green book: Appraisal and evaluation in central government: Treasury guidance. Available online at: http://www.hm-treasury.gov.uk/d/green_book_complete.pdf; accessed 31/07/12: The Stationery Office.

HM Treasury, 2009. Accounting for the Effects of Climate Change: Supplementary Guidance to the Green Book. Available online at:

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/191501/Accounting_for_the_effects_of_climate_change.pdf; accessed 13/05/2015: The Stationery Office.

HM Treasury, 2011. Valuing infrastructure spend: Supplementary guidance to the green book. http://www.hm-treasury.gov.uk/d/valuing_infrastructure_spend_291111.pdf; The Stationery Office.

HM Treasury, 2013. Green Book supplementary guidance: Optimism bias. Available online at: <https://www.gov.uk/government/publications/green-book-supplementary-guidance-optimism-bias>; accessed 25/03/2015: The Stationery Office.

HM Treasury, 2015. Valuing infrastructure spend: Supplementary guidance to the green book. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/417822/PU1798_Valuing_Infrastructure_Spend_-_latest_draft.pdf; accessed 09/04/2015: The Stationery Office.

Horowitz, A.J., 2004. Lowry-type land use models. In: D.A. Hensher, K.J. Button, K.E. Haynes and P.R. Stopher, eds, Handbook of transport geography and spatial systems. Handbooks in transport Volume 5. Kidlington, Oxford: Elsevier, pp. 167-184.

HS2 Limited, 2013. The economic case for HS2. Available online at: http://assets.hs2.org.uk/sites/default/files/inserts/S%26A%201_Economic%20case_0.pdf; accessed 26/11/2013: HS2 Limited.

Humphrey, M., 2014. Fracking and Shale Gas in the UK: Is the Balcombe Effect Taking Hold? Available online at: <http://nottspolitics.org/2014/02/04/fracking-and-shale-gas-in-the-uk-is-the-balcombe-effect-taking-hold/>; University of Nottingham

iBUILD, 2015a. Are you being served? Alternative infrastructure business models to improve economic growth and well-being, iBUILD manifesto and mid-term report. ISBN 978-09928437-1-7. Available online at: <https://research.ncl.ac.uk/media/sites/researchwebsites/ibuild/ibuildreport%20optimised.pdf>; accessed 27/03/2015: University of Newcastle.

iBUILD, 2015b. iBUILD (Infrastructure BUsiness models, valuation and Innovation for Local Delivery) project website. Available online at: <https://research.ncl.ac.uk/ibuild/>; accessed 28/10/2015: iBUILD.

ICIF, 2015. ICIF (International Centre for Infrastructure Futures) project website. Available online at: <http://www.icif.ac.uk/>; accessed 28/10/2015: International Centre for Infrastructure Futures.

Infrastructure UK, 2010. National infrastructure plan 2010. <http://www.hm-treasury.gov.uk/d/nationalinfrastructureplan251010.pdf>; The Stationery Office.

Infrastructure UK, 2011. National infrastructure plan 2011. Available online at: http://cdn.hm-treasury.gov.uk/national_infrastructure_plan291111.pdf; accessed 30/01/2012: The Stationery Office.

Infrastructure UK, 2012. National infrastructure plan: Update 2012. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/188348/nip_update_as2012.pdf; accessed 18/06/2015: The Stationery Office.

Infrastructure UK, 2013a. National infrastructure plan: Infrastructure delivery update. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/204634/infrastructure_delivery_update_200313_1_.pdf; accessed 18/06/2015: The Stationery Office.

Infrastructure UK, 2013b. National infrastructure plan 2013. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263159/national_infrastructure_plan_2013.pdf; accessed 15/04/2014: The Stationery Office.

Infrastructure UK, 2014. National infrastructure plan 2014. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/381884/2902895_NationalInfrastructurePlan2014_acc.pdf; accessed 18/03/2015: The Stationery Office.

Interdepartmental Group on Costs and Benefits, Air Quality Subject Group, 2013. Air quality: Economic analysis. Available online at: <https://www.gov.uk/air-quality-economic-analysis#selecting-a-technique>; accessed 04/10/2013: Interdepartmental Group on Costs and Benefits, Air Quality Subject Group.

International Symposium for Next Generation Infrastructure, 2013. International symposium for next generation infrastructure, Summary of proceedings: Cutting through the infrastructure impasse - Ways and means. Available online at: <http://smart.uow.edu.au/content/groups/public/@web/@smart/documents/doc/uow161448.pdf>; accessed 27/03/2015: SMART Infrastructure Facility.

IPCC, 1995. Intergovernmental Panel on Climate Change, Working Group 3, Economic and social dimensions of climate change. Cambridge: Cambridge University Press.

ITRC, 2015. ITRC (Infrastructure Transitions Research Consortium) project website. Available online at: <http://www.itrc.org.uk/>; accessed 28/10/2015: Infrastructure Transitions Research Consortium.

Jenkins, R.R., Owens, N., and Wiggins, L.B., 2001. Valuing reduced risks to children: The case of bicycle safety helmets. *Contemporary Economic Policy*, 19(4), pp. 397-408.

Johansson, J., Hassel, H., 2010. An approach for modelling interdependent infrastructures in the context of vulnerability analysis. *Reliability Engineering and System Safety*, 95 (12), pp. 1335–1344.

Jyoti, J., and Soni, N., 2013. Comparative study of adhoc routing protocol AODV, DSR and DSDV in mobile adhoc network. *International Journal of Applied Engineering Research*, 7(11), pp. 1865-1868.

Kahneman, D., and Tversky, A., 1979. Prospect theory: An analysis of decision under risk. *Econometrica*, 47(2), pp. 263-292.

Kahneman, D., Slovic, P., and Tversky, A., eds, 1982. *Judgement under uncertainty: Heuristics and biases*. Cambridge: Cambridge University Press.

Keeney, R.L., 1992. *Value-focused thinking: A path to creative decisionmaking*. Cambridge, Massachusetts; London: Harvard University Press.

Klein, B., and Meckling, W., 1958. Application of operations research to development decisions. *Operations Research*, 6(3), pp. 352-363.

Kline, P.M., and Moretti, E., 2014. Local economic development, agglomeration economies, and the big push: 100 years of evidence from the Tennessee Valley Authority. *The Quarterly Journal of Economics*, 129(1), pp. 275-331.

Kørnø, L. and Thissen. W.A.H., 2000. Rationality in decision- and policy-making: Implications for strategic environmental assessment. *Impact Assessment and Project Appraisal*, 18(3) pp. 191-200.

Kroes, E.P., and Sheldon, R.J., 1988. Stated preference methods: An introduction. *Journal of Transport Economics and Policy*, 22(1), pp. 11-25.

- Krüger, N.A., 2012. To kill a real option – Incomplete contracts, real options and PPP. *Transportation Research Part A: Policy and Practice*, 46(8), pp. 1359-1371.
- Kuik, O., Brander, L., Nikitina, N., Navrud, S., Magnussen, K., and Fall, E.H., 2007. WP3 Report on the monetary valuation of energy related impacts on land use changes, acidification, eutrophication, visual intrusion and climate change. D.3.2. Available online at: http://cordis.europa.eu/publication/rcn/12384_en.html; accessed 12/08/2014: European Commission.
- Kuik, O., Hof, A. and Rayner, T., 2013. Guidance on the costs, benefits, and trade-offs in integrated climate action. Deliverable D9.5. Available online at: <http://www.responsesproject.eu/pdf/D9.5%20RESPONSES%20project%20report.pdf>; accessed 25/04/2014: RESPONSES project - European responses to climate change: Deep emissions reductions and mainstreaming of mitigation and adaptation, Grant agreement number 244092.
- Kwakkel, J.H., Haasnoot, M., and Walker, W.E., 2014. Developing dynamic adaptive policy pathways: A computer-assisted approach for developing adaptive strategies for a deeply uncertain world. *Climatic Change*, pp. 1-14.
- Lambert, J.H., Parlak, A.I., Zhou, Q., Miller, J.S., Fontaine, M.D., Guterbock, T.M., Clements, J.L., and Thekdi, S.A., 2013. Understanding and managing disaster evacuation on a transportation network. *Accident Analysis and Prevention*, 50, pp. 645-658.
- Langmead, D. and Garnaut, C., 2001. *Encyclopedia of architectural and engineering feats*. Oxford: ABC-CLIO.
- Larrick, R.P., 1993. Motivational factors in decision theories: The role of self-protection. *Psychological Bulletin*, 113(3), pp.440-450.
- Layard, R., and Glaister, S., eds, 1994. *Cost-benefit analysis*. 2nd edn. Cambridge: Cambridge University Press.
- Le Blond, P., 1999. Heathrow Express. *Japan Railway & Transport Review*, No. 19, pp. 20-24.
- Lempert, R.J., 2002. A new decision sciences for complex systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99(SUPPL. 3), pp. 7309-7313.
- Lempert, R.J., Popper, S.W., and Bankes, S.C., 2003. *Shaping the next one hundred years: New methods for quantitative, long-term policy analysis*. MR-1626-RPC. Santa Monica, California: RAND Corporation.
- Lewis, B., 2015. Progress report on the development of the Ebbsfleet Garden City. Available online at: <https://www.gov.uk/government/speeches/ebbsfleet-garden-city>; accessed 15/07/2015: UK Government.
- Li, Y., and Florig, H.K., 2006. Modeling the operation and maintenance costs of a large scale tidal current turbine farm, *OCEANS 2006, IEEE*, pp. 1-6.
- London Transport Data, 2012. Long-run trend in commuting into central London. Available online at: <http://londontransportdata.wordpress.com/?s=commuter>; accessed 30/10/2013: London Transport Data.
- López, E., Gutiérrez, J., and Gómez, G., 2008. Measuring regional cohesion effects of large-scale transport infrastructure investments: An accessibility approach. *European Planning Studies*, 16(2), pp. 277-301.
- Louviere, J.J., Hensher, D.A., and Swait, J.D., 2000. *Stated choice methods: Analysis and applications*. Cambridge: Cambridge University Press.

- Lowry, I.S., 1964. A model of metropolis. Memorandum RM-4035-RC. Santa Monica: The Rand Corporation.
- Lyons, G., Jain, J., and Holley, D., 2007. The use of travel time by rail passengers in Great Britain. *Transportation Research Part A: Policy and Practice*, 41(1), pp. 107-120.
- Mace, G.M., Bateman, I., Albon, S., Balmford, A., Brown, C., Church, A., Haines-Young, R., Pretty, J.N., Turner, K., Vira, B., and Winn, J., 2011. Chapter 2: Conceptual Framework and Methodology to the UK national ecosystem assessment. The UK national ecosystem assessment technical report. Cambridge: UNEP-WCMC, pp. 11-26.
- Mackie, P., 2010. Cost-benefit analysis in transport: A UK perspective. Available online at: <http://www.internationaltransportforum.org/jtrc/DiscussionPapers/DP201016.pdf>; accessed 31/07/2014: International Transport Forum.
- Mackie, P., Graham, D. and Laird, J., 2011. The direct and wider impacts of transport projects: A review. In: A. De Palma, R. Lindsey, E. Quinet and R. Vickerman, eds, *A handbook of transport economics*. Cheltenham: Edward Elgar, pp. 501-526.
- Mamun, Q., 2012. A qualitative comparison of different logical topologies for wireless sensor networks. *Sensors*, 12(11), pp. 14887-14913.
- Marcial Echenique and Partners Ltd, 2001. EUNET/SASI final report: EUNET socio-economic and spatial impacts of transport. ST-96-SC037. Available online at: <http://www.transport-research.info/Upload/Documents/200310/eunet.pdf>; accessed 12/04/2013: EUNET.
- Marques, R.C., Simões, P., and Berg, S., 2013. Water sector regulation in small island developing states: An application to Cape Verde. *Water Policy*, 15(1), pp. 153-169.
- Marshall, T., 2013a. *Planning major infrastructure: A critical analysis*. London: Routledge.
- Marshall, W.E., 2013b. An evaluation of livability in creating transit-enriched communities for improved regional benefits. *Research in Transportation Business and Management*, 7, pp. 54-68.
- Martinez, L., Lambert, J.H., and Karvetski, C., 2012. Public perception of the risks of liquefied natural gas terminals in Mexico: A prioritisation of communication strategies. *International Journal Critical Infrastructures*, 6(4), pp. 327-346.
- Mayor of London, 2006. Mayor backs plans for £2 billion Kings Cross regeneration. Available online at: <http://www.london.gov.uk/media/mayor-press-releases/2006/03/mayor-backs-plans-for-2-billion-kings-cross-regeneration>; accessed 23/06/2015: Mayor of London.
- McCubbin, D.R., and Delucchi, M.A., 1999. The Health Costs of Motor-Vehicle-Related Air Pollution. *Journal of Transport Economics and Policy*, 33(3), pp. 253-86.
- McLoughlin, I.V., and Prakash, S., 2013. Mobile communications using source-selected multi-antenna AF relays over dual-hop nakagami-m channels. *Wireless Personal Communications*, 71(4), pp. 3045-3057.
- Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., and Stouffer, R.J., 2008. Stationarity is dead: Whither water management? *Science*, 319(5863), pp. 573-574.
- Morel, B., 2013. Real options analysis applied to environmental policy decisions, 7 November 2013, Presentation at the University of Oxford.
- Morrissey, J., Iyer-Raniga, U., McLaughlin, P., and Mills, A., 2012. A strategic project appraisal framework for ecologically sustainable urban infrastructure. *Environmental Impact Assessment Review*, 33(1), pp. 55-65.

- Myers, S.C., 1977. Determinants of corporate borrowing. *Journal of Financial Economics*, 5(2), pp. 147-175.
- Navrud, S., 2000. Valuation techniques and benefit transfer methods: Strengths, weaknesses and policy utility. In: OECD, ed, *Valuing rural amenities*. France: OECD Publishing, pp. 15-40.
- Nellthorp, J., Bristow, A.L. and Day, B., 2007. Introducing willingness-to-pay for noise changes into transport appraisal: An application of benefit transfer. *Transport Reviews*, 27(3), pp. 327-353.
- Network Rail, 2009. Comparing environmental impact of conventional and high speed rail. Available online at: http://www.networkrail.co.uk/5878_Comparingenvironmentalimpactofconventionalandhighspeedrail.pdf; accessed 23/07/2013: Network Rail.
- OECD, 2010. *Globalisation, transport and the environment*. France: OECD Publishing.
- OECD, 2011. Improving the practice of transport project appraisal, ITF Round Tables. No. 149. Available online at: <http://dx.doi.org/10.1787/9789282103081-en>; accessed 31/05/2015: OECD Publishing.
- Office for National Statistics, 2001. *Census: Special Workplace Statistics (England, Wales and Northern Ireland)*. Available online at: <http://cids.census.ac.uk>; accessed 20/03/2012: UK Data Service Census Support.
- Office for National Statistics, 2011. Population density, local authorities in England and Wales. QS102EW. Available online at: <http://www.ons.gov.uk/ons/rel/census/2011-census/key-statistics-and-quick-statistics-for-wards-and-output-areas-in-england-and-wales/rft-qs102ew.xls>; accessed 21/02/2014: Office for National Statistics.
- Ofwat, 2008. The guaranteed standards scheme (GSS): Applicable to England and Wales from 1 April 2008. Available online at: https://www.ofwat.gov.uk/consumerissues/rightsresponsibilities/standards/gud_pro_gss08.pdf; accessed 31/05/2015: Ofwat.
- Olympic Design Authority, 2011. *Learning legacy: Lessons learned from the London 2012 Games construction project - Programme assurance on the Olympic Delivery Authority construction programme*. Available online at: <http://learninglegacy.independent.gov.uk/documents/pdfs/programme-organisation-and-project-management/204-programme-assurance-ppm.pdf>; accessed 27/11/2014: Olympic Design Authority.
- Omega Centre, 2014a. Project profile (Hong Kong): Airport railway. Available online at: http://www.omegacentre.bartlett.ucl.ac.uk/wp-content/uploads/2014/12/HK_AIRTRAIN_PROFILE.pdf; accessed 11/06/2015: Bartlett School of Planning, UCL.
- Omega Centre, 2014b. Project profile (UK): Jubilee Line extension. Available online at: http://www.omegacentre.bartlett.ucl.ac.uk/wp-content/uploads/2014/12/UK_JLE_PROFILE.pdf; accessed 11/06/2015: Bartlett School of Planning, UCL.
- Omega Centre, 2014c. Project profile (France): TGV Méditerranée. Available online at: http://www.omegacentre.bartlett.ucl.ac.uk/wp-content/uploads/2014/12/France_TGV_MED_PROFILE.pdf; accessed 11/06/2015: Bartlett School of Planning, UCL.
- Omega Centre, 2014d. Project profile (UK): M6 toll road. Available online at: http://www.omegacentre.bartlett.ucl.ac.uk/wp-content/uploads/2014/12/UK_M6_PROFILE.pdf; accessed 11/06/2015: Bartlett School of Planning, UCL.

Omega Centre, 2014e. Project profile (USA): New York Airtrain. Available online at: http://www.omegacentre.bartlett.ucl.ac.uk/wp-content/uploads/2014/12/USA_AIRTRAIN_PROFILE.pdf; accessed 11/06/2015: Bartlett School of Planning, UCL.

Omega Centre, 2014f. Project profile (Japan): Kyushu Shinkansen Kagoshima route. Available online at: http://www.omegacentre.bartlett.ucl.ac.uk/wp-content/uploads/2014/12/JAPAN_SHINKANSEN_PROFILE.pdf; accessed 11/06/2015: Bartlett School of Planning, UCL.

Omega Centre, 2014g. Project profile (UK): Channel Tunnel Rail Link. Available online at: http://www.omegacentre.bartlett.ucl.ac.uk/wp-content/uploads/2014/12/UK_CTRL_PROFILE.pdf; accessed 11/06/2015: Bartlett School of Planning, UCL.

O'Rourke, T.D., 2007. Critical infrastructure, interdependencies, and resilience. 'The Bridge' National Academy of Engineering, 37(1), pp.22-29.

Oswald, M., Li, Q., McNeil, S., and Trimbath, S., 2011. Measuring infrastructure performance: Development of a national infrastructure index. *Public Works Management and Policy*, 16(4), pp. 373-394.

Pachamanova, D.A., and Fabozzi, F.J., 2010. *Simulation and optimization in finance: Modeling with MATLAB, @Risk, or VBA*. Hoboken, NJ: Wiley.

Pallis, A.A., and Syriopoulos, T., 2007. Port governance models: Financial evaluation of Greek port restructuring. *Transport Policy*, 14(3), pp. 232-246.

Panel on America's Climate Choices, 2010. *Informing an effective response to climate change*. 978-0-309-14594-7. Washington, D.C.: National Academies Press.

Passenger Focus, 2012. National passenger survey: Autumn 2012 main report. Available online at: <http://www.transportfocus.org.uk/research/publications/national-passenger-survey-autumn-2012-nps-main-report#>; accessed 31/05/2015: Passenger Focus.

Pearce, D.W., and Turner, R.K., 1990. *Economics of natural resources and the environment*. London: Harvester Wheatsheaf.

Pearce, D.W., Markandya, A., and Barbier, E.B., 1989. *Blueprint for a green economy*. London: Earthscan.

Pitcher, C.A. 2008. *Investigation of a behavioural model for financial decision making: A dissertation submitted for the degree of : MSc Mathematical & Computational Finance*, University of Oxford.

Pitt, M., 2008. The Pitt review: Learning lessons from the 2007 floods. Available online at: http://webarchive.nationalarchives.gov.uk/20100807034701/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html; accessed 19/03/2015: Cabinet Office.

Popper, K., 1959. *The logic of scientific discovery*. London: Routledge.

Powell, J.C., Pearce, D.W., and Craighill, A.L., 1997. Approaches to valuation in LCA impact assessment. *The International Journal of Life Cycle Assessment*, 2(1), pp. 11-15.

Priemus, H., 2010. Decision-making on mega-projects: Drifting on political discontinuity and market dynamics. *European Journal of Transport and Infrastructure Research*, 1(10), pp. 19-29.

PwC, 2014. *Additional airport capacity: Economy impact analysis - Wider impacts assessment*. Available online at:

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/371810/2-economy--wider-impacts-assessment.pdf; accessed 20/11/2015: Airports Commission.

RAC Foundation, 2013. Transport Minister response to Parliamentary Question. Available online at: racfoundation.wordpress.com/2013/09/04/how-many-people-does-it-take-to-run-a-railway-not-already-built-hs2/; accessed 26/11/2013: RAC Foundation.

Raiffa, H., 1968. *Decision Analysis: Introductory Lectures on Choices Under Uncertainty*. Massachusetts: Addison-Wesley Publishing Company.

Raven, R.P.J.M., and Verbong, G.P.J., 2009. Boundary crossing innovations: Case studies from the energy domain. *Technology in Society*, 31(1), pp. 85-93.

Ready, R., Navrud, S., Day, B., Dubourg, R., Machado, F., Mourato, S., Spanninks, F., and Xosé Vázquez Rodriquez, M., 2004. Benefit transfer in Europe: How reliable are transfers between countries? *Environmental and Resource Economics*, 29(1), pp. 67-82.

Reed, 2012. UK average salaries. Available online at: <http://www.reed.co.uk/average-salary/>; accessed 01/12/2013: Reed.

Reeder, T., and Ranger, N., 2011. How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project. *World Resources Report*. Available online at: www.wri.org/sites/default/files/uploads/wrr_reeder_and_ranger_uncertainty.pdf; accessed 23/04/2014: World Resources.

Rinaldi, S.M., 2004. Modeling and simulating critical infrastructures and their interdependencies, *System sciences*, 2004. Proceedings of the 37th annual Hawaii international conference on 2004, IEEE, pp. 1-8.

Rinaldi, S.M., Peerenboom, J.P., and Kelly, T.K., 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. *Control Systems, IEEE*, 21(6), pp. 11-25.

Roca, E., Gamboa, G., and Tàbara, J.D., 2008. Assessing the multidimensionality of coastal erosion risks: Public participation and multicriteria analysis in a Mediterranean coastal system. *Risk Analysis*, 28(2), pp. 399-412.

Roelich, K., Dawson, D.A., Purnell, P., Knoeri, C., Revell, R., Busch, J., and Steinberger, J.K., 2014. Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. *Applied Energy*, 123(2014), pp.378-386.

Rogers, M., and Duffy, A., 2012. *Engineering project appraisal*. 2nd edn. Oxford; Ames, Iowa: John Wiley & Sons, Ltd.

Rosenberg, G., and Carhart, N., 2014. Investigation into the development of a framework for the identification and appraisal of infrastructure interdependencies with application to critical UK infrastructure: Case study report for Infrastructure UK - Review of potential infrastructure interdependencies in support of proposed route HS2 phase 2 consultation. Available online at: <http://www.icif.ac.uk/networks/123/portfolio.html#t67>; accessed 10/06/2015: International Centre for Infrastructure Futures.

Rothausen, S.G.S.A., and Conway, D., 2011. Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, 1(4), pp. 210-219.

Salling, K.B., and Banister, D., 2010. Feasibility risk assessment of transport infrastructure projects: The CBA-DK decision support model. *European Journal of Transport and Infrastructure Research*, 1(10), pp. 103-120.

Salzman, J., 1997. Review essay: Valuing ecosystem services. *Ecology Law Quarterly*, 24, pp. 887-904.

- Sansom, T., Nash, C., Mackie, P., Shires, J., and Watkiss, P., 2001. Surface transport costs and charges: Great Britain 1998. London: Department of the Environment, Transport and the Regions.
- Santos, J.M.L., 2000. Problems and potential in valuing multiple outputs: Externality and public-good non-commodity outputs from agriculture. In: OECD, ed, Valuing rural amenities. France: OECD Publishing, pp. 41-90.
- Sayers, P.B., Hall, J.W., and Meadowcroft, I.C., 2002. Towards risk-based flood hazard management in the UK. *Proceedings of the ICE - Civil Engineering*, 150(5), pp. 36-42.
- Schipper, Y., 2004. Environmental costs in European aviation. *Transport Policy*, 11, pp. 141-154.
- Schroeder, M.J., and Lambert, J.H., 2011. Scenario-based multiple criteria analysis for infrastructure policy impacts and planning. *Journal of Risk Research*, 14(2), pp. 191-214.
- Schwab, K., 2012. The global competitiveness report 2011-2012. Available online at: <http://www.weforum.org/reports/global-competitiveness-report-2011-2012>; accessed 31/05/2015: World Economic Forum.
- Schwab, K., 2014. The global competitiveness report 2014-2015. Available online at: http://www3.weforum.org/docs/WEF_GlobalCompetitivenessReport_2014-15.pdf; accessed 06/03/2015: World Economic Forum.
- Sebastian, R., Claeson-Jonsson, C., and Di Giulio, R., 2013. Performance-based procurement for low-disturbance bridge construction projects. *Construction Innovation*, 13(4), pp. 394-409.
- Shankleman, J., 2013. Siemens dives into Wales' first tidal array project. Available online at: <http://www.businessgreen.com/bg/feature/2251138/siemens-dives-into-wales-first-tidal-array-project>; accessed 26/06/2013: Business Green.
- Siggelkow, N., 2007. Persuasion with case studies. *The Academy of Management Journal*, 50(1), pp. 20-24.
- Simon, H.A., 1972. Chapter 8: Theories of bounded rationality. In: C.B. McGuire and R. Radner, eds, *Decision and organization: A volume in honor of Jacob Marschak*. Amsterdam: North-Holland Publishing.
- Simon, H.A., 1976. From substantive to procedural rationality. In: S.J. Latsis, ed, *Method and appraisal in economics*. Cambridge: Cambridge University Press, pp. 129-148.
- Slovic, P., Fischhoff, B., and Lichtenstein, S., 1980. Facts and fears: Understanding perceived risk. In: R.C. Schwing and W.A. Albers, eds, *Societal risk assessment: How safe is safe enough*. New York; London: Plenum Press, pp. 181-213.
- Small, K.A., Winston, C., and Yan, J., 2005. Uncovering the distribution of motorists' preferences for travel time and reliability. *Econometrica*, 73(4), pp. 1367-1382.
- Smit, H.T.J., 2003. Infrastructure investment as a real options game: The case of European airport expansion. *Financial Management*, 32(4), pp. 27-57.
- Smith, V.K., and Huang, J.C., 1993. Hedonic models and air pollution: Twenty-five years and counting. *Environmental and Resource Economics*, 3(4), pp. 381-394.
- Soelberg, P., 1967. Unprogrammed decision making: Working paper (Sloan School of Management). Cambridge: MIT, pp. 239-267.
- Southern Water, 2013. Draft water resources management plan: Strategic environmental assessment. Available online at: https://www.southernwater.co.uk/Media/Default/PDFs/WRMP_SEA_Summary_May20_2013.pdf; accessed 31/05/2015: Southern Water.

- Squire, L., 1975. *Economic analysis of projects*. Baltimore; London: Johns Hopkins University Press.
- Stagl, S., 2006. Multicriteria evaluation and public participation: The case of UK energy policy. *Land Use Policy*, 23(1), pp. 53-62.
- Stake, R.E., 1995. *The art of case study research*. Thousand Oaks, Calif; London: Sage.
- Stanton, E.A., and Ackerman, F., 2008. Generated user benefits and Heathrow expansion: Understanding consumer surplus. Available online: http://www.sei-international.org/mediamanager/documents/Publications/Climate/generated_user_benefits_heathrow_expansion.pdf; accessed 15/11/2013: Stockholm Environment Institute.
- Stern, N., 2006a. *The Stern review on the economics of climate change*. Cambridge: Cambridge University Press.
- Stern, J., 2006b. Written account of: Evaluating infrastructure regulators - Developing UK and international practice: A CRI occasional lecture held at the Royal Society on 26th September 2006. Available online at: http://www.bath.ac.uk/management/cri/pubpdf/Occasional_Lectures/17_stern.pdf; accessed 15/12/2015: University of Bath.
- Stevens, T.H., Belkner, R., Dennis, D., Kittredge, D., and Willis, C., 2000. Comparison of contingent valuation and conjoint analysis in ecosystem management. *Ecological Economics*, 32(1), pp. 63-74.
- Sumner, R., 2011. *Audit and development of RAILMOD*, prepared for the European Investment Bank. Client Report: Halcrow.
- Suttinon, P., and Nasu, S., 2010. Real Options for Increasing Value in Industrial Water Infrastructure. *Water Resources Management*, 24(12), pp. 2881-2892.
- Thames Water Utilities Ltd, 2009. *Water resource management plan 2010-2035*, volume 5. Available online at: www.thameswater.co.uk/about-us/5392.htm; accessed 29/01/2013: Thames Water.
- Thekdi, S.A., and Lambert, J.H., 2012. Decision analysis and risk models for land development affecting infrastructure systems. *Risk Analysis*, 32(7), pp. 1253-1269.
- Townley, B., 1992. In the eye of the gaze: The constitutive role of performance appraisal. In: P. Barrar and C.L. Cooper, eds, *Managing organisations in 1992: Strategic responses*. London: Routledge, pp. 185-202.
- Train, K.E., 1998. Recreation demand models with taste differences over people. *Land Economics*, 74(2), pp. 230-239.
- Tran, M., Hall, J., Hickford, A., Nicholls, R., Alderson, D., Barr, S., Baruah, P., Beavan, R., Birkin, M., Blainey, S., Byers, E., Chaudry, M., Curtis, T., Ebrahimi, R., Eyre, N., Hiteva, R., Jenkins, N., Jones, C., Kilsby, C., Leathard, A., Manning, L., Otto, A., Oughton, E., Powrie, W., Preston, J., Qadrdan, M., Thoung, C., Tyler, P., Watson, J., Watson, G., and Zuo, C., 2014. *National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain, Interim results*. Available online at: <http://www.itrc.org.uk/wordpress/wp-content/results/ITRC-First-results-WEB.pdf>; accessed 24/02/2014: Environmental Change Institute, University of Oxford.
- Transport for London, 2013. *Tube, DLR and London Overground fares*. Available online at: <http://www.tfl.gov.uk/tickets/14414.aspx>; accessed 30/10/2013: Transport for London.

Transport for London, 2014. Tfl planning briefing note - The Airports Commission interim report: Key Issues. Available online at: <http://www.tfl.gov.uk/assets/downloads/corporate/ac-interim-report-key-issues.pdf>; accessed 10/02/2014: Transport for London.

Ugwu, O.O., and Haupt, T.C., 2007. Key performance indicators and assessment methods for infrastructure sustainability - A South African construction industry perspective. *Building and Environment*, 42(2), pp. 665-680.

Ugwu, O.O., Kumaraswamy, M.M., Wong, A., and Ng, S.T., 2006. Sustainability appraisal in infrastructure projects (SUSAIP): Part 1. Development of indicators and computational methods. *Automation in Construction*, 15(2), pp. 239-251.

UK Government, 2007. Statutory instrument no. 3072: The renewable transport fuel obligations order 2007. Available online at: <http://www.legislation.gov.uk/uksi/2007/3072/contents/made>; accessed 01/07/2014: Office of Public Sector Information.

UK Government, 2014. Jobseekers allowance (JSA) website. Available online at: <https://www.gov.uk/jobseekers-allowance/overview>; accessed 29/07/2014: UK Government.

United Nations General Assembly, 2005. 2005 World Summit Outcome, Resolution A/60/1, adopted by the General Assembly on 15 September 2005. UN: Available online at: <http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N05/487/60/PDF/N0548760.pdf?OpenElement>; accessed 21/05/2015: United Nations.

University of Bristol, 2013. Investigation into the development of a framework for the identification and appraisal of infrastructure interdependencies with application to critical infrastructure: Case study report for Infrastructure UK - Identification of high-level infrastructure interdependencies for the Lower Thames Crossing. Available online at: <http://www.icif.ac.uk/networks/123/portfolio.html#t67>; accessed 10/06/2015: International Centre for Infrastructure Futures.

University of Maryland, 2012. Global terrorism database. Available online at: <http://www.start.umd.edu/gtd/>; accessed 23/08/2013: University of Maryland.

Van Den Bergh, J., Barendregt, A., Gilbert, A., Van Herwijnen, M., Van Horssen, P., Kandelaars, P., and Lorenz, C., 2001. Spatial economic-hydroecological modelling and evaluation of land use impacts in the Vecht wetlands area. *Environmental Modeling and Assessment*, 6(2), pp. 87-100.

Vickerman, R., 2007. Cost-benefit analysis and large-scale infrastructure projects: State of the art and challenges. *Environment and Planning B: Planning and Design*, 34(4), pp. 598-610.

Vickerman, R., 2008. Recent evolution of research into the wider economic benefits of transport infrastructure investments. In: OECD/ITF, ed, *The wider economic benefits of transport: Macro-, meso- and micro-economic transport planning and investment tools*, ITF Round Tables, No. 140. Paris: OECD Publishing, pp. 29-50.

Von Thünen, J.H., 1826. *The isolated state*. Translated from German by C.M. Wartenberg, edited with an introduction by P. Hall, 1966. Oxford: Pergamon Press.

Waddell, P. and Ulfarsson, G.F., 2004. Introduction to urban simulation: Design and development of operational models. In: D.A. Hensher, K.J. Button, K.E. Haynes and P.R. Stopher, eds, *Handbook of transport geography and spatial systems*. Handbooks in transport Volume 5. Kidlington, Oxford: Elsevier, pp. 203-236.

Walker, W.E., Haasnoot, M. and Kwakkel, J.H., 2013. Adapt or perish: A review of planning approaches for adaptation under deep uncertainty. *Sustainability*, 5(3), pp. 955-979.

Wang, T. and de Neufville, R., 2005. Real options 'in' projects, 9th Annual Real Options International Conference, Paris, France, 22-25/06/2005. Available online at:

http://realoptions.org/papers2005/Tao_Wang_RO_in_projects.pdf; accessed 06/09/13: Real Options Group

Ward, J., 2014. Investigation into the development of a framework for the identification and appraisal of infrastructure interdependencies with application to critical UK infrastructure: Case study report for Infrastructure UK - Phase 2 desk study report of Northern Line extension. Available online at: <http://www.icif.ac.uk/networks/123/portfolio.html#t67>; accessed 10/06/2015: International Centre for Infrastructure Futures.

Water Technology, 2014. CETO wave-powered desalination pilot plant, Garden Island, Australia. Available online at: <http://www.water-technology.net/projects/ceto-wave-powered-desalination-pilot-plant-garden-island/>; accessed 16/07/2015.

Weaver, C.P., Lempert, R.J., Brown, C., Hall, J.A., Revell, D., and Sarewitz, D., 2013. Improving the contribution of climate model information to decision making: The value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews: Climate Change*, 4(1), pp. 39-60.

Wegener, M., 2004. Land use and transportation modeling. In: D.A. Hensher, K.J. Button, K.E. Haynes and P.R. Stopher, eds, *Handbook of transport geography and spatial systems*. Handbooks in transport Volume 5. Kidlington, Oxford: Elsevier, pp. 125-146.

Weijnen, M.P.C. and Bouwmans, I., 2004. Innovation in networked infrastructures, IEEE International Conference on Systems, Man and Cybernetics, The Hague, The Netherlands, 10/10/2004.

Weijnen, M.P.C., Herder, P.M., and Bouwmans, I., 2008. Designing complex systems, a contradiction in terms. In: M. Eekhout, R. Visser and T. Tomiyama, eds, *Research in Design Series, Volume 3: Delft Science in Design 2*. Netherlands: IOS Press, pp. 235-254.

Weisbrod, G.E. and Alstadt, B., 2007. Progress and challenges in the application of economic analysis for transport policy and decision making. OECD/ITF Joint Transport Research Centre Discussion Papers, No. 2007/14. Paris: OECD Publishing.

Weitzman, M.L., 2007. A review of the Stern Review on the economics of climate change. *Journal of Economic Literature*, 45(3), pp. 703-724.

Wessex Water, 2011. Sustainability indicators 2011. Available online at: <http://www.wessexwater.co.uk/sustainability/sustainability/default.aspx?id=7955&linkidentifier=id&itemid=7955>; accessed 09/03/2012: Wessex Water.

Westcott, R., 2013. HS2: Predicted benefits lowered in new government report. Available online at: <http://www.bbc.co.uk/news/business-24721214>; accessed 01/11/2013: BBC.

Willis, K.G., 1989. Option value and non user benefits of wildlife conservation. *Journal of Rural Studies*, 5(3), pp. 245-256.

Willis, K.G., and Whitby, M.C., 1985. The value of green belt land. *Journal of Rural Studies*, 1(2), pp. 147-162.

Willis, K.G., Garrod, G.D., and Saunders, C.M., 1995. Benefits of environmentally sensitive area policy in England: A contingent valuation assessment. *Journal of environmental management*, 44(2), pp. 105-125.

Willis, K.G., Garrod, G.D., and Harvey, D.R., 1998. A review of cost-benefit analysis as applied to the evaluation of new road proposals in the U.K. *Transportation Research Part D: Transport and Environment*, 3(3), pp. 141-156.

Wise, R.M., Fazey, I., Stafford Smith, M., Park, S.E., Eakin, H.C., Archer Van Garderen, E.R.M., and Campbell, B., 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, 28, pp. 325-336.

World Bank Climate Change Group, 2014. Agreeing on robust decisions: New processes for decision making under deep uncertainty. 6906. Available online at: http://econ.worldbank.org/external/default/main?pagePK=64165259&piPK=64165421&theSitePK=469382&menuPK=64166093&entityID=000158349_20140604102709; accessed 17/09/2014: World Bank.

World Bank Independent Evaluation Group. 2012. Cost-benefit analysis in World Bank projects. Washington D.C.: The International Bank for Reconstruction and Development/The World Bank.

Young, K. and Hall, J., 2014. Strategic appraisal of interdependent infrastructure provision: A case study from the Thames Hub, P. Campbell and P. Perez, eds. In: Proceedings of the International Symposium of Next Generation Infrastructure, 1-4 October 2013 2014, SMART Infrastructure Facility, University of Wollongong, Australia.

Young, K., and Hall, J.W., 2015. Introducing system interdependency into infrastructure appraisal: from projects to portfolios to pathways. *Infrastructure Complexity*, 2(2).

Zandersen, M., Termansen, M., and Jensen, F.S, 2007. Testing benefits transfer of forest recreation values over a twenty-year time horizon. *Land Economics*, 83(3), pp. 412-440.

Zaréa, M., Pognonec, G., Schmidt, C., Schnur, T., Lana, J., Boehm, C., Buschmann, M., Mazri, C., and Rigaud, E., 2013. First steps in developing an automated aerial surveillance approach. *Journal of Risk Research*, 16(3-4), pp. 407-420.

A. Appendix A: Developments, Constraints and Prerequisites Applied to the Thames Hub Time Dependency Analysis

A.1 Development alternatives and minimum implementation times

No.	Alternative	Minimum Implementation Time (yrs)	Earliest Implementation Date	Notes
a ₀	Minor road upgrades	0.5	2011	Upgrades to ease areas with highest level of congestion
a ₁	Full road upgrades	5	2015	Design with provision for significant infrastructure growth
a ₂	Flood barrier only	8	2018	Thames barrier build (1974 - 1982)
a ₃	Flood barrier with generation	8	2018	Thames barrier build (1974 - 1982)
a ₄	Integrated barrier (generation and road only)	8	2020	Thames barrier build (1974 - 1982) + 2 years additional complexity
a ₅	Integrated barrier (generation and provision for rail)	8	2023	Thames barrier build (1974 - 1982) + 5 years additional complexity
a ₆	Integrated barrier (generation, road and provision for rail)	8	2023	Thames barrier build (1974 - 1982) + 5 years additional complexity
a ₇	Rail (commuter line only)	9	2019	High Speed 2 build time
a ₈	Rail (commuter and high speed provision, commuter enacted)	9	2019	High Speed 2 build time
a ₉	Rail (upgrade from commuter only to commuter and high speed)	9	2019	High Speed 2 build time
a ₁₀	Rail (high speed only)	9	2019	High Speed 2 build time
a ₁₁	Rail (commuter and high speed provision, high speed enacted)	9	2019	High Speed 2 build time
a ₁₂	Rail (upgrade from high speed only to commuter and high speed)	9	2019	High Speed 2 build time
a ₁₃	Rail (commuter and high speed lines)	9	2019	High Speed 2 build time
a ₁₄	Airport phase 1	10	2028	Estimate from Thames Hub Vision proposal
a ₁₅	Airport phase 2	2	2028	Estimate from Thames Hub Vision proposal

A.2 Constraints and prerequisites

C₀ – C₁₅ Asset earliest implementation dates (see A.1)

A.2.1 General

C₁₆ Developments once taken are final and cannot be reversed or delayed
C₁₇ Once selected, an Development cannot be selected again

A.2.2 Barrier

C₁₈ Development a₂ is invalid unless (a₀ OR a₁) was enacted at an earlier delivery point
C₁₉ Development a₃ is invalid unless (a₀ OR a₁) was enacted at an earlier delivery point
C₂₀ Development a₄ is invalid unless (a₀ OR a₁) was enacted at an earlier delivery point
C₂₁ Development a₅ is invalid unless (a₀ OR a₁) was enacted at an earlier delivery point
C₂₂ Development a₆ is invalid unless (a₀ OR a₁) was enacted at an earlier delivery point

A.2.3 Rail

C₂₃ Development a₇ is invalid unless (a₅ OR a₆) was enacted at an earlier delivery point
C₂₄ Development a₈ is invalid unless (a₅ OR a₆) was enacted at an earlier delivery point
C₂₅ Development a₉ is invalid unless a₈ was enacted at an earlier delivery point
C₂₆ Development a₁₀ is invalid unless (a₅ OR a₆) was enacted at an earlier delivery point
C₂₇ Development a₁₁ is invalid unless (a₅ OR a₆) was enacted at an earlier delivery point
C₂₈ Development a₁₂ is invalid unless a₁₁ was enacted at an earlier delivery point
C₂₉ Development a₁₃ is invalid unless (a₅ OR a₆) was enacted at an earlier delivery point

A.2.4 Airport

C₃₀ Development a₁₄ is invalid unless a₁ was enacted at an earlier delivery point
C₃₁ Development a₁₅ is invalid unless a₁₄ was enacted at an earlier delivery point
C₃₂ Development a₁₅ is invalid unless (a₄ OR a₅ OR a₆) was enacted at an earlier delivery point

A.3 Conflicts

A.3.1 Road

C₃₃ Development a₀ is invalid if a₁ was enacted at an earlier delivery point

C₃₄ Development a₁ is invalid if a₀ was enacted at an earlier delivery point

A.3.2 Barrier

C₃₅ Developments a₃, a₄, a₅, and a₆ are invalid if a₂ was enacted at an earlier delivery point

C₃₆ Developments a₂, a₄, a₅, and a₆ are invalid if a₃ was enacted at an earlier delivery point

C₃₇ Developments a₂, a₃, a₅, and a₆ are invalid if a₄ was enacted at an earlier delivery point

C₃₈ Developments a₂, a₃, a₄, and a₆ are invalid if a₅ was enacted at an earlier delivery point

C₃₉ Developments a₂, a₃, a₄, and a₅ are invalid if a₆ was enacted at an earlier delivery point

A.3.3 Rail

C₄₀ Developments a₈, a₁₀, a₁₁, and a₁₃ are invalid if a₇ was enacted at an earlier delivery point

C₄₁ Developments a₇, a₁₀, a₁₁, and a₁₃ are invalid if a₈ was enacted at an earlier delivery point

C₄₂ Developments a₇, a₈, a₁₁, and a₁₃ are invalid if a₁₀ was enacted at an earlier delivery point

C₄₃ Developments a₇, a₈, a₁₀, and a₁₃ are invalid if a₁₁ was enacted at an earlier delivery point

C₄₄ Developments a₇, a₈, a₁₀, and a₁₁ are invalid if a₁₃ was enacted at an earlier delivery point

B. Appendix B: Assumptions Made in Deriving Travel Modes for Passengers Travelling To and From the Thames Hub Vision Airport

The assumptions used in adapting current passenger travel behaviour (taken from Civil Aviation Authority (2003)), to that for the Thames Hub Vision airport are listed below.

General assumptions:

- Passengers use the same mode of transport to travel to and from the airport;
- Travel modes defined as 'other' or 'not specified' have been ignored;
- Passengers using 'airport car' or 'hire car' travel modes do not change mode¹;
- Interlining passengers do not require transport to or from the airport²;
- The percentage of interlining passengers stays constant; and
- An active traffic management approach is taken at the Thames Hub airport (see Foster+Partners et al., 2011a); as such, parking is restricted at the airport, 'park and ride' facilities are built at all rail stations and the orbital is treated as an extended airport shuttle service;

Pathway specific assumptions:

Pathway	Assumptions
All Thames Hub Vision airport pathways	• Bus/Coach users in Kent change to Taxi/Minicab given the short proximity to the airport
High Speed rail pathways	• Tube/Train users from outside London (to the North or West) switch to using the rail orbital • Car, Taxi/Minicab, and Bus/Coach users from HS2 stations (Manchester, Birmingham, Sheffield and Leeds) switch to using the rail orbital
Commuter rail pathways	• Tube/Train users from outside London (to the North or West) switch to using the rail orbital • Tube/Train users in North London, or originating from locations with new orbital stations switch to using the rail orbital • Car and Taxi/Minicab users originating from locations with new orbital stations switch to using the rail orbital (Ashford, Barking, Bromley and Dartford)

¹ This is a conservative assumption, if hire car facilities were provided at the orbital stations, passengers may choose to use the orbital rather than drive around the M25.

² It is recognised that this is a simplification as passengers with more than an hour between flights may choose to leave the airport.

Pathway	Assumptions
Commuter rail pathways (continued)	• Car, Taxi/Minicab and Bus/Coach users from mainline regional stations switch to using the rail orbital (Midland Mainline and Westcoast Mainline (main) stations: Basingstoke & Dene, Bath, Birmingham, Bristol, Cardiff, Cardiff Airport, Carlisle, Chester, City Of Edinburgh, Coventry, Crewe & Nantwich, Derby, Doncaster, Exeter, Gloucester, Great Grimsby, Leeds, Leicester, Luton, Luton Airport, Manchester, Milton Keynes, Newcastle Upon Tyne, Nottingham, Oxford, Plymouth, Portsmouth, Preston, Reading, Sheffield, Shrewsbury & Atcham, Slough, Southampton, Southampton Airport, St Albans, Stafford, Stoke On Trent, Taunton Deane, Watford, Winchester, Windsor & Maidenhead, Wolverhampton, York) • Car users crossing (or driving close to) orbital switch to using 'park and ride' facilities due to the restricted parking at the airport • Bus/Coach users in Essex, or originating from locations with new orbital stations switch to using the rail orbital • Taxi/Minicab users, whose ride has been made longer will change to using the rail orbital if this is closer
Full rail pathways	• Tube/Train users from outside London (to the North or West) switch to using the rail orbital • Tube/Train users in North London, or originating from locations with new orbital stations switch to using the rail orbital • Car and Taxi/Minicab users originating from locations with new orbital stations switch to using the rail orbital (Ashford, Barking, Bromley and Dartford) • Car, Taxi/Minicab and Bus/Coach users from mainline regional stations switch to using the rail orbital (Midland Mainline and Westcoast Mainline (main) stations: Basingstoke & Dene, Bath, Birmingham, Bristol, Cardiff, Cardiff Airport, Carlisle, Chester, City Of Edinburgh, Coventry, Crewe & Nantwich, Derby, Doncaster, Exeter, Gloucester, Great Grimsby, Leeds, Leicester, Luton, Luton Airport, Manchester, Milton Keynes, Newcastle Upon Tyne, Nottingham, Oxford, Plymouth, Portsmouth, Preston, Reading, Sheffield, Shrewsbury & Atcham, Slough, Southampton, Southampton Airport, St Albans, Stafford, Stoke On Trent, Taunton Deane, Watford, Winchester, Windsor & Maidenhead, Wolverhampton, York) • Car users crossing (or driving close to) orbital switch to using 'park and ride' facilities due to the restricted parking at the airport • Bus/Coach users in Essex, or originating from locations with new orbital stations switch to using the rail orbital • Taxi/Minicab users, whose ride has been made longer will change to using the rail orbital if this is closer