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Introducing system interdependency into infrastructure appraisal: from projects to portfolios to pathways

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Abstract

Current methods for appraisal of infrastructure projects have been developed to consider multiple criteria, wider economic impacts and uncertainty, yet their focus on standalone projects and sector specific methods ignores the widely acknowledged 'system of system' interactions between infrastructure networks. Here we draw inspiration from real options 'in' projects to build on current appraisal methods, extending the analysis from single projects to cross-sector regional portfolios and finally to temporally differentiated development pathways; quantifying each stage through a case study on the Thames Hub Vision. The result is a system perspective of the investments, including: (i) the emergent effects of infrastructure asset interactions and how these are affected by the timing and order of development; (ii) an understanding of the 'opportunity' value of an investment through its ability to restrict or enable further developments; and (iii) the total required resources and potential environmental outcomes. Through our case study we demonstrate these effects, identifying system effects sufficient to reverse the outcome of the analysis from a net negative, to a net positive result. Furthermore, we show that the enabling effects of an asset on future developments can create impacts an order of magnitude larger than those observed through current individual asset appraisals. Our developments allow the creation of a decision support tool capable of more fully evaluating the effects of infrastructure investments, with a focus on the long-term opportunity provided by development strategies. The work provides a platform for prioritisation of investments across sectors and for highlighting cross-sector effects, thereby encouraging stakeholder engagement and collaboration. Further work is necessary to explore the effects of intrinsic socio-economic uncertainty in the modelling assumptions and feedbacks between investments and future projections, such as population change and economic growth.

Keywords: Infrastructure systems; Interdependency; Appraisal; Cost benefit analysis; Decision support

Background

Taking a systems approach to infrastructure development

The UK, like all developed countries, relies on its infrastructure to support all aspects of its economy, from the wellbeing of its population to the day to day market operations of its industries. The UK Government has noted its criticality for the success of the country and has identified an infrastructure pipeline of over £450bn (Infrastructure UK 2014) to secure these services for the future. Given the multi-decadal planning and operational life of infrastructure and its extensive interactions with the economy, it will be essential to understand the effects of these investments as a whole, if the resulting system of systems is to be functionally efficient and robust to future socioeconomic change (Frischmann 2012; Beuthe 2002).

However, with some infrastructure assets dating back over 100 years, the UK's networks are extensive and highly interrelated, both within and between the sectors. This interdependency has been particularly evident during recent extreme weather events and has been highlighted by the UK government in a number of internal and commissioned reports (Infrastructure UK 2010; Frontier Economics 2012; Engineering the Future 2013). Yet while there is an appreciation of the system effects of infrastructure centrally, the responsibility for delivering the future pipeline of infrastructure assets falls to siloed government agencies and departments. While some of these agencies have highly

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developed appraisal methodologies and guidance, including multiple criteria and wider economic impacts, they focus on the appraisal of single projects. Interdependencies between the sectors are all but ignored, with appraisals assuming that services from the other sectors will continue to be available and reliable despite changes in demand. Investments that might be necessary to achieve this level of service tend not to be considered[a]. Indeed most analyses are made against a static development environment, disregarding all potential parallel and future developments and the opportunities and constraints these create[b]. Furthermore, whilst all public sector appraisal is based on the Treasury's Green Book (HM Treasury 2003), aspects of appraisal methodologies are specific to each sector preventing a joint understanding of interdependencies and balanced prioritisation across sectors (Rogers and Duffy 2012; Mackie 2010).

There is growing recognition that to understand how regions and cities function we must understand the interactions of infrastructure networks (Batty 2013). Furthermore, that ignoring interdependencies will limit (or perhaps negate) the efficacy of development policies (Rinaldi 2004). There has been a call for appraisal approaches to be extended to reflect this complexity (Booth 2012), enabling a more strategic approach to infrastructure development. As a first, fundamental step, this necessitates the development of a common appraisal framework capable of appraising infrastructure assets from any sector, allowing assets to be combined and compared in a common language. Secondly, we must capture system effects, including both the operational interdependencies between the infrastructures (the demands on each other and potential system efficiencies) and their temporal interdependencies: their strategic enabling (or constraining) effects on future developments, recognising that these effects are not attributable to a single project or asset alone, but to the development pathway of the system as a whole.

Incorporating the long-term: system opportunities and constraints

The long life of infrastructure assets can lead to vast changes in the socio-economic environment and regulatory frameworks they must operate within. Infrastructure investment decisions are therefore made under conditions of 'deep uncertainty'[c]. Under such conditions, utility maximising methods, such as those used for appraisal, become highly sensitive to the projected future environment, reducing the robustness of the answers produced. This uncertainty is often seen purely as a negative, indeed, many of the existing studies of infrastructure interdependency focus on the vulnerabilities this creates (see for example, Buldyrev et al. 2010; Rinaldi 2004; Haimes et al. 2005; Apostolakis and Lemon 2005). However, alongside risks, there are also opportunities, particularly where flexibility is maintained and used to create additional value when opportunities arise (Ford et al. 2002). In order to understand the temporal interdependency effects of infrastructure investments we require a methodology able to capture these opportunities as well as manage the risks.

Perhaps the most well-known methodology for capturing the value of flexibility is real options analysis (see Myers 1977), the use of which is now recommended by UK Government departments (HM Treasury 2003; Frontier Economics 2013), although limited guidance is given regarding its application. The method provides the opportunity to consider the various alternatives available to the decision maker, to understand the temporal nature of the investment and to strategically plan for actions as more information is available. Real options analysis provides a structured methodology for evaluating the benefits (relative to the costs) of investing to keep options open for the future. 'Real options' exist where an opportunity has a defined cost that must be paid if that option is to remain open. The choice of whether to exercise the option is made at a future date, when more information is available. An example might be investing now to enable physical expansion of a plant in the future: initial costs of providing space for expansion are higher than for a small facility, but provide the opportunity for growth and hence greater future revenues should demand be high. Should demand remain low, the option is not exercised (the facilities are not expanded) and costs remain lower than those of constructing a large facility immediately. The more commonly applied methodology, coined "real options 'on' projects" by Wang and de Neufville (2005), relates asset value to stock prices or assumed elasticities, valuing outcomes over time against the options available (often to expand or abort).

While the validity of the key assumptions in real options analysis are questioned (Pachamanova and Fabozzi 2010; Borison 2003; Wang and de Neufville 2005; de Neufville and Scholtes 2011), it has been found to produce useful insights (Pachamanova and Fabozzi 2010) and has been applied to a number of infrastructure case studies (for example, Guo and Jiang 2010; Fernandes et al. 2011; Ashuri et al. 2011). However, all of these studies have concentrated on a single infrastructure sector and, for many, the case of a single asset. Furthermore, with the need to associate asset value to a stock price or elasticity, the method creates little potential for a simple extension to multiple sectors which are unlikely to share such characteristics.

Analysis of real options 'in' projects deals with the appraisal of investments in optionality within projects. A real world case provides an example; with the Thames Estuary 2100 project (Reeder and Ranger 2011) taking a real options 'in' projects approach and using this to consider various measures and assets to provide flood protection to London. While only one sector (water) is considered, this adaptation of the standard methodology (see Wang and de Neufville 2005) creates options through varying the design and/or function of elements within the investment. It thereby focuses on how elements within an investment portfolio of physical assests interact over time and build upon one another to achieve benefits.

The focus in this paper is on groups of assets across different sector networks (portfolios) rather than individual projects within a single sector. Nonetheless, the methodology of real options 'in' projects provides the potential to consider assets, the value of which is contingent upon future uncertainties as well as upon the existence of other assets in the network. Here we extend the concepts (though not the probabilistic details of the appraisal methodology) to consider the staged implementation of interdependent projects from different infrastructure sectors. We refer to these staged and coordinated sequences of investments as "pathways". In particular we consider: (i) the ordering necessary to understand the system effects; (ii) the timing required to quantify the impacts and understand the benefits and costs of early implementation or delay; (iii) the incorporation of options, to allow consideration of how flexibility within the individual asset designs affects the total system impacts; and (iv) the creation of pathways to understand the total system flexibility to long term uncertainty and the opportunities and constraints imposed on other developments. We thereby build a cross-sectoral appraisal methodology, able to encapsulate the system effects, the benefits of flexibility and the constraints and opportunities provided by sequences of investments, to provide a proactive strategy for infrastructure decision making.

Current use of portfolios and pathway assessments

Consideration of portfolios and pathways, while limited for infrastructure appraisal, are becoming more commonplace in fields such as climate change adaptation, where the deep uncertainty of conditions and the need for robust solutions over the long term is recognised. Portfolio examples have captured the vast range of possible project combinations (see, for example, Louisiana's 'Comprehensive Master Plan for a Sustainable Coast' (Coastal Protection and Restoration Authority of Louisiana 2012)), or examined a smaller number of designed portfolios against thousands of futures to test for vulnerabilities (see, for example, the Colorado River Basin Study by Groves et al. (2013)). The studies also recognise the multi-sector nature of the plans and although focused on the water sector, include some consideration of effects on existing and/or future energy and transport infrastructures. Their inclusion of resource constraints and mutually exclusive developments (in the case of the Louisiana study) and dynamic decision making (in the case of the Colorado study) suggests that extension to pathways methods may be soon realised, with the limitations of not considering system effects noted explicitly in the Louisiana study.

Work by Hasnoot et al. (2012; 2013) and Kwakkel et al. (2014) into Adaptation Pathways and Dynamic Adaptive Policy Pathways proves this extension to pathway analysis possible for similar water sector concerns. The methods align with the approach proposed in this paper, providing understanding of decision pathways. In particular, they present a multi-attribute appraisal, aggregating costs and benefits under subject headings to highlight how these differ across the pathways and therefore who may gain, or lose from such investments. Furthermore they provide insights into the lock-in and path dependency of projects, a necessary step for the inclusion of system impacts into the assessment results. The studies differ from the approach applied here, which is less focussed upon sensitivity to exogenous drivers and concentrates instead on quantifying the system effects of the developments. The studies, however, highlight the need to consider a range of possible futures and the vulnerability of pathways to uncertainty, an important extension to the work considered herein.

Aims and structure of this paper

The aim of the research described in this paper is to demonstrate a methodology capable of more completely appraising multi-sector infrastructure investments through the incorporation of the interdependency between the sectors. This will be completed in two stages. Firstly we build portfolios of possible infrastructure capital investments and develop a common cross-sector appraisal methodology to capture the cross-sector demand and system efficiencies. Secondly we combine these portfolios into implementation pathways to capture the dynamic constraints of the investment landscape and through this the value inherent in the opportunities provided for future development. We discuss the approach and findings in the remaining three sections of this paper: In section 4 we outline the methodology and case study, developing a consistent cross-sector multi-attribute cost benefit analysis (CBA), to allow aggregation of projects into investment portfolios. We go on to introduce time dependency and options to create a system pathway analysis. The multi-attribute CBA builds on the welfare economic approach currently used within standard appraisal methodologies, capturing the direct effects of the assets themselves and their secondary effects through their interdependencies with the other developments. In section 5 we review the results of the analysis, discussing the impacts for appraisal, focusing on the emergent system effects captured and the appraisal of opportunities presented by the pathway approach. Finally we draw conclusions and review the priorities for further research in section 6, including consideration of wider effects of infrastructure on regional economic and spatial development.

Methods

Model overview

The proposed approach (Figure 1) begins with the development of alternative plausible infrastructure investment pathways (as previously defined). The set of possible investment pathways is constrained by requirements for ‘prerequisite’ infrastructure upon which a potential investment necessarily depends. Furthermore, mutually exclusive investments are excluded from the feasible set. A time period of 100 years is split into 20 equal intervals of 5 years, with implementation allowed at the start of any 5 year period once precedent and development time conditions had been fulfilled.

Each alternative pathway is evaluated with respect to fifteen cross-sector performance metrics, which were derived from existing sector priorities and aggregated under four attributes: (1) environment (air quality, carbon dioxide emissions, habitat loss/creation, landscape/visual amenity, noise and water quality); (2) social (safety and security[d]); (3) service (utilised capacity, congestion/reliability and physical protection[e]); and (4) financial (cost, revenue, tax implications and employment). These four aggregated attributes were evaluated for each year

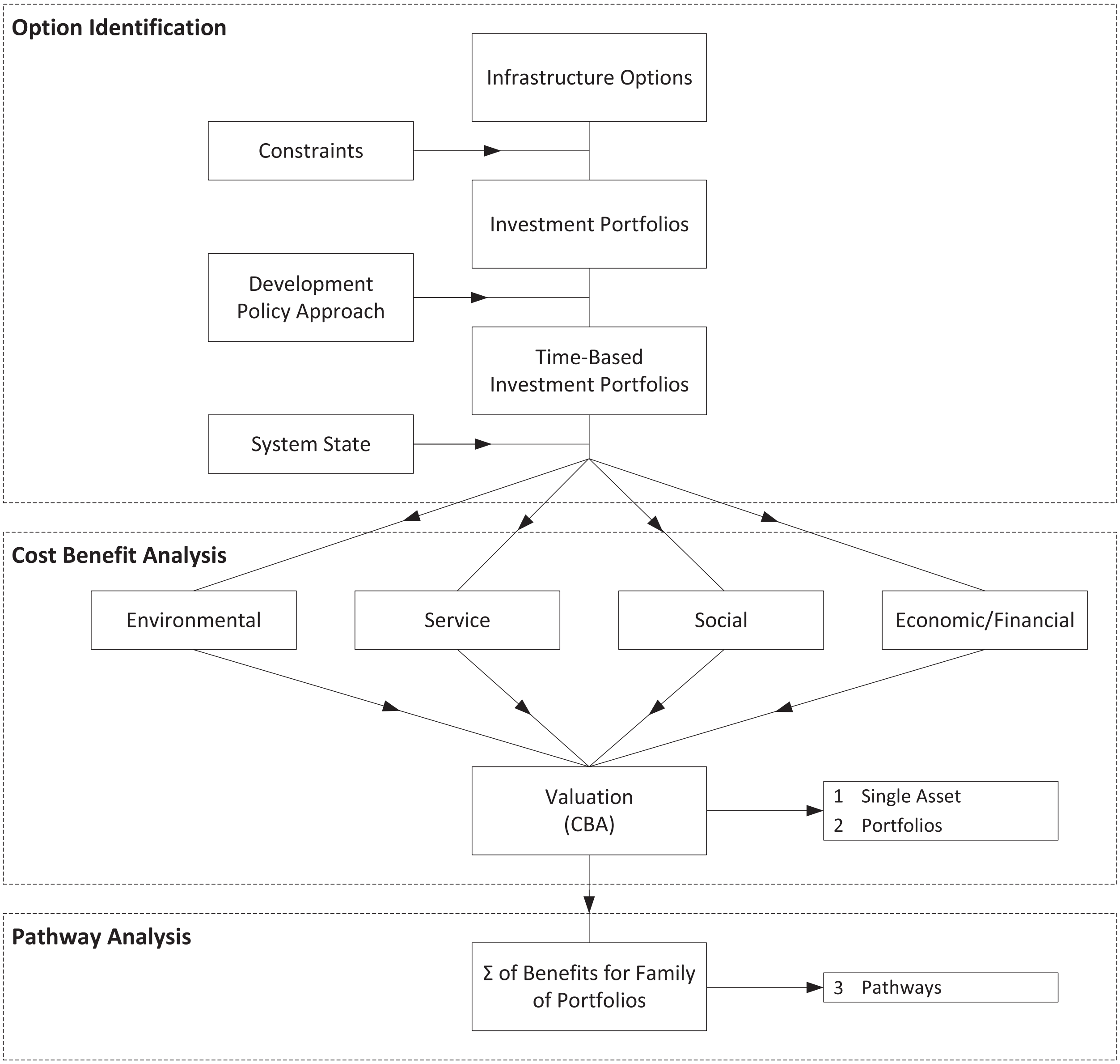


Figure 1 Overview of methodology.

of the appraisal period. The benefits were evaluated relative to a baseline investment path (referred to as the 'do minimum' pathway).

Figure 2 presents the pathway valuation methodology, comparing three portfolio development pathways against the 'do minimum' pathway. Each line represents an asset present within the given pathway, with the length of the line indicating the period for which that asset is producing costs and/or benefits. The value of each asset is the product of a set of model projections for the year considered $\{y_m\}$ and a value vector $\{a_{\text{asset n}}\}$ for the given asset, consisting of a calculation for each of the four aggregated attributes. The pathway value for a given year is calculated by summing the asset values for all assets present and subtracting the asset values for the 'do minimum' pathway. For example, the value of Pathway 1 in year 5 is given by:

$$\left\{V_{Pathway\ 1,\ y5}\right\} = (\{a_{A1}\} + \{a_{A2}\})\{y_5\} - \{a_{DM1}\}\{y_5\}$$

Some assets are mutually exclusive due to spatial or operational requirements (represented by the dashed lines). Here, the latterly implemented asset is assumed not to occur. For example, in year 50, Asset A_3 in Pathway 3 is mutually exclusive to asset DM_2 in the 'do minimum' pathway. A3 is implemented first and so DM2 is assumed not to occur. The value of Pathway 3 in year 50 is therefore given by:

$$\begin{aligned}\left\{V_{Pathway\ 3,\ y50}\right\} &= (\{a_{A1}\} + \{a_{A3}\})\\ &\quad \times \{y_{50}\} - (\{a_{DM1}\} + \{a_{DM3}\})\{y_{50}\}\end{aligned}$$

Monetization was calculated using established valuation methods. To enable comparison with individual asset appraisals, valuation methodologies are taken, where possible, from the existing sector specific analyses (summarised in Table 1 and further detailed within the Additional file 1). In many cases these rely on revealed or stated preference data and are subject to well-known limitations (see Pearce et al. 1989, Navrud S 2000 and Hanley N, Barbier EB 2009 for a discussion of these methods). The net present value (NPV) of each attribute was then calculated against a base year of 2010 using the HM Treasury reducing discount rates for long term infrastructure projects[f] (HM Treasury 2003).

Finally, combining each portfolio with multiple temporal implementation strategies, we determine a number of potential pathways. These pathways are grouped into families according to the assets implemented, with the appraisal results reported against these family groups. Pathway families are denoted by the assets they have in common. For example, in Figure 2, all three pathways would be in the A1 asset pathway family, but only Pathway 1 and Pathway 2 would be in the A2 pathway family. The four attributes produced by the appraisal are combined into minimum and maximum ranges for each pathway family and are presented for each portfolio or pathway to maintain segregation of results and to allow consideration of effects from multiple stakeholder perspectives. The pathway family attributes are then used to determine the opportunity value of each portfolio of assets, and the total potential system effects.

Case study

To demonstrate the methodology, we examine the 'Thames Hub Vision' proposal for an integrated infrastructure hub in and around London (Foster+Partners, Halcrow, Volterra 2011a)[g]. As shown in Figure 3 the proposal centres around a new 150 million passenger per annum hub airport and a

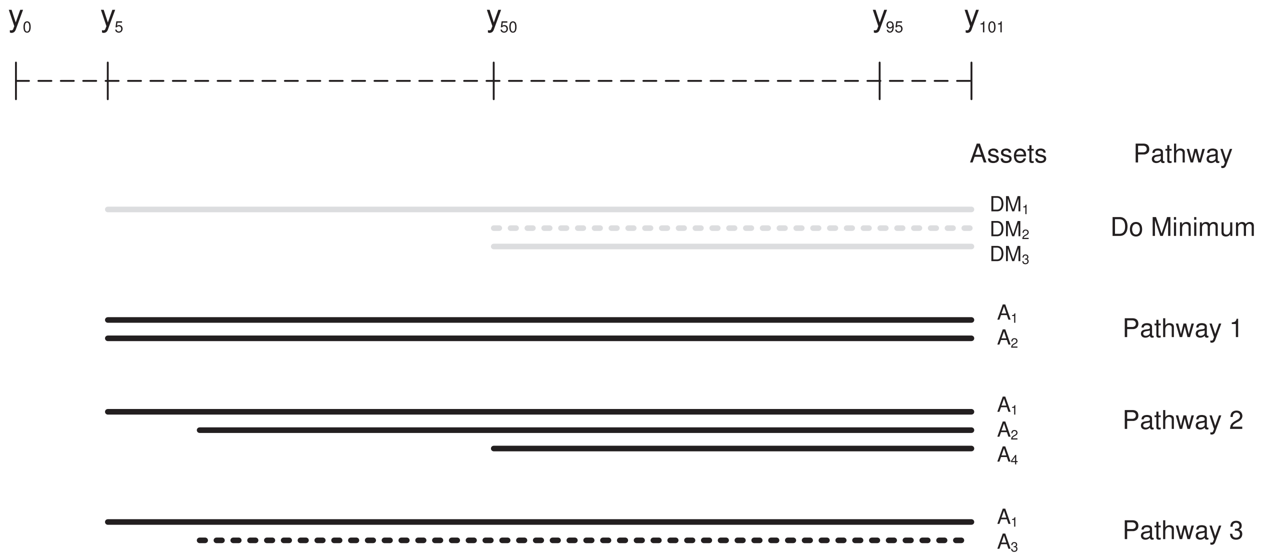


Figure 2 Combination of asset investments into pathways.

Table 1 Performance metrics and recorded effects

Metric		Description [assets included]
Environment	Air quality	NO_x and PM_{10} emissions generated or negated by individual development or required supporting infrastructure [airport landing and take-off; additional electricity required/negated; road demand from airport]. Quantified according to infrastructure demand/operation levels and predicted emissions (Highways Agency (2007) and European Parliament (2007) for buses and cars, Department for Transport (2011b) for electricity, (AMEC 2014a) airports). Valued based on marginal abatement cost avoidance approach (Interdepartmental Group on Costs and Benefits, Air Quality Subject Group 2013).
	Carbon dioxide emissions	Carbon dioxide emissions generated or negated by individual development or required supporting infrastructure [airport landing and take-off; additional electricity required/negated; road demand from airport]. Quantified according to infrastructure demand/operation levels (Department for Transport 2011b; AMEC 2014b) and valued according to European Trading Scheme projections (Department for Transport 2011b).
	Habitat	Habitat land lost/gained due to development [all assets]. Quantified according to predicted landtake (Foster+Partners, Halcrow, Volterra 2011a) and land designations (Natural England 2014). Valued according to willingness to pay for conservation (Willis 1989), using UK Water Company multiplication factors.
	Landscape and visual amenity	Amenity value of land lost/gained due to development [all assets]. Quantified according to predicted landtake (Foster+Partners, Halcrow, Volterra 2011a) and valued according to willingness to pay for preservation (Entec 2004).
	Noise	Noise impact on local population caused by individual development or required supporting infrastructure [road, rail and airport]. Quantified through comparison with similar infrastructure assets (Department for Food and Rural Affairs 2012; Civil Aviation Authority 2012) and population projections (Hall et al. 2012). Valued according to hedonic pricing for quiet (Department for Transport, 2011b).
	Water quality	Degradation/improvement of water quality caused by individual development or required supporting infrastructure [barrier]. Quantified accord to conservative estimate of degradation from medium to low quality. Valued according to willingness to pay for water quality improvements (Georgiou et al. 2000).
Service	Utilised capacity	User value derived through provision of service (assumed to be half of revenue created) [rail, airport and electricity generation]. Quantified according to air passenger demand projections (Department for Transport 2011a) limited by asset design constraints (Foster+Partners, Halcrow, Volterra 2011a) and assessment of modal use of surface transport. Valued through ticket/utility prices for surface access and electricity (Transport for London 2013; Department of Energy and Climate Change 2011) and through predicted landing fees and 'additional revenue' for the airport (Foster+Partners, Halcrow, Volterra 2011a).
	Congestion or reliability	Value of time lost or gained due to capacity constraints of infrastructure provided [road and airport]. Quantified according to predicted congestion for road types used (Department for Transport 2011b) and current delay at Heathrow (Civil Aviation Authority 2013). Valued according to willingness to pay for time savings (Department for Transport 2011b).
	Physical protection	Asset protection provided by the development under extreme conditions (weather) [barrier]. Valued according to expert estimation as part of the TE2100 project (Environment Agency 2009) for the barrier.
Social	Safety	Injuries created or avoided through everyday provision of infrastructure service (user and employee accidents) [road and airport]. Quantified through historic accident rates (Department for Transport 2011c; Health and Safety Executive 2012) and valued through willingness to pay to avoid injury (Department for Transport 2011b).
	Security	Injuries created or avoided through provision of infrastructure under extreme conditions (weather, terrorism) [barrier, airport]. Quantified according to expert estimation as part of the TE2100 project (Environment Agency 2009) and valued through willingness to pay to avoid injury (Department for Transport 2011b). Terrorist threat quantified and valued through comparison with historic events (University of Maryland 2012; Institute for the Analysis of Global Security 2003).
Financial	Cost	Cost of implementing infrastructure (capital, operational and maintenance costs) by individual development or required supporting infrastructure [all assets]. Quantified according to proposal documentation (Foster+Partners, Halcrow, Volterra 2011a).
	Revenue	Gain or loss from provision of services (split with capacity effect) [rail, airport and electricity generation]. Quantified according to air passenger demand projections (Department for Transport 2011a) limited by asset design constraints (Foster+Partners, Halcrow, Volterra 2011a) and assessment of modal use of surface transport.

Table 1 Performance metrics and recorded effects *(Continued)*

		Valued through ticket/utility prices for surface access and electricity (Transport for London 2013; Department of Energy and Climate Change 2011) and through predicted landing fees and 'additional revenue' for the airport (Foster+Partners et al 2011b). Airport revenues also include sale of redeveloped Heathrow site.
	Tax implications	Gain or loss to tax from implementation of development [road, rail, airport and electricity generation]. Quantified according to current income tax and national insurance and duty rates for petrol and rail tickets, with demand estimated via to air passenger demand projections (Department for Transport 2011a) and assessment of modal use of surface transport.
	Employment	Salaries and unemployment benefit generated or negated by development [rail, airport and electricity generation]. Quantified using average salary data (REED 2012) and current unemployment benefit rates.

Further detail on data sources provided within the Additional file 1.

new flood barrier with integrated energy generation (525 GWh) and transport crossings in the Thames Estuary. To service these key infrastructures, road upgrades and a new rail orbital provide access to the airport and the potential to circumvent the heavily utilised M25 motorway and central London rail and tube networks. While versions of most of the proposed infrastructure assets are already being considered by the separate government agencies, the Thames Hub Vision presents an opportunity to explore the benefits of integration and the system effects of the designs when combined. It also presents the potential for much wider economic benefits than most infrastructure asset developments, increasing international connectivity (via the airport and Channel Tunnel rail link) and potentially providing additional agglomeration benefits through its proximity to England's capital city and financial centre. While some appraisal methodologies have been adapted to consider wider economic aspects, the value of such effects are widely debated, particularly for mature economies like the UK (Marcial Echenique and Partners Ltd 2001; Banister and Berechman 2003). We have therefore not endeavoured to quantify the macro economic impacts of the scheme. Instead we have sought to quantify the direct impacts alongside employment and revenue benefits. A more spatial consideration of the feedbacks between the developments and their socio-economic environment is considered an important next step in the work and should consider the agglomeration and indirect employment benefits of the scheme.

For the appraisal of benefits and impacts of the Thames Hub Vision we draw on the proposal documents, in particular the estimates of the costs, service provision and spatial footprints of the assets (Foster+Partners 2011b). Some system effects can be estimated from these documents directly (for example, the use of electricity by the airport). However, others need further assessment. The most significant of these is the modal shift of air passengers between surface access modes. The Thames Hub Vision proposal documents suggest that 60 per cent of passenger arrivals and departures could be serviced by rail. This is a major increase from current levels at Heathrow (less than

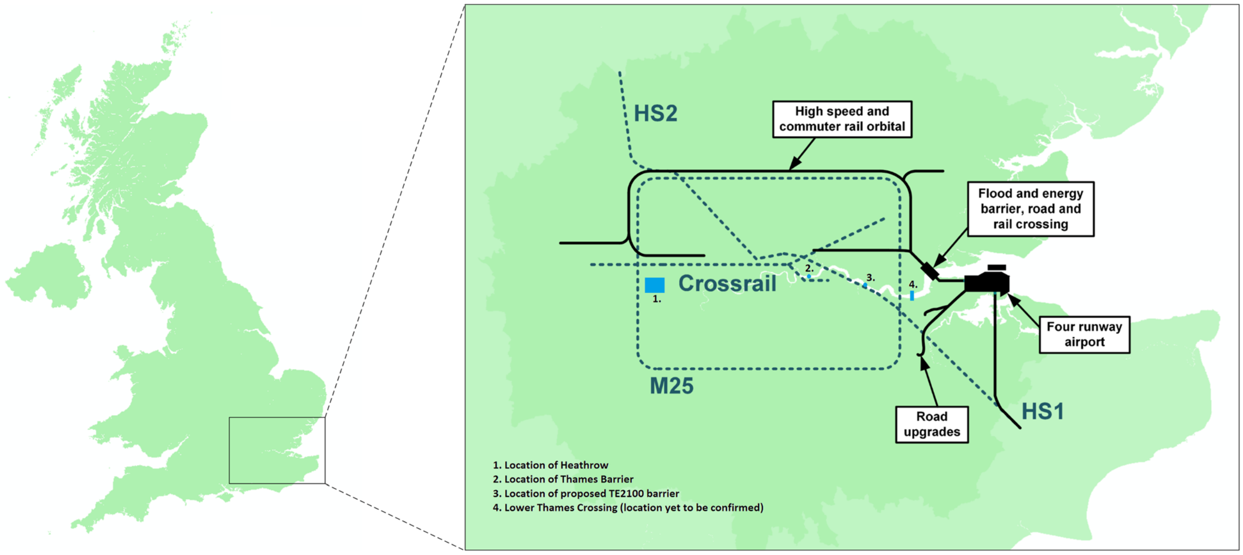


Figure 3 Location and elements of the Thames Hub Vision.

30 per cent by rail or London Underground (Heathrow Airport Limited 2014)). A strict traffic management approach is proposed, limiting onsite parking and providing extensive park and ride facilities at the rail orbital stations, such that the orbital becomes an extended rail shuttle service. A model of potential surface access changes has been created based on origin–destination data for Heathrow (Civil Aviation Authority 2003), with passengers whose journey length has increased and who pass an orbital station on route to the airport, assumed to be open to a modal shift from car to rail. A full list of assumptions used within the modal shift analysis is included in the Additional file 1. The projections align well with the Foster + Partners proposal, with 43 per cent using the orbital and 18 per cent using central London tube and train services.

In addition to the new demand for ground transportation to the airport, given the predicted growth in the UK in both transport and energy demand (Tran et al. 2014), any relieved capacity on the central London tubes and trains or energy generated by the barrier is assumed to be fully utilised and are captured in the 'utilised capacity' benefits.

The portfolio and pathway valuations are referenced through a pairwise comparison with the 'do minimum' development pathway. The appropriate 'do minimum' pathway for the region was constructed through consideration of previous analyses of infrastructure development in the Southeast of England, including the Engineering the Future infrastructure timelines report (Engineering the Future 2013), the National Infrastructure Plan (Infrastructure UK 2014) and the sectoral development plans for central and east London. The 'do minimum' pathway includes provision for the following assets over the 100 year timeframe:

- Expansion of London's airport capacity, assuming development of the current hub airport (Heathrow) in west London, from a two runway airport into a three runway hub airport in line with the Heathrow Airport Ltd proposal ('North West option') to the Davis Commission (Heathrow Airport Limited 2013). The potential capacity of the extended airport is predicted to be 130 million passengers per annum, therefore demand is restricted to this level. Operational and maintenance costs are assumed to be the same as the current airport.
- Flood defence investment in line with the Environment Agency's Thames Estuary 2100 plans including the replacement of the current Thames Barrier at Greenwich with a new barrier at Long Reach in 2070 (Environment Agency 2009). This barrier does not include any transport crossings or energy generation and is further west than the proposed Thames Hub Vision barrier, reducing the area protected from flooding. Maintenance required on other estuary flood defences is also included within the plan and has conservatively been assumed to be necessary in both the 'do minimum' and Thames Hub Vision pathways.
- Delivery of High Speed 2 phase 2, a high speed rail service connecting north and central England to London, with stations at Manchester, Birmingham, Sheffield and Leeds (HS2 Limited 2013). The proposed route runs north-west from Euston Station in central London, passing approximately 12 km north of Heathrow Airport.
- Commissioning of an additional east London River Thames road crossing assumed to be in line with the Lower Thames Crossing proposals. Given that construction of the Lower Thames Crossing is expected to commence in 2021 (University of Bristol, 2013), the crossing has been assumed to negate the road capacity benefits delivered by the Thames Hub Vision barrier crossing. Benefits generated by the increased road capacity created by the Thames Hub Vision barrier road crossing have therefore conservatively been ignored in the results.
- Delivery of the full Crossrail rail network from Maidenhead (Berkshire) through central London to Shenfield (Essex) and Abbey Wood (Greenwich/Bexley), with a spur connection to Heathrow airport. The effect of this development on the modal use of the different transport networks to and from Heathrow Airport is assumed to be negligible given the high levels of rail connectivity currently available. Instead it is assumed that the current modal distribution is maintained (Civil Aviation Authority 2003), with Crossrail providing the additional rail capacity necessary to accommodate the growing number of aircraft passengers.

Of these developments, not all can proceed as planned if the Thames Hub Vision proposal goes ahead (see Table 2). For example, the expansion of Heathrow is mutually exclusive to the Thames Hub Vision airport, due to hub airport operations and airline commercial factors. The Thames Hub Vision proposal assumes that the Heathrow area will be redeveloped (as new residential or commercial development) and allows for this as part of the business case. The Thames Hub Vision barrier will negate the benefits of the Thames Estuary 2100 barrier at Long Reach so it will be assumed that if the Thames Hub barrier is implemented prior to 2070, the proposed barrier at Long Reach will not go ahead. The other three developments will be assumed to occur in parallel to implementation of the Thames Hub Vision elements.

Demand for the surface transport infrastructure is derived from air traffic demand projections (Department

Table 2 Summary of 'do minimum' and Thames Hub Vision infrastructure elements

Asset [and Infrastructure Service(s)]	Scenario	Construction	Prerequisites/Constraints
Expanded Heathrow [Transport (air)]	Do minimum	Planned delivery by 2026	Mutually exclusive to Thames Hub Vision airport
TE2100 flood protection measures [Water (flood)]	All (with restrictions)	Plan until 2170; barrier delivery by 2070	Benefits negate/negated by Thames Hub Vision barrier
High Speed 2 [Transport (rail)]	All	Planned delivery by 2032	Non assumed
Lower Thames Crossing [Transport (road)]	All	Under consultation	Non assumed
Crossrail [Transport (rail)]	All	Planned delivery by 2019	Non assumed
Thames Hub Vision road upgrades [Transport (road)]	Thames Hub Vision scenarios	Planned delivery by 2014	Some road upgrades necessary to allow construction of other Thames Hub Vision elements
Thames Hub Vision barrier [Transport (road and rail), Energy (generation), Water (flood)]	Thames Hub Vision scenarios	Planned delivery by 2015	Requires some road upgrades, prerequisite for rail orbital; flood benefits negate/negated by TE2100 barrier
Thames Hub Vision rail orbital [Transport (rail)]	Thames Hub Vision scenarios	Planned delivery by 2019	Requires some road upgrades and barrier
Thames Hub Vision airport [Transport (air)]	Thames Hub Vision scenarios	Planned delivery by 2028	Requires some road upgrades for construction; requires barrier crossing and either the rail orbital or major road upgrades to operate at full capacity; mutually exclusive to Thames Hub Vision airport

for Transport 2011a), but limited by the capacities of the airports. Latent demand that is stimulated by the provision of additional road and rail capacity is ignored, allowing results to focus on the demand derived from the airport. This assumption, however, leads to a conservative perspective on any service benefits derived from these infrastructures. It is recognised that the provision of additional connectivity is likely to create demand, particularly for road networks, and that by making central London increasingly accessible from the north Kent region there is the potential for increased population growth that could add to this demand and the associated impacts. As noted earlier, the inclusion of interdependencies between the infrastructure assets and their socio-economic environment will be an important future extension to this work and should include the population change facilitated by the increased connectivity.

From projects to portfolios

The aim of the proposed portfolio analysis is to understand the total system demands and efficiencies possible from the simultaneous consideration of multiple assets. We therefore take the four assets (road, rail, barrier with integrated energy generation and transport crossings and airport) as originally proposed and apply the cross-sector appraisal methodology; firstly determining the value of the elements as individual assets (as compared to the 'do minimum' case), then comparing this with a similar appraisal assuming that the commissioning of the other infrastructures has already been agreed, capturing the effects of the system interdependencies. Knowing that the introduction of the rail asset (along with the associated traffic management proposals) has the potential to divert passengers from road to rail, we focus on the rail and airport infrastructures and the effects of this behavioural change on the four categories of impacts.

From portfolios to pathways

The aim of the pathway analysis is to build on the portfolio analysis outlined above, to investigate the sequencing of the costs and benefits of the Thames Hub Vision proposal assets. This has two facets. Firstly, we evaluate the magnitude of the pathway opportunity created by an investment, through its enablement or constraint of further infrastructure developments, compared to its individual appraisal valuation. Secondly, we consider the synergistic effects inherent in the case study, particularly the aggregation of transport, energy and water infrastructure services within the single barrier asset and the connectivity effects of including commuter rail stations alongside the high speed orbital. To expose these system effects we develop a number of alternatives to the four major Thames Hub Vision assets considered within the portfolio analysis (namely the road, barrier, rail and airport developments). We therefore extrapolated the road, barrier and rail elements of the design to include:

- Two road development levels: Full ('major') development in line with the Thames Hub Vision proposal documentation and limited ('minor') development sufficient to allow other elements to be built, but not support surface access to the airport;
- Five mutually exclusive alternatives for the flood barrier, including barrier energy 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 proposal documentation; and

- Five rail development alternatives, consisting of only commuter or only high speed lines, each of the single line alternatives with the facilities to upgrade at a later date and the full Thames Hub Vision rail proposal with both lines.

The assumed prerequisites are therefore: that at least minor road development is necessary to allow construction of any of the larger assets; that a rail river crossing is required for the rail orbital to be developed; and that major road upgrades along with either a road or a rail river crossing are necessary to support the surface access requirements of the full airport design. The developments are constrained such that the barrier alternatives are mutually exclusive, as are the rail developments without provision for further expansion. Combining these constraints and prerequisites with the proposed infrastructure elements, we can create a pathways analysis of the possible development routes, such as that shown in Figure 4[h]:

Combining this pathways analysis with cross-sector appraisal (see Table 1 for details) we can trace the opportunity provided by each development and the pathway opportunities that may follow each investment. This enables investigation of system effects and how these affect the value proposition of the developments as a whole rather than justifying each individual development through their standalone costs and benefits. Furthermore, through consideration of the pathway as a whole we can see the total effects of each strategy and compare this to available resources, environmental limitations and regional planning policies. Where there are specified requirements for infrastructure provision, these could also be added to the analysis to reduce the decision space by removal of pathways that do not conform to these requirements. Alternatively, where pathways exceed environmental or resource restrictions, the appraisal methodology results can be used to understand where the impacts are generated and to prioritise limited resources across the sectors to ensure maximum opportunity for the future.

Results and discussion

The portfolio approach

Table 3 compares the results of the standalone asset and a portfolio approach, taking the airport element of the Thames Hub Vision as an example. The first row of data presents the standard individual (standalone) asset appraisal, assuming only the current network of infrastructure services exists. The second row presents the appraisal assuming that the baseline of infrastructure services, notably the rail infrastructure, have been developed by the time the airport is implemented. The difference between the two rows therefore denotes the system effects of the airport and rail assets being implemented together.

The individual asset assessment indicates that although the Thames Hub Vision airport provides capacity for an additional 20mppa and a positive financial benefit, its NPV is negative (–£14.3bn). Despite £1.8bn in noise benefits from relocating to a significantly less populated area of London, the loss of 4000 ha of land creates a large negative landscape and habitat result (total -£1.3bn) and the pollution from increased road and air traffic (total -£2.7bn), lead to a negative environmental result of -£2.2bn. These impacts are shared between local residents, whose impacts are entirely negative (pollution, landscape, habitat and noise effects) and the wider population, who experience reduced

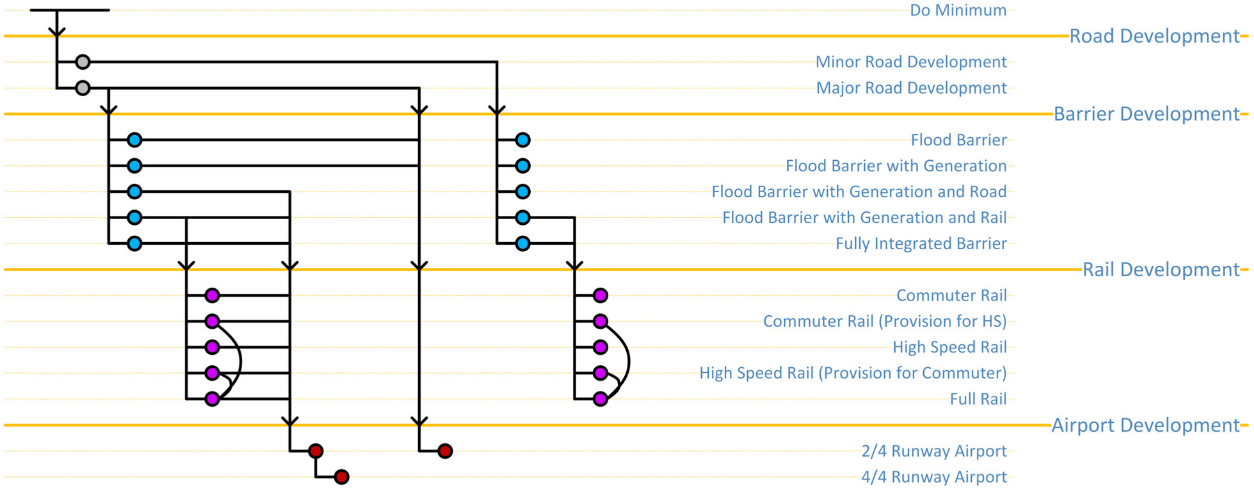


Figure 4 Pathway alternatives.

Table 3 CBA of airport as a single asset and as part of a portfolio infrastructure investment

Asset	Environmental (2010 prices, £bn)	Financial (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	1.84	2.32	39.18	2.80	46.13

noise near Heathrow, but increased emissions. Minor security benefits of reducing flights over London (£0.2bn) are outweighed by the accidents generated by increased road use and flights (−£3.8bn) to produce a negative social result of -£3.6bn. Both of these results are an order of magnitude smaller than the positive financial benefits (total of £35.2bn) which are split between the investors and the Treasury with £21.5bn in revenues, including landing fees and the sale of the redeveloped Heathrow land, −£19.8bn capital and operational costs, £10.1bn in income and petrol taxes and £23.4bn in employment benefits. This positive financial benefit is, however, strongly reliant on realising an additional 28,000 jobs through investment in the Thames Hub Vision airport, with £32.1bn attributable to job-related effects. It is also negated by the net negative service effects (capacity and reliability) produced by the increased travel required to access the airport. Given the high modal use of road (approximately 77% at Heathrow (Civil Aviation Authority 2003)), the additional passenger capacity of 20mppa and the more remote location of the Thames Hub Vision airport, kilometres travelled increases by 76%. This increases fuel costs by £1.4 per passenger and causes road congestion effects of approximately -£4.1 per passenger on existing roads compared to the Heathrow expansion's -£1.6 per passenger. These effects dominate the benefits from the increased capacity of the airport to give a total service attribute impact of -£43.7bn.

Comparing these results to the portfolio case we see that the system effects are substantial in all four categories, resulting in a reversal of the result from a total negative of -£14.3bn to total positive of £31.9bn. This change relates almost entirely to the surface access demands of the airport and the conversion of travellers from 77% road to 60% rail. The consequential reduction in road traffic reduces emissions, improves safety, reduces road congestion and increases utilisation of the rail infrastructure. These benefits are significant (a total of over £49.4bn) and despite the reduction in Treasury revenue from petrol duty (−£3.3bn), the total benefits are £46.1bn greater than the standalone case.

Considering these changes we can see the importance of presenting disaggregated results and understanding where the effects will be felt. For example, the implementation of a rail scheme and active traffic management are almost sufficient to negate the negative environmental effects of increasing airport capacity, with the majority of this benefit (98%) from a reduction in carbon emissions. This may affect public support for the scheme making it easier to implement, a factor not captured by the analysis, but likely to affect investor interest. Furthermore the combined rail and airport system significantly reduces the impact of airport expansion on UK climate change targets. The reliance of CBA on revealed and stated preference methods creates uncertainties for valuations of such finite, or legislatively restricted effects. As resources (such as rare earth minerals) become rarer or pollutants (such as carbon dioxide) become more restricted, their value changes and therefore the marginal change assumptions of CBA become inaccurate. By separating social (safety) and environmental considerations from the larger financial and service outputs, the trade-offs between different attributes remain explicit.

Subsequent investments clearly influence the benefits that are accrued to prior investments, for example, with the surface access requirements of the airport changing the viability of the rail investment. Development of the first asset (the rail infrastructure) provides the *opportunity* for system effects; however, current UK appraisal practice would only apply the benefits to the latterly implemented asset (in this case the airport) and then only if the first development was operational or at least mostly constructed. While the airport produces financial benefits as a standalone asset, this is not necessarily the case for the rail infrastructure, whose cost benefit ratio will be highly dependent on the latent demand, a factor that is known to be poorly estimated in the UK (Flyvbjerg 2009). The implementation of active traffic management at the airport, relies on the rail investment. It enables travel by over 50 million passengers per year by 2110 generating £11.2bn in service and financial benefits. Employee travel is not included within the results, but applying the average London commuter modal split would imply a further 44,000 journeys per day and approximately £62.6 m in fares per year (£3.5bn NPV over the 100 year period). Together these results substantially change the viability of the rail development, accounting for over 80 per cent of the total costs of the full rail development and reducing the reliance on latent demand.

The pathways approach

We now consider the sequencing of the alternative investment pathways. If the rail infrastructure is implemented first no further surface access investments are necessary for the airport, however, investment in rail may be restricted by the uncertainty of the demand profile. If the airport infrastructure is implemented first, the demand for rail becomes more certain and financial risk is reduced. However, facilities for access must be provided in its absence and traveller behaviour changed once it has been developed. As car use has been noted to be habitual (Gärling and Axhausen 2003), behaviour change may be difficult; therefore, by building the airport first, the potential demand for the rail infrastructure may be undermined. By considering the opportunity of the pathway as a whole we can evaluate the risks and benefits to assets outside that which we are currently appraising and understand the trade-offs made by changing the timing or sequencing of developments.

Opportunity value and total pathway impacts

Tables 4 and 5 compare the appraisal results for the standalone road investments and the pathways enabled through these investments. The pathway results are referred to by their common asset, as such, the 'minor road' pathways all start with the minor road development, but include all asset development routes made possible by this choice. The valuations of all common pathways are then collated and the minimum and maximum pathway results presented in Tables 4, 5, 6 and Figure 5.

Assuming no intrinsically derived road demand, the difference between the single asset assessment totals is –£1.06 billion, due to the additional land take and cost effects of the major road development. In comparison, the difference in benefit from the pathways enabled by the two road alternatives varies from –£41.0bn (service minimum) to £23.7bn (financial maximum). The opportunity value provided by the investments clearly far exceeds the effects of the standalone assets.

The difference in opportunity provided by the two road options is due to the assumed constraints of the minor road development. Referring to the pathway analysis in Figure 4, we are reminded that while the barrier and rail developments can be commissioned with only minor road developments, an airport would need more major developments to support the surface access demands of passengers. The minor road developments pathways therefore lack both the airport impacts and system effects from the airport interacting with the other elements, significantly changing its opportunity value compared to the major road development pathways.

System effects: aggregation of infrastructures

By providing a decision tree schematic alongside the pathway results we can clarify the assumed prerequisite conditions and constraints for future development. Through this we create a decision support tool that focuses the viewer on the flexibility and opportunity value provided by the developments rather than their standalone value. Figure 5, highlights decisions on the scale of road development (5A), whether a barrier should be built (5B) and whether energy generation should be included as part of the barrier (5C). The benefit assessment of each pathway is depicted as a bar denoting the maximum and minimum value produced. Use of two scales ensures the smaller environmental and social results remain clear, such that decision makers can draw their own conclusions regarding valuation uncertainties and trade-offs between different categories of benefit/impact.

The effects of the individual developments can still be discerned, but they are now placed against the effects of the pathway as a whole. Not only does this help decision makers look past the individual investments, but it further clarifies the trade-offs and benefits. Taking the tidal barrier as an example, the pathways with and without the barrier can be compared in Figure 5B and value of the five barrier alternatives in Figure 5C. Through a review of the change in social impact, we can determine the intrinsic security benefits of the barrier (£0.3bn change in maximum social value, see annotation (a) Figure 5B) and see that these are only 20% of the -£1.6bn difference in minimum social value (see annotation (b) in Figure 5B). By enabling higher levels of road traffic, the negative safety implications of the barrier pathway could be much greater than the security benefits derived from its implementation. Similarly, the potential financial benefits of including a rail crossing (£12.6bn difference in maximum financial value, see annotation (c) in Figure 5C) can be seen to be 70 per cent of the costs of implementing the full rail option (£17.9bn

Table 4 Environmental and social pathway analysis outputs for the two road investment alternatives[i]

	Environmental impact (£bn)			Social impact (£bn)		
	Single asset	Pathway minimum	Pathway maximum	Single asset	Pathway minimum	Pathway maximum
Minor Road	–0.39	–2.14	–0.39	0.00	0.00	0.33
Major Road	–0.78	–4.31	–0.78	0.00	–3.33	0.33
Difference	–0.39	–2.17	–0.39	0.00	–3.33	0.00

Table 5 Financial and service pathway analysis outputs for the two road investment alternatives[i]

	Financial impact (£bn)			Service impact (£bn)		
	Single asset	Pathway minimum	Pathway maximum	Single asset	Pathway minimum	Pathway maximum
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

difference in minimum financial value, see annotation (d) in Figure 5C). Finally, the environmental benefit of the renewable energy generation (£0.1bn difference in minimum environment cost, see annotation (e) Figure 5C) is only 2–4 per cent of the potential environmental costs of development (−£2.6-£4.3bn). Such insights create understanding of the contributions made by each element of the pathway and their interactions with the rest of the system. They therefore allow further exploration of how bundling investments may affect risks and the balance of benefits to stakeholder groups. By maintaining focus on the long term opportunities provided by the system as a whole, they also encourage stakeholders to see past the individual projects.

Annotation (e) in Figure 5C reflects feasible steps to reduce negative impacts, in this case by introducing renewable energy generation to reduce carbon dioxide emissions. While the proposed barrier generation could supply the airport's energy needs, the impact on the total environmental effect is two orders of magnitude smaller than the additional transport emissions and geographic footprint of the developments. Such reflections draw attention to the importance and variation in valuation methods used within the CBA. For example, the predicted market prices of carbon (as used herein) is less than 20 per cent of the cost of reducing carbon dioxide production, for example, through the implementation of renewable energy generation). The pathways approach again highlights these factors for the decision maker and allows them to draw their own conclusions on valuation and uncertainty.

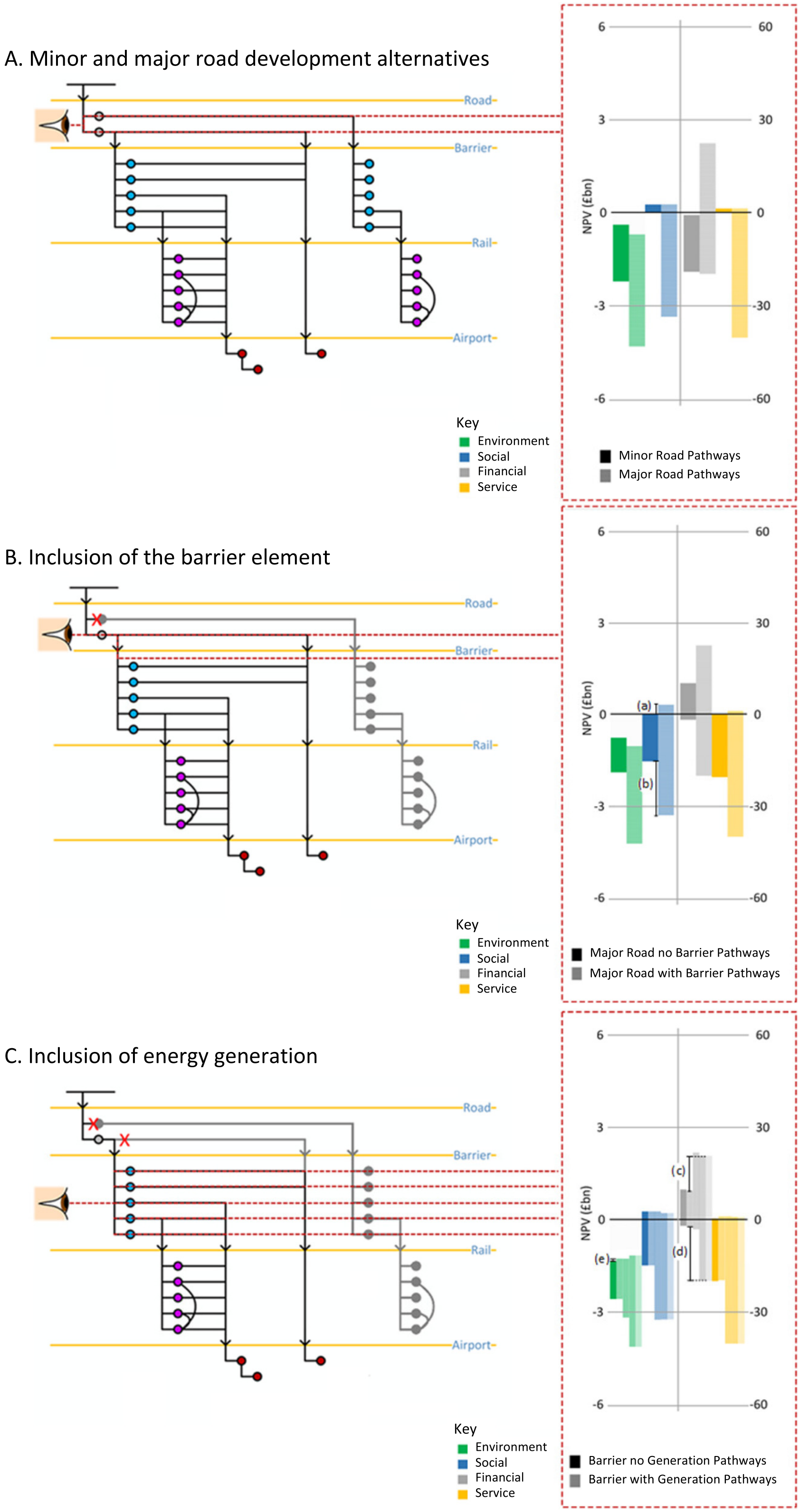
System effects: connectivity

The decision tree also demonstrates the connectivity effects of the rail investments. In Table 6 the pathway results for the five rail infrastructure alternatives are presented, assuming major road development and a fully integrated barrier are implemented. The commuter rail development provides six additional stations on the rail orbital each with significant long term park and ride facilities as part of an active transport management plan to reduce road use (Foster+Partners, Halcrow, Volterra 2011a). While the high speed lines provide access to the airport from the new HS2 stations (Manchester, Birmingham, Sheffield and Leeds), the commuter service provides additional access to those within the London area or using personal cars and taxis to travel on the M25 motorway (see Figure 3), as well as freeing up capacity on the London Underground.

Introducing the additional stations shifts the environmental and social pathway results, reducing both their minimum disbenefits by £1.4bn and £2.6bn respectively. In the case of the environmental attributes, it also changes the upper bound on the valuation, making this less negative by £0.04bn. By reducing both the maximum disbenefit and the variability of these factors, the outputs are made

Table 6 Pathway impacts for the five rail infrastructure alternatives[j]

	Environmental impact (£bn)			Social impact (£bn)		
	Pathway minimum	Pathway maximum	Range	Pathway minimum	Pathway maximum	Range
High Speed Rail	−4.31	−2.23	2.08	−3.20	0.29	3.49
High Speed Rail with Option to Expand	−4.31	−2.23	2.08	−3.20	0.29	3.49
Commuter Rail	−2.93	−2.19	0.74	−0.61	0.29	0.90
Commuter Rail with Option to Expand	−3.06	−2.19	0.87	−0.61	0.29	0.90
Full Rail	−3.06	−2.30	0.76	−0.61	0.29	0.90
	Financial impact (£bn)			**Service impact (£bn)**		
	Pathway minimum	**Pathway maximum**	**Range**	**Pathway minimum**	**Pathway maximum**	**Range**
High Speed Rail	−14.48	13.18	27.66	−40.13	0.90	41.03
High Speed Rail with Option to Expand	−20.39	11.38	31.77	−40.13	0.90	41.03
Commuter Rail	−16.26	13.63	29.89	−2.43	0.90	3.33
Commuter Rail with Option to Expand	−20.39	13.33	33.72	−2.43	0.90	3.33
Full Rail	−18.26	11.94	30.20	−2.43	0.90	3.33



A. Minor and major road development alternatives

B. Inclusion of the barrier element

C. Inclusion of energy generation

Figure 5 Pathway decision analysis of Thames Hub Vision elements.

more certain and less negative. Furthermore, we also see a reduction in the minimum service benefit by £37.7bn. While the financial effect of the commuter rail results in a £2.2bn larger range than those of the high speed rail, this only represents 8 per cent of the pathway value range and is therefore unlikely to have a strong influence on investment decisions. Given the large improvements to the environmental, social and service minimum pathway values and the relatively low additional cost to implement the commuter rail (assumed to be approximately £2.5bn in line with other developments[k]), the analysis promotes the continued maintenance of a commuter rail line, even if alternative rail developments are approved.

Conclusions

In this paper we have argued that the current appraisal of infrastructure investments as standalone assets is insufficient to capture their complex interactions with each other and the economy. Through the development of a common cross-sector appraisal methodology and the application of options analysis against a dynamic investment environment, we track the evolution of appraisal from projects to portfolios to pathways, analysing the information gain at each stage.

Our findings suggest that substantial system effects are hidden by current project appraisal methods and that these are sufficient to affect the risk and viability of investments. For the case study considered, these system effects are sufficient to change the outcome of the airport appraisal from a net negative to a net positive depending on whether supportive rail infrastructure is provided. Furthermore, by ignoring the temporal nature of investments, we may reduce benefits or constrain future developments.

Our methodology presents a number of benefits, focusing attention on the opportunity value of an investment and highlighting the total effects of the system as a whole rather than individual assets and the trade-offs that must be made. By disaggregating costs and impacts associated with the planned investments we provide more information for stakeholders to evaluate trade-offs, allowing stakeholders to have different preferences and to change these preferences over time. Furthermore, it ensures that impacts with a relatively small monetary value (by standard valuation methodologies) remain visible. Use of such a methodology could help ensure developments are strategically aligned and flexible to future uncertainty, allow prioritisation of projects where resources are constrained and increase understanding of cross-sectoral interactions thereby encouraging greater stakeholder engagement and collaboration.

While the methodology represents a development in strategic infrastructure decision-making under uncertainty further work is necessary to explore the effects of uncertainty on the robustness of the development pathways. A particular limitation is due to the feedbacks between the developments and their socio-economic environment, such as the interaction between infrastructure investment, population growth and service demand, and the macroeconomic effects of such changes. While these aspects are not presented here, they will be the focus of future investigation. Drawing on methods such as Adaptation Pathways and Dynamic Adaptive Policy Pathways, an ensemble of possible futures could also be used to consider the vulnerability of the pathways and explore how potential limits or sector-specific objectives could create tipping points for dynamic decision-making. Furthermore, given the region considered, a larger array of alternatives could be considered, analysing the performance of projects which are non-optimal in the short term, but offer greater flexibility in the long term, or opportunities for smaller complementary assets rather than larger developments that are likely to be mutually exclusive. Finally, it should be noted that as a decision support tool, the results must be reassessed as time progresses, adding additional projects, reassessing the data and assumptions which are known to be highly uncertain at the appraisal stage, and considering how the outputs interact with new legislatively limited or finite resources.

Endnotes

[a] Even within sectors, system effects are often ignored, with benefits restricted to the given project. For example, despite the UK having a single 'Department for Transport', transport development projects are the responsibility of different agencies depending on the mode being expanded; the demands placed on the other modes and the system benefits which could arise if planned together, are therefore commonly ignored by the appraisal process.

[b] For example: In the assumption of service provision, the recent review of air capacity expansion alternatives for London, the Airports Commission stated: "It appears reasonable to assume that background increases in traffic over the period to 2030 will already push the heavily congested local motorway network beyond capacity and therefore action will need to be taken with or without expansion at the airport. For this reason, more significant motorway enhancement costs are not included in the Commission's cost estimate." (Airports Commission 2013); and in the case of a static development environment, despite over a decade of debate on the need for expansion of Heathrow, London's current hub airport and demand projections suggesting that the airport will reach capacity in the next decade (Tran et al. 2014), the new 'Crossrail' rail development through central London has not been designed with the capacity to support an expanded Heathrow, or the flexibility to expand to provide this (Transport for London 2014).

[c] 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).

[d] Both social metrics capture injuries, fatalities and associated externalities of the infrastructure assets, with safety including events related to everyday accidents and security relating to extreme events.

[e] Here physical protection represents the reduction of the non-human cost of extreme events, for example property damage, delivered as a direct service of the infrastructure asset.

[f] Discount rates of 3.5% for years 0–30, 3.0% for years 31–75 and 2.5% from year 76–100.

[g] While the figure shows sequential implementation and few end points it should be noted that the methodology allows development pathways to stop after each branch division and for procurement of assets in groups.

[h] The Thames Hub vision as applied in this paper is the original proposal launched by Foster+Partners, Halcrow and Volterra 2011a (Foster+Partners, Halcrow, Volterra 2011a). The proposal was made as a response to London's growing infrastructure needs, particularly due to predicted population growth in east London, which has relatively few transport connections, increasing air transport demand, aging infrastructure and growing freight congestion between the London ports and distribution centres in central and northern England. In September 2012, the Airports Commission was created to consider how the UK could sustain its status as a hub for aviation. Given the remit of the Commission, the non-airport elements of the proposal would only be considered as costs and therefore a simplified proposal centred around the airport alone was submitted by Foster + Partners with CH2M HILL as an independent advisor in 2013 (Foster +Partners 2013). While the original Thames Hub Vision proposal remains, the non-airport elements have not been progressed since 2012.

[i] Pathway 'minimum' reflects the most negative/least positive result and pathway 'maximum' the least negative/most positive result.

[j] Assumes major road development and a fully integrated barrier are implemented (asset groups implemented as soon as possible while sustaining group and order restrictions).

[k] For example High Speed 2 (HS2 Limited 2012).

Additional file

Additional file 1: KYoung Introducing System Interdependency into Regional Infrastructure Appraisal - Additional Info.pdf.

Abbreviations

CBA: Cost benefit analysis; HS2: High Speed 2 rail development; NPV: Net present value; WTP: Willingness to pay.

Competing interests

The primary author's research is sponsored by CH2M HILL, who, through acquisition of Halcrow in 2011, were partners in the Thames Hub Vision proposal.

Authors' contributions

The study was conceived by both KY and JH. The analysis was undertaken by KY under the supervision of JH. The manuscript was written by KY and edited by JH. Both authors read and approved the final manuscript.

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