Department for Transport

Programmatic Appraisal

Stage 5 Report

F3

Final 3 | 6 August 2019

Job number 258561

Ove Arup & Partners Ltd
13 Fitzroy Street
London
W1T 4BQ
United Kingdom
www.arup.com

ITS

ARUP

Document Verification

ARUP

Job title		Programmatic Appraisal			**Job number** 258561
Document title		Stage 5 Report			**File reference**
Document ref		F3			
Revision	**Date**	**Filename**	Programmatic Appraisal - Stage 5 Report - May 2018 - ISSUE.docx		
Final	8 May 2018	**Description**	Stage 5 Deliverable		
			Prepared by	Checked by	Approved by
		Name	James Laird Richard Connors Hannah Norman Margot Finley Peter Mackie	Peter Mackie Margot Finley	Chris Bruce
		Signature			
Final 2	6 June 2018	**Filename**	Programmatic Appraisal - Stage 5 Report - June 2018 - ISSUE.docx		
		Description	Stage 5 Deliverable		
			Prepared by	Checked by	Approved by
		Name	James Laird Richard Connors Hannah Norman Margot Finley Peter Mackie	Peter Mackie Margot Finley	Chris Bruce
		Signature			
Final 3	8 August 2019	**Filename**	Programmatic Appraisal - August 2019 - FINAL.docx		
		Description	Final Report		
			Prepared by	Checked by	Approved by
		Name	James Laird Richard Connors Hannah Norman Margot Finley Peter Mackie	Peter Mackie Margot Finley	Chris Bruce
		Signature			
		Filename			
		Description			
			Prepared by	Checked by	Approved by
		Name			
		Signature			

Issue Document Verification with Document ✓

Contents

Appendices

1 Executive Summary

The Study Context

This report is about the appraisal treatment of a specific transport scheme which is part of a programme and which interacts with other schemes in the programme. These other schemes may be complementary with the scheme under consideration, for example, a series of schemes in a corridor. Or they may be competing, for example, if improvements in parallel corridors are also under consideration.

The key feature of this problem is interdependence. The value for money of schemes A plus B plus C together may be greater (if the schemes are complementary) or less (if competitive) than the value for money of A plus B plus C each taken in isolation. The whole may be greater (or less) than the sum of the parts. There may be many cases where the difference is not material to the value for money category of the schemes. But our focus is on the case where interdependence exists and is material to the value for money assessment.

Pure independence, pure complementarity and pure competitiveness are polar cases. The general reality is a mixed picture in which schemes interact with each other in various ways, for example being complementary for some traffic flows and competitive for others, as our case study shows. Our appreciation is that the concept of interdependence applies to a range of practical circumstances which might include:

- a series of loosely related schemes in a corridor or region which are expected to be appraised and delivered on a standalone basis but where some synergies exist;
- a strategic initiative in a corridor or region containing some core elements (without which the strategy will not work) and other peripheral elements which may add value to the strategy as a whole; and
- regional strategies in which cross-modal effects and policies such as demand management may feature as well as infrastructure.

A further consideration at the time of making a decision about a specific transport scheme is uncertainty about which of the other schemes which share these interdependencies will be included in the final approved programme. Decision makers may need to be able to make a start on a programme while retaining some flexibility about its future composition. The value for money of the scheme under consideration is therefore contingent on other future uncertain decisions and decision makers need to be aware of this uncertainty where interdependency between schemes is material to the decision.

The terms scheme, project, programme, package, investment, intervention are all used in discussions on programmatic appraisal, and are used with a high degree of interchangeability. Given the strong policy backdrop to this study, in this report we use these terms in their policy/institutional context. We take each Transport Business Case that is developed to represent a scheme – even if it is made up of several component parts. A programme is an administrative collection of schemes that address the same or similar needs – so there is a common rationale but the schemes are delivered independently. In contrast a package of transport schemes would be considered for investment in its entirety in a single funding decision.

Programmatic Appraisal within this context therefore is the appraisal of a scheme that lies within a programme of interdependent schemes. Current practice within DfT is for decision makers to make decisions on a 'scheme' basis and not on a programme basis. ***However, a key recommendation of this report is that decision makers should have sight of a programmatic appraisal if the scheme they are making a decision about is materially related to other schemes.***

The methods proposed in the report build firmly on established Departmental guidance, although it may be guidance which is unfamiliar to some analysts as some of it has been withdrawn or is unpublished. An important first step in the report was to re-establish what Departmental thinking has been on this issue in the past and then to build on that. The report therefore commences with a review of both official and academic literature. Interviews were undertaken with a number of international experts to determine whether our appreciation of the state of the art was incomplete or deficient. Our conclusion from the review is that the problem of interdependence is viewed widely as a real one with no simple solution which readily fits the administrative context in which it will be used. Our research confirms this view, though circumstances of low congestion do make the problem much more tractable.

We therefore proceed by defining relevant concepts, developing a proposed methodology which is intended to be a flexible framework rather than a prescriptive requirement, and then testing the methodology in a case study.

Benefits and Costs in Programmatic Appraisal

In this part of the study, the key techniques and concepts relevant to programmatic were collated and summarised.

Key techniques include:

1. incremental analysis;
2. decremental analysis;
3. pair-wise analysis; and
4. higher-order analysis.

In **incremental analysis**, a programmatic appraisal is conducted by taking it that no other schemes will be constructed after the scheme that is being appraised. So, if there are 3 schemes (A, C and D) within a programme, and we are considering the value for money categorisation of scheme A, and the phasing of the programme is Scheme C, A and then D, there would be two scenarios and model runs: DM+C, DM+C+A (where DM is the 'do-minimum'). In this type of analysis, a sequencing or ordering of the schemes is required. A comparison of the two scenarios shows the 'incremental benefits' associated with the addition Scheme A. Note here we use a definition of incremental analysis consistent with previous DfT published and unpublished guidance.

In **decremental analysis**, the scheme being appraised is 'taken away' from the whole programme. So, with the same 3 schemes there would be two scenarios and model runs: DM+A+C+D and DM+C+D. The 'decremental benefit' is the difference between the scenarios.

In **pairwise analysis**, the schemes are appraised in pairs. So, with the same 3 schemes there would be 2 pairs of schemes with interactions with Scheme A – our scheme of interest. This gives two scenarios and model runs: DM+A+C, DM+A+D. Pairwise analysis can be used to get a sense of how each of the schemes are dependent on each of the others.

In a **higher-order analysis**, the schemes are appraised in either triples or larger combinations. For example DM+A+C+D.

Key concepts identified during the literature review include:

- stand-alone benefits;
- independent, complementary and competing schemes; and
- assessment of interdependency benefits.

Stand-alone benefits refers to the benefits of a scheme if it was built/implemented without the others. This is what is done in a typical appraisal, where one scheme is tested in a scenario and compared with a do-minimum.

A set of schemes are **independent** if each of their BCRs is not affected by the inclusion of the other schemes. A set of schemes are **complementary** if the BCR of the programme of schemes is greater than the sum of the individual BCRs. A set of schemes are **competing** if the BCR of the programme is less than the sum of the individual BCRs. It is also possible to have a mix of independent, complementary and/or competing schemes within the one programme.

Assessment of interdependency benefits

Schemes that are complementary *and/or* compete in traffic terms, are said to be **interdependent**. An assessment of interdependency benefits is a key topic in programmatic appraisal.

Interdependency benefits or disbenefits refers to the benefits associated with inter-dependent schemes. I.e. if schemes 'complement' or 'compete' with each other then they will have interdependency benefits or disbenefits. Independent schemes have zero interdependency benefits. These interdependency benefits arise due to, for example, the manner that re-routeing and induced travel behaviour stimulated by other schemes in the programme create additional demand for the scheme being appraised. On the cost side cost synergies or dependencies may also exist.

Analysing interdependency benefits

The literature review, a consideration of theoretical first principles and discussions with experts and peer reviewers indicate that there is no simple formula that can be recommended for attributing the 'interdependency benefits' to specific schemes within a programme.

We find that schemes that complement each other in traffic terms (e.g. lie in the same route corridor) can have both positive and negative interdependency benefits. This is also the case for schemes that compete in traffic terms. WE found that in addition to whether schemes complement or compete in traffic terms, congestion was also an important determinant as to the sign of the interdependency benefit. This is summarised in the table below.

Table 1: Interdependency benefits and congestion

Scheme types (in terms of travel demand)	Sign of interdependency benefits if network is:	
	Uncongested	Congested
Complementary	**Positive**	Positive if congestion is ameliorated Negative if congestion is worsened
Competing	**Negative**	Positive if congestion remains in the Do Something and both routes using either scheme are viable. Negative if sufficient capacity on one route is created such that that route dominates route choice

Theoretical models also show us that pairwise interdependency benefits form the majority of the interdependency benefits with no or low congestion. This is a simple rule that can be applied in an assessment of interdependency benefits. At higher levels of congestion this rule no longer applies and a more detailed assessment of the higher order interdependency benefits is needed (triples, etc.). At these higher levels of congestion a pairwise analysis would act as a starting point for a more detailed assessment.

The importance of congestion in determining the sign of the interdependency benefits means that if the level of congestion changes during the appraisal period then the sign of the interdependency benefit may switch from positive to negative or vice versa.

Treatment of uncertainty and risk

The economic literature provides techniques that allow risk to be brought into the calculation of the expected net present value of a transport project. This requires a set of probabilities for the different scenarios that may come to pass. If the decision is made in a staged way, then the expected value has to be calculated using a set of conditional probabilities – this is also known as applying a quasi- or real- option value.

Both techniques require that the probability of different scenarios occurring is known. UK practice, and as far as we are aware practice overseas, does not ascribe probabilities to different future scenarios – either in terms of traffic growth or in terms of which schemes may be in a future network.

The alternative to a probabilistic (or quantitative) treatment of risk is a qualitative treatment through an uncertainty log or risk register. In the UK WebTAG Unit M4 uses such an approach. It explicitly addresses the uncertainty of travel demand, uncertainty of other transport schemes and uncertainty in land uses. Within WebTAG, programmatic appraisal therefore naturally aligns itself with this TAG Unit.

Methodology Development

A methodology for undertaking programmatic appraisal was developed at this stage in the study. This method applies to a single scheme being appraised, to assess the extent to which that scheme is impacted by other related schemes.

The intention is that this analysis would be presented alongside an individual scheme appraisal. For example, if a practitioner was doing an appraisal on scheme A, and there existed related schemes C and D, then the method outlined here would be undertaken from the point of view of 'A' being the 'primary scheme' and the other schemes being the related schemes. So, this is a method that can be used within DfT's existing approach of assessing each scheme individually, but decision makers can consider the extent to which a scheme is inter-dependent with others. In cases where very high levels of interdependence are found at early stages of analysis, a judgement might need to be made about whether A, C and D should continue to be viewed as standalone schemes.

The proposed methodology includes 6 steps as follows:

- Step 1 – Assessment of interdependencies;
- Step 2 – Modelling the benefits;
- Step 3 – Apportionment of net benefit;
- Step 4 – Scheme costs and net benefit metrics;
- Step 5 – Assessment of likelihood of net interdependency benefits; and
- Step 6 – Reporting and value for money conclusion criteria.

The method is based in economic theory, interlinks with DfT appraisal practice as embodied in WebTAG (particularly TAG Unit M4 and the Value for Money guidance), aims to be proportionate and recognise the limitations of practical appraisal. It also embodies the concept of proportional appraisal, based on the position that the crucial level for operational decision-making is the scheme level. The method promotes transparency, objectivity and a holistic approach in the analysis.

Step 1 – Assessment of inter-dependencies

Step 1 is a qualitative assessment as to whether or not there are competing or complementary schemes to the scheme being appraised which can be done with a 'matrix of dependencies'.

Step 2 – Modelling the benefits

In this step, a number of analyses are done, including:

- standalone;
- pairwise;
- higher order analysis;
- incremental; and
- decremental.

This gives practitioners a comprehensive set of information that can produce various metrics to inform decisions. The number of model runs will be 2n+4, where n is the number of schemes within the programme that have dependencies with the scheme being appraised. This is a pragmatic approach that reduces the set of model runs, but it does require that the pairwise benefits capture the majority of the interdependency benefits, which is likely to be the case in lightly congested conditions only. Where congestion effects are significant and schemes worsen congestion bottlenecks up or downstream it is likely that **higher order analysis** will need to be undertaken. Certainly, this is the experience that we found in our case study.

Step 3 – Apportionment of net benefit

This step uses the modelling in Step 2. The output from this step is a set of metrics showing: (a) the benefit of implementing the scheme; (b) the incremental benefit of the scheme within the programme; (c) how the scheme contributes to the whole programme (from the decremental analysis); and (d) how the interdependency benefits can be broken down between the different schemes.

Step 4 – Scheme costs and net benefit metrics

This step combines estimates of costs with the benefits to produce BCRs.

Step 5 – Assessment of likelihood of net interdependency benefits

This will be a qualitative assessment and would utilise guidance in TAG Unit M4 classifying schemes as near certain, more than likely, reasonably foreseeable and hypothetical. The output from this step is an opinion on the likelihood of the interdependency benefits occurring.

Step 6 – Reporting and value for money conclusion criteria

The final step collates and summarises the findings of Steps 1 to 5. However there is a need to be broader in the description than simply setting out the numbers. Here it is important to understand the context of the scheme and its inter-relationship with the programme as a whole. This was analysed in Step 1 of the method. The way in which the analyst will wish to structure the presentation is context dependent. For example, if the situation is that there is a scheme that is central to the programme, it is important to understand whether the scheme we are appraising (say Scheme A) is that central scheme or is one of the more peripheral elements of the programme. If it is the central element of the programme we start with the standalone value of the scheme against the Reference Case. If the business case for this scheme is weak, we know we are dependent on the value of the strategy as a whole, and in this sense the scheme is then dependent on the results of the programmatic appraisal.

Case Study

This method was tested with a case study. This application demonstrated that transport networks and modelling results can be complex. The combination of congestion costs and variable demand, along with the re-routeing of traffic, led to complex findings, such as where competing schemes (e.g. Scheme C and Scheme E) complemented in a pairwise test, but compete at a full programme level. Similarly, we found that schemes can complement early in the appraisal period and then compete later in the period. These affects are attributed to the levels of congestion present in the various Do Minimums and Do Somethings. Our higher order analysis confirmed that the results we observed at a pairwise level were due to the presence of up or downstream congestion and/or re-routeing effects. In these situations the higher order triples are more relevant from an interdependency perspective – though this is likely to be case study specific.

What we draw from this is as follows.

- It is essential that a holistic approach is taken to consider which schemes are tested in the programmatic appraisal. In our case study, excluding Schemes D & E, which lie in a competing route corridor, from the analysis would clearly overestimate the benefit of the scheme – as can be seen by comparing the incremental and decremental analysis.
- It is necessary to use more than one model year in the analysis, unless congestion is considered not to be an issue. This is because the complementary/competing effects can change through the appraisal period. Undertaking the analysis on one model year may not give conclusive results.
- The combination of competing and complementary schemes, along with high travel time delays (congestion), are likely to result in higher order model runs being required;
- The incremental and decremental benefits remain important indicators of a scheme's economic worth within a programme of investment. The pairwise and higher order analysis then helps us understand the drivers of these benefits.

Conclusions & Recommendations

1. We have found evidence in our case study and in the broader literature that **interdependency benefits can be material**. Programmatic appraisal may therefore be needed in some cases.
2. Programmatic appraisal is complex particularly where congestion is large. Careful consideration of when it is proportionate to undertake a full programmatic appraisal is therefore required.
3. **Incremental and decremental benefits** remain a key part of any programmatic appraisal and their use along with pairwise and higher order

interdependency benefits should be encouraged within the context of the risk and uncertainty analysis undertaken as part of a WebTAG appraisal.

4. We believe new official guidance is going to be required. However, given the relatively small amount of road testing that has been undertaken, we are cautious about recommending immediate incorporation into WebTAG. We recommend some next steps:

    a) that the method is **tested further with practitioners**, with particular consideration of modelling impacts; and

    b) that further case studies are brought forward to test the method on.

5. We recommend that DfT give further consideration to the implications of this report for appraisal of programmes **other than strategic roads** where a range of issues such as cost side interdependency and demand side feedback to public transport provision may be relevant.
6. In terms of further analytical research we recommend that consideration is given to identifying congestion thresholds where interdependency benefits switch sign from positive to negative or vice versa. We also recommend that efforts are made to address how the uncertainty of other schemes is described: as the two categories in TAG Unit M4 are rather limiting. Possibly both of these research avenues can be progressed through the road testing recommended above.

2 Introduction

2.1 Background

Appraisal is an important tool in the government's planning armoury. The framework approach and within that cost-benefit analysis is the Government's preferred methodology for constructing the Transport Business Case[1]. These tools help ensure public funds are spent on activities that provide the greatest benefits to society[2]. Within the Transport Business Case is a Value for Money criterion of the intervention. This criterion indicates whether an intervention is viewed as representing poor, low, medium, high or very high value for money. The starting point for determining the value for money criterion is the benefit cost ratio, where the cost is the cost to the broad transport budget (DfT, 2017)[3]. The criterion is then adjusted to reflect uncertainties and non-monetised impacts. As such the final value for money of an intervention represents a judgemental decision. By primarily funding projects with high or very high value for money the Department therefore ensures that its transport budget maximises society's benefits.[4]

However, an issue arises when road projects are inter-connected. Including inter-dependencies between the scheme being appraised and other schemes into the appraisal may be sufficient to shift the scheme between different value for money categories, or even to change the NPV from negative to positive. In such a situation the different schemes reinforce each other, and the benefits of the programme is larger than the sum of the parts. Contrastingly, there may be situations where schemes compete with each other – e.g. where they are both viable route choices between the same origin-destination pair. Here the total benefits of doing both schemes might be less than the sum of doing the individual schemes. In these situations, a simple value for money criterion based on each project being independent from every other project may fail to maximise society's benefit.

For large road investment programmes such as RIS1 and RIS2 this potentially may be a cause of concern. We can for example see that four of the six strategic challenges[5] facing the road network, and being examined in the RIS2 preparation phase, may either complement or compete with one another for road traffic:

---

[1] DfT (2013) The Transport Business Case. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/85930/dft-transport-business-case.pdf [accessed 15th December 2017]

[2] HM Treasury (2011) The Green Book. https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent [accessed 15th December 2017]

[3] WebTAG Value for Money Framework, DfT, 2017

4 In this report, we largely neglect consideration of environmental and wider economy impacts although the arguments in the report apply conceptually to the Framework as a whole, not just the monetised elements.

5 https://www.gov.uk/government/collections/road-investment-strategy-post-2020 [accessed 15th December 2017]

- the A66 and A69 compete with each other and to an extent with the Trans-Pennine tunnel for east-west traffic;
- Manchester north west quadrant investments (along the M60) might be expected to be complementary to the Trans-Pennine tunnel, but may be competing with the A66; and
- the A1 upgrades may be complementary to all three of the above-mentioned investments.

Whilst the schemes[6] that make up a programme are inherently inter-connected, the Department's decision as to whether to fund a scheme is taken independently of other schemes in that programme. This is for institutional reasons. This practical aspect of decision-making then raises questions as how to best incorporate scheme to scheme inter-dependencies into the appraisal, whilst also ensuring that the interdependency benefits are not counted two or more times. These considerations apply not only to the yes/no question of scheme approval but also to questions of optimal design, layout and capacity which may be contingent on whether or not competing or complementary schemes are implemented.

Our primary interest in this study therefore is how to address the problem of informing decision makers about the likely value for money category of a specific transport scheme which is part of a programme and which interacts with other schemes in that programme.

2.2 Scheme, package, programme

The terms scheme, project, programme, package, investment, intervention are all used in discussions on programmatic appraisal, and are used with a high degree of interchangeability. Ultimately any single investment is made up of component parts. A bypass round a small town consists of new carriageway and a set of new junctions, with the whole bypass conceived as single scheme, project or investment. In another context a series of carriageway and junction improvements may divert traffic away from a small town, but each of the components are viewed individual schemes or projects. Collectively however they could be viewed as a programme or package of improvements. Similarly, a route improvement, that could for example consist of a series of bypasses around small towns might be viewed as a programme. If a set of traffic management, public transport priority or active travel schemes were associated with the bypassing of one of these small towns, that could either be viewed as part of a programme or as a package of measures aimed at addressing noted transport problems along a route or in the town.

Given the strong policy backdrop to this study, in this report we use these terms in their policy/institutional context. We take each Transport Business Case that is developed to represent *a scheme* – even if it is made up of several component parts.

[6] Here we use the term scheme to refer to the smallest investment component. A programme, project, corridor or strategic study is a collection of schemes.

A programme is an administrative collection of schemes that address the same or similar needs. In the context of RIS1 and RIS2, the programmes are typically route centred. Each scheme within the programme is considered on a case by case basis as to whether it merits investment. Within this terminology inter-dependencies between schemes can exist within programmes and between programmes.

In contrast *a package* of transport schemes would be considered for investment in its entirety. Recently transport investment packages have been associated the 2004 to 2010 Transport Innovation Fund (TIF) and more recently releasing Growth and City Deal funding.

2.3 The Transport Appraisal Process

Transport appraisal practice in the UK is set out in WebTAG. The starting point is an assessment of need, followed by an option generation and sifting process. A detailed appraisal of options then follows. A final stage in the appraisal process is evaluation. These three stages in the transport appraisal process are described in WebTAG as follows:

- Stage 1 – Option Development. This involves identifying the need for intervention and developing options to address a clear set of locally developed objectives which express desired outcomes. These are then sifted for the better performing options to be taken on to further detailed appraisal in Stage 2. See Section 2.
- Stage 2 – Further Appraisal of a small number of better performing options in order to obtain sufficient information to enable decision-makers to make a rational and auditable decision about whether or not to proceed with intervention. The focus of analysis is on estimating the likely performance and impact of intervention(s) in sufficient detail. See Section 3.
- Stage 3 – Implementation, Monitoring and Evaluation. See Section 4.

DfT (2014 p3)[7]

In this study we are concerned with Stage 2 of the appraisal process. That is, the need for an intervention has been identified, potential options have already been generated and these options have already been sifted. The starting point for Stage 2 of the appraisal process is a set of potential schemes that will address the identified need to greater or lesser degree.

A significant amount of analytical effort is devoted to the Stage 2 aspect of transport appraisal. It includes modelling and forecasting, identification of impacts, in both qualitative and quantitative terms, and monetisation of those impacts where possible. It also includes stakeholder engagement. The large amount of analytical effort demanded is reflected in the number of TAG units directed towards this task. There is guidance directed towards the appraisal

[7] DfT (2014) The Transport Appraisal Process. Transport Analysis Guidance. https://www.gov.uk/guidance/transport-analysis-guidance-webtag

practitioner (TAG Units A-1 to A5-5), and guidance directed towards the modelling practitioner (TAG Units M1-1 to M5-2).

The outcome from a Stage 2 appraisal is the Transport Business Cases for a particular scheme, contained within which, as already discussed, is the expected value for money category in which the scheme is expected to fall. Inter-dependencies with other schemes may be expected to influence the value for money category of the scheme, and how best to reflect that in a Stage 2 appraisal is the subject of this report. The TAG Units of particular relevance to this study are:

- *TAG unit A1-1 cost-benefit analysis, December 2017*: setting out the principles of cost benefit analysis and setting out the issues associated with the appraisal period and discounting.
- *TAG unit A1-3 user and provider impacts, March 2017*: describing the calculation of user benefits and the impacts on transport providers. This TAG unit provides formulas for these calculations.
- *TAG unit M4 forecasting and uncertainty, July 2017*. This provides advice on using transport models to prepare future forecasts of demand and supply. It also sets out the procedures for understanding uncertainty in the appraisal, as well as discussing how the without and with scheme cases should be defined.

In addition to these TAG Units the policy documents on the Transport Business Cases and the Value for Money are also relevant as they provide the policy frameworks in which the outputs from this study would be utilised within. These documents are:

- *The Transport Business Cases. January 2013:* describing the Strategic, Economic, Commercial, Management and Financial Cases for transport investment.
- *Value for Money Framework. July 2017:* setting out the different inputs to the determination of a Value for Money category for a transport investment
- *Value for Money: Supplementary Guidance on Categories. July 2017:* giving detailed guidance on the relationship between the Benefit Cost Ratio (BCR) and the Value for Money category.

The overarching principles for ex ante appraisal for public sector funded projects is *The Green Book* published by The Treasury. The TAG Units and other policy guidance are drafted to be consistent with it.

2.4 RIS1 and RIS2

The road transport investment policy backdrop to the research are the large-scale investments represented by the Road Investment Strategies 1 and 2 (RIS1 and RIS2). RIS1 represents the investment period from 2015 to 2020, and RIS2 from 2021 to 2026. These strategies are clearly in different stages of development. For RIS1 over one hundred schemes have been identified. These schemes are being developed in both their detailed engineering design and their appraisal. Some of the schemes have been approved for construction, but significant numbers still require a final decision on investment by the Department. RIS2 in contrast is in a much more formative state. No doubt RIS3 and 4, content currently undefined, will follow, well within the lifetime of the schemes in RIS1 and 2.

The Highways England route strategies[8] form the basis of the identification of potential schemes. These schemes have been grouped together into for example corridors and strategic studies. Decisions have yet to be made regarding which of the potential schemes are to be taken forward for detailed consideration as part of RIS2. As with RIS1 the schemes that are taken forward to the next stage will still be subject to more detailed appraisal and will only be constructed should they continue to show sufficient value for money. An illustration of this process for the A303 is given in **Figure 1**.

Figure 1: A303 route corridor

The A303 Corridor

- Forms part of Highways England's South West Peninsula route strategy
- Consists of 8 schemes
- 3 of the 8 schemes appear in RIS1
- 1 of these 3 have reached Preferred Route Announcement Stage (the Stonehenge scheme) and the other 2 are at Options development stage.
- The other 5 schemes are being considered for inclusion in RIS2.

Value for money conclusion criteria are used in each stage of the decision-making process: for entry into the RIS1 or RIS2 programmes, and for the final decision as to whether to proceed or not.

Value for money conclusion criteria are developed as part of the decision process to include a scheme in the current RIS programme, and as part of the decision as to whether to proceed to construction. This research therefore supports the development of both RIS1 and RIS2. Value for money conclusion criteria form only one input (as part of the Economic Case) to the Transport Business Case.

2.5 Study objectives and research questions

Given this policy background this research study is therefore concerned with the how the appraisal of a scheme that lies within a transport investment programme should be dealt with. That is we are interested in the problem of informing decision makers about the likely value for money category of a specific transport scheme, which interacts with other schemes in that programme or in other programmes.

Its objectives are to:

[8] https://www.gov.uk/government/publications/route-strategies-april-2015-march-2020 [accessed 15th December 2017]

[1] Set out a theoretical framework and suggest a method of appraising schemes which form part of a package or part of a programme.

[2] Develop a value for money conclusion criteria from a rigorous economic appraisal framework which can be practically applied to assess the impact of road investments within a package of schemes.

[3] Suggest how the methodology and the proposed Value for Money (VfM) conclusion criteria can be incorporated into the Department for Transport's appraisal guidance (WebTAG).

Sitting under these three research objectives lie some more specific research questions:

- What transport-economics theoretical framework will need to be adopted for programmatic appraisal?
- What should be the criteria for grouping schemes into programmes?
- How to treat uncertainty of uncommitted schemes?
- How to correctly attribute benefits between schemes in an incremental analysis?
- What VfM criteria should be used in programmatic appraisal?

2.6 Report scope

This report represents the second deliverable of the study. Its focus is on the literature review and the development of the methodology to be applied to the appraisal of schemes that lie within investment programmes.

2.7 Report Structure

Following this introductory section, Section 2 presents our review of the literature. In section 3 we develop some of the methods identified in the literature for application to programmatic appraisal. Section 4 then presents our method for programmatic appraisal. Section 5 presents an application of the method on a case study.

3 Literature Review

3.1 Introduction

A rapid review of key literature was undertaken as a first step in this study. A long list of literature we will use a set of keywords to search the literature databases of TRID[9] and Scopus. Google Scholar was also used. This in combination with a set of key starting references helped us identify further relevant papers using a type of 'paper trail'. That is further papers are identified by utilising information on which papers cite papers already identified, and which papers are cited within a paper already identified. We identified three inter-related strands of literature – each which are related to the research questions posed. These are papers on decision criteria in programme appraisal (including existing guidance), papers on the treatment of uncertainty particularly quasi-option values, and papers on the packaging and analysis of projects within a programme (the network design problem).

This chapter is structured as follows. In the next section, Section 2.2 we consider how the scope of this research maps onto other UK guidance within the field – including draft guidance and withdrawn guidance. Section 2.3 sets out the decision criteria in the value for money (VfM) guidance and identifies the issues associated with the treatment of inter-dependencies within these metrics. Section 2.4 discusses how the benefit that can be attributed to a scheme is not a unique measure – when it forms part of a programme. The benefit of the scheme is contingent on other components of the programme. Different measures of how one can estimate this benefit are then set out. Section 2.5 identifies the scale of the modelling challenge when a large number of components to the programme exist. Several heuristics are identified. The final section of this chapter, Section 2.6, sets out the correct treatment of benefit measures under uncertainty when new information becomes available. These models however can be hard to parametrise and a more process driven approach might be used in their place. Monte Carlo analysis has a place in understanding uncertainty.

3.2 Appraisal Guidance and Practice

It is useful to compare the scope and focus of other UK guidance reviewed against the scope/outputs of this research. In addition to the policy and appraisal guidance identified in Section 2.3 there are three guidance papers that are either in draft form or have been withdrawn that have relevance to this study. These are:

- The COBA Manual[10],
- draft DfT guidance on package appraisal[11]; and

[9] Transport Research International Documentation

[10] DfT (2002)The COBA Manual. Withdrawn from guidance.

[11] DfT (2009 unpublished) Draft TAG Unit 3.X.X Package Appraisal

- Highway England's (HE)s draft guidance on programmatic appraisal[12]

Our primary interest in this research is in appraising the impact of inter-dependencies with other schemes in a programme, as opposed to the appraisal of a programme of schemes per se. This either differs substantially or subtly from the starting points of other UK guidance.

The Green Book[13] has little to say on programmatic appraisal and inter-dependencies specifically. The guidance it primarily offers is that NPV should be maximised subject to non-monetised impacts not dominating/affecting choices. The COBA Manual, whilst officially withdrawn from the suite of appraisal guidance, does contain some advice on programmatic appraisal. However, there the focus is on maximising the NPV of the programme – by designing it correctly. The section on incremental analysis discusses maximising the NPV of a particular route section (e.g. choice of standard), whilst the section on competing and complementary schemes is about designing a good investment programme. Part of the latter is understanding the contribution of different route sections to the overall value.

The draft DfT guidance on package appraisal was put together following DfT's experience in assessing TIF packages. As such the focus of the note is in assessing the VfM of the 'package' and whether the package has been designed correctly (e.g. Are all the interventions included justified? Is the phasing correct?). The interest is therefore on the optimal design of the programme.

In contrast the HE's draft guidance on programmatic appraisal takes as a starting point that the programme is identified. Its interest then is in seeing if the benefits of the programme differ from the sum of its parts, and if so how the additional benefits can be allocated between schemes. This is much more aligned with the interests and focus of this study, than the draft package appraisal guidance.

As part of this study we conducted a number of interviews with overseas practitioners (Norway, Sweden and USA) and a summary of this can be found in Appendix A. In summary, in Norway, if it is believed that a scheme may have interdependencies, they are appraised as if they are one project. This forms part of the guidance for appraisal in Norway. In addition, if a practitioner is undertaking an appraisal on project (A), and there is a chance that a particular project (B) might also go ahead, then project (B) should be included in a sensitivity test.

Sweden doesn't generally undertake programmatic appraisal but the interviewee noted that it is a topic of interest, particularly to the railway sector and the development of the ideal timetable. In the USA, in general when a project is defined, there needs to be a consideration of synergies. If it is to be considered alone, it must be shown to have 'independent utility'.

---

[12] HE (2017) Appraisal Manual: Programmatic Appraisal Technical Annex. What is programmatic appraisal and how can I use it? Working Draft.

[13] HMT (2011) The Green Book (2003 version updated in 2011).

The HE Draft guidance seems closest to the objectives of this study. The interest is in the appraisal of an individual scheme and how the benefits of that scheme change when it is part of a package.

In terms of the treatment of uncertainty the HE guidance mentions uncertainty in funding and recommends the use of isolation analysis – where benefits are assessed if future phasing does not occur. The explicit incorporation of uncertainty into the VfM framework does not occur. The DfT draft package appraisal guidance discusses risk in the context of the Quantified Risk Assessment. The point made here is that risks within a package are likely to be correlated between projects (due to similarity in a lot of the underlying factors – e.g. physical proximity). However, it might also be possible to adopt risk mitigation strategies at the programme level that can't be undertaken at the individual project level. The draft guidance note does not elaborate on the nature of these risk mitigation strategies.

3.3 Decision criteria

3.3.1 Value for money criteria

Appraisal in general, and cost benefit analysis which is a subset of that, is an important tool in the government's planning armoury. These tools help ensure public funds are spent on activities that provide the greatest benefits to society (HMT, 2011).

The theoretical foundation to WebTAG is an economic welfare analysis. In policy terms it follows guidance in the Green Book. Broadly speaking economic welfare defined in WebTAG is the sum of changes in safety and environmental externalities, changes in user benefits, changes to transport providers and changes to government relative to some reference case and all suitably discounted and summed over project life. In the WebTAG Value for Money Framework, this then leads to a net present public value (NPPV)[14] identity of

$$NPPV = E + B_{NB} + B_B + BTB + ITR \quad (1)$$

Where:

E = externalities: the sum of changes in noise, local air quality, greenhouse gases, journey quality, physical activity and accidents

B_{NB} = Non-business user benefits

B_B = Business user benefits plus transport provider impacts less developer contributions

BTB = Broad Transport Budget (revenue directly received by Government from the transport scheme, operating costs directly incurred, investment costs including capital grants to transport

[14] WebTAG terminology has been used here. In economic texts, this is referred to as the net present value (NPV).

operators netted of developer contributions, and revenue support/concession payments received to/from transport operators)

ITR = Indirect Taxation Revenues

The BCR is defined as follows.

$$BCR = \frac{E + B_{NB} + B_B + ITR}{BTB} \qquad (2)$$

The BCR forms the basis of the value for money criteria. A BCR of less than or equal to 0 is very poor, between 0 and 1 is poor, between 1 and 1.5 is low, between 1.5 and 2 is medium, between 2 and 4 is high and above 4 is very high.[15]

The final value for money criteria is a judgemental decision that is based on:

- a formal estimate of the scheme's monetised benefits in which the DfT has a lot of confidence in (established monetised impacts such as time savings, operating costs, etc);
- an adjusted BCR that also includes impacts which are regarded as evolving in a monetisation sense (reliability and some wider economic impacts); and
- an analysis of 'indicative monetised impacts' (for example land use change); an analysis of non-monetised impacts; as well as risk.

Switching values are used as part of this judgement decision. This broad decision making is consistent with the Green Book.[16]

It can be shown that selecting projects based on BCR (as the VfM criteria effectively promotes) will maximise the social benefit (NPV) if they are independent and the marginal project(s) are small relative to the size of the budget (Minken, 2016)[17].

Analytically this 'problem' is known as the knapsack problem[18]. The knapsack is of a finite size and one wishes to maximise the value of what one places in it. If all projects are independent then the knapsack problem, is what is known as the Linear Knapsack Problem (LKP) (see **Figure 2**). If projects only have pairwise inter-dependencies the problem is known as the Quadratic Knapsack Problem (see **Figure 3**). Finding efficient programming solutions to these problems has been studied extensively in the operational research literature[19]. Efficient programming

---

[15] For projects that result in cost savings to government a different set of categorisations are used. These are based on the NPPV.

[16] The analysis which follows is conceptually applicable to the non-monetised as well as the monetised components of value although the precision of optimising on a single value indicator is lost.

[17] Minken, H., 2016. Project selection with sets of mutually exclusive alternatives. Economics of Transportation, 6, pp.11-17.

[18] Found in the works of Tobias Dantzig (1884-1956), the linear knapsack problem derives from the intuitive problem of packing the most valuable/useful items into a knapsack of fixed size.

[19] See for example: Kellerer, H., Pferschy, U., & Pisinger, D (2004) *Knapsack problems* Berlin: Springer-Verlag

methods found in the literature on the knapsack problems are necessary where the optimum combination from a large number of potential combinations. If however the resource constraint is in generating all the combinations (e.g. long model run times as is often the situation in transport modelling) brute force programming solutions that examine and compare all the combinations for which model results are available are quite feasible in terms of run times.

Figure 2: The Linear Knapsack Problem [LKP]

You have a "knapsack" with capacity/budget W. You can choose from items $\{i = 1, \dots, n\}$ that have costs $\{c_1, \dots, c_n\}$ and benefits $\{b_1, \dots, b_n\}$. How to maximise the total benefit within the capacity/budget constraint? With $x_i \in \{0,1\}$ an indicator to show whether item i is included or not, the problem is:

$$\max \sum_i b_i x_i \text{ subject to } \sum_i c_i x_i < W$$

The brute force solution is to try all 2^n possible subsets. Brute force methods look at every possible combination and then select the best combination. However, the problem can be solved much more efficiently by dynamic programming.

A simple greedy algorithm considers items by "value density" i.e. b_i/c_i. A greedy algorithm is an algorithm that uses the heuristic of making the locally optimal choice at each stage with the hope of finding a global optimum. Briefly, this would scan all items by value density and include all those that fit in the knapsack or the single item of largest benefit that fits in. While this approach will not always find the optimal solution, it is guaranteed to give more than half the benefit of the true optimal solution.

3.3.2 Interdependencies

However, an issue arises when schemes are inter-dependent. Here if different schemes reinforce each other, it is likely that the benefits of the total investment will be larger than the sum of the parts. Contrastingly, there may be situations where schemes compete with each other – e.g. where they are both viable route choices between the same origin-destination pair. Here the total benefits of doing both projects might be less than the sum of doing the individual projects. In these situations, a simple value for money criterion based on each project being independent from every other project may fail to maximise society's benefit. Different decision criteria are needed.

Mutually exclusive schemes can also be thought of as inter-dependent schemes. Here the interdependency is that they cannot both be implemented. In a programming sense this can be represented by allocating a mutually exclusive scheme as delivering zero benefit if its mutually exclusive 'partner' has already been constructed.

Both the COBA Manual and Minken (2016) set out approaches for addressing this problem in the context of mutually exclusive schemes (e.g. different route standards or alignments between the same scheme end points). Their equivalence is demonstrated in Annex 2. A solution to the decision requires an understanding of what, in economic terminology, the Government's budget constraint is. The budget constraint would usually be expressed as BCR (e.g. the BCR of the marginal scheme needs to be greater than 2). Given that Government in general and the DfT in particular do not advertise or promote a defined budget constraint this makes the dependency analysis hard to implement in a VfM criteria.

The methods set out by the COBA manual and Minken are brute force examples of methods that can be used to solve the problem of choosing between schemes which have inter-dependencies and are subject to a resource constraint[20]. If one can make some simplifications however more efficient analytical approaches exist. If costs are independent and only pairwise inter-dependencies between schemes are relevant the problem becomes what is known as the Quadratic Knapsack Problem (see **Figure 3**). An example of an application of the Quadratic Knapsack Problem algorithm to a transport appraisal is given by Raith et al. (2011)[21] for a set of cycling initiatives in Auckland. Here, by taking account of pairwise inter-dependencies, one would choose to take forward different sections of the cycle route upgrade, than if one treated all the potential schemes as independent.

[20] The approaches detailed in COBA and Minken would require that all combinatorial possibilities are treated as mutually exclusive options. This is not the most efficient way at solving this problem.

[21] Raith, A., Nataraj, U., Ehrgott, M., Miller, G. and Pauw, K. (2011) Prioritising cycle infrastructure projects. In Australasian Transport Research Forum (ATRF), 34th, 2011, Adelaide, South Australia, Australia.

Figure 3: The Quadratic Knapsack Problem [QKP]

This extends the linear knapsack problem above. Here the items are not independent; there can be additional (synergy) benefits from including i and j over and above $b_i + b_j$. The quadratic knapsack problem allows up to pairwise dependency of benefits (note that costs are still independent):

$$\max \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j \text{ subject to } \sum_{i=1}^{n} c_i x_i < W$$

This can be solved (see Raith et al. 2011) by appropriate solvers such as the open source COIN-OR CBC.

Two approaches are possible. The first follows from the LKP. Consider the absolute BCR density to be the sum of all associated benefits (including those not already included in the knapsack):

$$d_i = \frac{b_i + \sum_{j \neq i} b_{ij}}{c_i}$$

Compute the density of each item and sort in descending order. Scan in this order and (in turn) include all objects that fit within the budget constraint.

An alternative algorithm only considers interaction terms with those objects already included in the knapsack. Hence if, thus far, the items already included are S then the relative BCR density is

$$r_i = \frac{b_i + \sum_{j \in S} b_{ij}}{c_i}$$

i.e. the numerator only sums additional benefits over those items already included. Algorithm proceeds as above but as each object is added, the relative BCR densities are recomputed.

A more specialized project portfolio selection problem that has received attention in its own right in the transport field is known as the **Network Design Problem** [NDP], which aims

at finding the optimal set of links that should be improved in a road network in order to achieve a certain objective (minimise congestion, pollution or energy consumption)[22]*. A distinction is made between the* ***discrete problem*** *and the* ***continuous one****. In the* ***discrete problem*** *a predefined set of projects designated for improving the network is considered; links are chosen for addition or improvement and their additional capacity is defined in advance. In the* ***continuous problem*** *on the other hand, a more general approach is taken, and a decision is made regarding the links that will serve as part of the network, and*

[22] Leblanc, L.J., 1975. Algorithm for the discrete network design problem. Transportation Science 9, 183–199.

their appropriate capacities[23]. Both problems have been extensively investigated in the literature[24, 25, 26], and still serve as a fertile ground for research today.

Haas & Bekhor (2016)[27]

Within the formulation of the NDP, typically, is a transport network model that considers the flow of vehicles through the network, arising from an OD matrix, and assigned to the network links according to an equilibrium principle such as User Equilibrium [UE]. The underlying network model accounts for any interactions between changes to different links/components of the network. However, any intervention can only be evaluated once the network flows have re-equilibrated.

The more general project portfolio selection problem is relevant to many non-transport sectors: for example, associated with research and development, financial analysis, energy provision, pharmaceuticals and information systems (Almeida and Duarte, 2011)[28]. **Figure 4** summarises the project portfolio selection problem and solutions.

---

[23] Abdulaal, M., LeBlanc, L.J., 1979. Continuous equilibrium network design models. Transportation Research Part B 13, 19–32.

[24] Magnanti, T.L., Wong, R.T., 1984. Network design and transportation planning: models and algorithms. Transportation Science 18, 1–55.

[25] Yang, H., Bell, M.G.H., 1998. Models and algorithms for road network design: A review and some new developments. Transport Reviews 18, 257–278.

[26] Farahani, R.Z., Miandoabchi, E., Szeto, W.Y., Rashidi, H., 2013. A review of urban transportation network design problems. European Journal of Operational Research 229, 281–302.

[27] Haas, I., Bekhor, S., 2016. A parsimonious heuristic for the discrete network design problem. Transportmetrica A: Transport Science 12, 43–64.

[28] Almeida, A.T.D. and Duarte, M., 2011. A multi-criteria decision model for selecting project portfolio with consideration being given to a new concept for synergies. Pesquisa Operacional, 31(2), pp.301-318.

Figure 4: Project Portfolio Selection

Consider n projects/schemes. Note that some schemes may be mutually exclusive, and some combinations of schemes may exceed the budget, therefore not all combinations are feasible. Taking account of these constraints gives the set of all feasible project portfolio combinations P (a subset of Ω).

Key issue the number of potential project portfolios is large.

A single project portfolio $p \in P$ corresponds to some combination of schemes, for example $p = \{1,3,10\}$.

The benefit from each potential project (combination of schemes) is evaluated using some value function $b = v(p)$ e.g. the NPV of project p.

Key issue the parameters of $v(\quad)$ may be uncertain/inaccurate (see also the discussion on uncertainty in section 3.6).

Key issue evaluating $v(p)$ for a single project portfolio may be time consuming.

The optimisation problem is to find (over all possible scheme combinations) the maximum benefit (NPV for example)

$$\max_{p \in P} v(p)$$

If there are n schemes having benefits b and **without interactions** or conflicts then we have the LKP

$$\max \left\{ \sum_{i=1}^{n} x_i b_i \right\} \text{ such that } \sum_{i=1}^{n} x_i w_i \leq B$$

Where $x_i \in \{0,1\}$ is the decision variable indicating whether or not the i-th scheme will be implemented; the benefit from the i-th scheme is b_i and its cost is w_i. The total budget is B, giving the constraint. This requires n model runs to compute $\{b_i: i = 1, \ldots, n\}$.

We extend this formulation to include interactions that give rise to additional benefits/disbenefits. With b_{ij} the additional benefit (or disbenefit) from implementing both scheme i and j (additional to the benefit $b_i + b_j$) then the formulation with interactions can be written

$$\max \left\{ \sum_{i=1}^{n} x_i b_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} x_i x_j b_{ij} + \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \sum_{k=i+j+1}^{n} x_i x_j x_k b_{ijk} + \cdots + b_{1,\ldots,n} \prod_{i=1}^{n} x_i \right\}$$

This formulation considers not just pairwise synergies/interference, but allows for additional interactions between any combinations of schemes. Considering interactions leads to many more model runs. With just pairwise interactions we have the QKP.

Following Carazo et al 2016 we can add time scheduling with the following formulation.

$$x_{it} = \begin{cases} 1 \text{ if project } i \text{ starts in time period } t \\ 0 \qquad\qquad \text{otherwise} \end{cases}$$

Each project may also have finite duration d_i and hence project i is active in period k if $\sum_{t=k-d_i+1}^{k} x_{it} = 1$. An objective function would be

$$C_{q,k}(x) = \sum_{i=1}^{I}\sum_{t=1}^{k} c_{i,q,k+1-t}x_{it} + \sum_{j=1}^{S} g_{jk}(x)a_{j,q,k}$$

Here $c_{i,q,k+1-t}$ is the individual contribution of project i (if implemented and started at time t) to attribute q in period k. This project would be at execution time $k + 1 - t$ in period k. Interactions/synergies are identified between subgroups of schemes with $g_{jk}(x) = 1$ when synergy j occurs (0 otherwise) and $a_{j,q,k}$ is the effect on attribute q in period k.

References

Carazo, A.F., Gómez, T., Molina, J., Hernández-Díaz, A.G., Guerrero, F.M., Caballero, R., 2010. Solving a comprehensive model for multiobjective project portfolio selection. Computers & Operations Research 37, 630–639.

The discrete NDP is the formulation of most relevance to the present focus: selecting the optimal combination of individual schemes to implement. The discrete NDP is well-known to be non-convex[29] i.e. there are typically many local optima making it very difficult to determine the global optimum. Only recently have attempts been made to identify the global optima of such problems, and these approaches have only been applied to restricted classes of problems; they are not yet ready to tackle the complexity and diversity of issues faced in real world analyses. One variant of the NDP is the toll setting problem, as there are many variants to the tolls that can be set and the links that can be included in a cordon. In the particular case of a cordon toll, the topological complexity of maintaining a closed cordon has led to short cut approaches being developed such as that derived from select link analysis in Shepherd, Koh, May and Verhoef[30, 31]. Here the short cut utilised that took information from the first best marginal cost

[29] See for example Liu H, Wang AW (2016) J. Adv. Transp. 2016; 50:1295–1313

[30] Shepherd, S.P., May, A.D., Koh, Andrew (2007) How to Design Effective Road Pricing Cordons. In: 11th WCTR, 2007, Berkeley, USA.

[31] Verhoef, E.T., Koh, A. and Shepherd, S., 2010. Pricing, capacity and long-run cost functions for first-best and second-best network problems. *Transportation Research Part B: Methodological*, *44*(7), pp.870-885.

pricing tolls and select link analysis (to determine which origins and destinations use which links) to indicate the links to be included in a toll cordon. There may be some types of portfolio selection problems that are susceptible to an approach of this sort, though the effectiveness of such heuristics would have to be determined and inevitably it would depend on the problem structure arising from the schemes under consideration.

A lot of the literature in this field is concerned with the optimal design of transport investment packages or programmes rather than the assessment of inter-dependencies between the scheme that is being appraised and other schemes per se. Having said that a number of points can be drawn from this literature that are pertinent to our interest. These are that:

- It is non-trivial in terms of analytical effort in identifying the optimal investment programme – particularly for our case where we are looking at selecting the optimal combination of individual schemes. There is a large literature on linear programming solutions (e.g. those associated with the knapsack problems). However, for our context there is a need to undertake many transport model runs which act as inputs to these programming algorithms. This is likely to be a large resource constraint, and makes the task non-trivial.
- The linear programming algorithms in the literature on discrete NDP use the benefit cost definitions present within the existing VfM metrics (see for example **Figure 2**, **Figure 3** and **Figure 4**). That is, they do not adjust the metrics, but aim to maximise the benefits; and
- The level of synergistic benefit between schemes is a function of the schemes within that package.

The implication is that there is no generalisable formula to adjust the VfM criteria used in transport appraisal in the UK for programmatic appraisal. Instead the literature points us towards a series of linear programming routines that can identify maximum benefit given a set of constraints and conditions (the so-called knapsack problem). In an economic context those constraints would include the minimum acceptable rate of return (the opportunity cost) and may also include a budget constraint. Transport modelling runs are still required.

Given this, in the next section we review the methods used in the literature to identify a scheme's benefit within a programme, before considering what heuristics can be employed to minimise the analytical effort necessary.

3.4 Identifying a scheme's benefit

The principal problem with inter-dependent schemes is that there is **no unique level of benefit** that can be attributed to a scheme, unlike the situation when schemes are independent.

The level of benefit a scheme will deliver, when it has inter-dependencies with other schemes, is a function of:

- Its complementarity with other schemes that will be constructed;

- It's substitutability with other schemes that will be constructed; and
- The phasing of the inter-dependent schemes.

The COBA Manual, the DfT draft TAG unit and the HE draft guidance acknowledge this issue, and we now review the methods set out in those to identify scheme benefits, before broadening the discussion to see what other authors have said on the matter.

Before doing so it is worth noting that in our review of the literature there is a gap in that there is no discussion on the source of these interdependency benefits. Are they driven by re-routeing behaviour, changes in mode or destination/origin, or changes in land use? One interpretation of the inclusion of these interdependency benefits in the now withdrawn COBA Manual, which used a fixed matrix approach to appraisal, is that interdependency benefits can arise from re-routeing behaviour as well as from the traditional sources of induced traffic. The larger literature on the Network Design Problem use models that vary from fixed matrix highway assignment models to land use transport interaction models (e.g. Verhoef, et al. 2010) – which would also imply that interdependency benefits can arise from re-routeing behaviour as well as other forms of induced traffic.

3.4.1 Benefit measures

The literature sets out three benefit measures when schemes are inter-dependent: stand alone, decremental and incremental.

Using the example set out in The COBA Manual, for illustrative purposes we take the programme of options that are generated from Stage 1 of the appraisal (identification of needs, and option generation and sifting) to comprise of Scheme A, C and D[32]. If all schemes are independent of each other (i.e. no inter-dependencies), and we are interested in the benefit of Scheme A, this can be found by appraising it against a Do Minimum with none of the considered schemes in it. This would give one measure of the benefit of Scheme A. However, if the scheme has inter-dependencies with Schemes C and D then it would not be the full picture.

Another viewpoint of the benefit that Scheme A would deliver would be to consider what its contribution to the programme of A, C & D is. This can be done by assessing the benefits of the programme with and without Scheme A in it.[33] The difference in benefits between the two scenarios is the benefit that Scheme A adds to the programme. This method is known as *exclusion analysis* in The COBA Manual, or *decremental analysis* in the DfT and HE draft guidance. This has also sometimes known as the 'last link in the network method'.

---

[32] In the example set out in the COBA Manual Scheme B has been sifted out of the programme being appraised.

[33] On a technical point as Schemes A, C and D open at different times (year 0 to year 10) and the appraisal period has to be common across the schemes. The end point of the appraisal period for all three schemes is set to be that of the end point of the appraisal period of the last scheme that opens.

If Scheme A is complementary to both Schemes C and D then the benefits from the decremental analysis will be greater than the benefits from treating Scheme A as independent. If it competes then the benefits will be lower.

Another viewpoint of the benefit delivered by Scheme A within a programme is to consider the level of benefit the scheme would deliver if no other elements of the programme were constructed after it was built. Is Scheme C is constructed first, and Scheme A second, then such an analysis would assume Scheme D was never constructed. This is known as *incremental analysis*[34] in the DfT guidance and *isolation analysis* in the COBA manual.

It is possible that incremental analysis may indicate that there is no economic justification for Scheme A in the absence of Scheme D (incremental analysis gives a negative NPV, and decremental analysis gives positive NPV). This would indicate the sensitivity of the value for money of the scheme to the completion of the overall programme.

3.4.2 Double counting

When the institutional framework for investment decisions considers each scheme on a scheme by scheme basis, as it does in the UK, there is a risk for the same interdependency benefits to be included in the Transport Business Cases for different schemes. That is interdependency benefits could be ‘double-counted’. This is double counting in an institutional sense, rather than in the cost benefit analysis sense – for example land values double count transport user benefits. The potential for this institutional double counting arises as the interdependency benefits are attributable to the scheme, but they are also attributable to the other schemes that give rise to the interdependency. In our example for example the interdependency benefits between Schemes A and D would appear in the decremental analysis of both schemes. Thus, if individual scheme business cases are produced the same benefit will appear in more than one Transport Business Case.

The draft HE and DfT guidance address this issue in both an analytical and procedural manner. Analytically the use of decremental and incremental analysis makes it possible to demonstrate the economic worth of the scheme. However, procedurally these benefits, and the decremental benefits in particular, need to be set in the context of the overall programme. The draft HE and DfT guidance is cognisant of this issue and therefore recommends that the value for money of the programme or package is presented along with the results of decremental analysis (and incremental analysis if necessary).

3.4.3 Identifying Interdependencies

This literature on the identification of scheme benefits presents different methods for identifying benefits under different conditions. The benefit attributable is

[34] Note HE refer to incremental analysis as the stand alone analysis used in the development of the Core Value for Money Metrics in the Transport Business Case. We have chosen to use the terminology in the draft DfT guidance document, which is also more closely aligned to how the term incremental analysis is used in The COBA Manual.

dependent on what other schemes are constructed. There is nothing in the literature that identifies a simple adjustment to the NPV or BCR formulas (the metrics used in assessing value for money) to reflect that the appraisal is being undertaken as part of a programme of investments.

Part of the process of identifying scheme benefits therefore is an understanding of what other schemes will be part of the programme. This is most tractable when the shape of the programme is well defined. Though where programmes are large there still may exist substantial modelling challenges – due to the sheer number of scenarios that will need to be analysed (see for example Section 5 of this note). Sometimes, however, the programme is fuzzy. For example, whilst the needs analysis will have identified the areas of the transport network that need addressing, the option generation and sifting process is likely to have generated multiple solutions, which could be at quite different scales of investment and impact.

None of the texts reviewed have addressed this issue directly. However, some papers have advanced the role of experts in the decision-making for programmatic appraisal (Roland, et al., 2016[35]; Almeida & Duarte, 2011[28]) and Cochrane (2017)[36] also advised an understanding of inter-dependencies as part of the process of programmatic appraisal. Our interviews with appraisal practitioners in the UK and overseas have also pointed towards such an assessment – albeit in quite ad hoc manners.

The draft DfT package appraisal guidance promotes the development of a dependency matrix. This is reproduced below as an example. They also suggest splitting packages down into sub-packages, though care needs to be taken in the design of these sub-packages in terms of: the size of sub-packages, and the placing of highly dependent schemes within or between sub-packages.

Highways England also gives the following advice regarding potential schemes to consider for interactions (though this is in the context of impact on the programme):

- The largest investments in terms of likely expected impacts; for roads schemes, this would be in terms of the scale of impact on traffic to test the impact on other schemes;
- The most expensive investments as these may well have the greatest impact on the overall value for money consideration;
- Investments that are central to the delivery of the whole programme or upon which significant numbers of the remaining investments depend for delivery;
- Investments with considerable operational inter-linkages with the other investments in the programme;
- Investments with the most contentious or uncertain characteristics, which may include the investments with the most marginal value for money cases. For

[35] Roland, Figueira, Smet, 2016, Finding compromise solutions in project portfolio selection with multiple experts by inverse optimization. Computers & Operations Research, 66, pp. 12-19.

[36] Cochrane (2017) Email discussion with authors

these, the decremental approach enables a more thorough test of the full impact and a foundation for further qualitative or benchmarked assessment.

Source: Highways England (2017 p7)

Clearly a good understanding of the interactions within the road network and the dependencies (see an example in **Table 2**) of one route section on another, both complementary and competitive, will go a long way towards the identification of a set of potential schemes that may generate interdependency benefits (or dis-benefits for that matter). Obtaining that understanding will also aid transparency. We discuss analytical heuristics and their role in the next section.

Table 2: Example of matrix of dependency between projects

	Bus Rapid Transit project in South West of a City	Congestion Charging Project covering City Centre	Tram extension to the South West of a City	New Bus Interchange in the City Centre
Bus Rapid Transit project in South West of a City		Required to fund BRT. Will also increase PT market.	Will compete leading to lower patronage for BRT.	Required to provide termination point for BRT.
Congestion Charging Project covering City Centre	Potentially minor impact on Charging revenues		Potentially minor impact on Charging revenues	Negligible
Tram extension to the South West of a City	Will compete leading to lower patronage for Tram.	Required to fund Tram. Will also increase PT market.		Negligible
New Bus Interchange in the City Centre	Complementary – significant increase in number of passengers using interchange.	Required to fund interchange. Will also increase PT market.	Potentially minor reduction in passengers using interchange.	

3.5 Modelling Challenges and Heuristics

Whilst economic methods are available to choose between combinations of schemes in a manner to maximise net social benefit and to identify how benefits of a particular scheme may increase or decrease if they form part of a 'package' or programme', these require a complete set of analytical results for each scheme in all its possible combinations with every other scheme. There therefore exists a practical challenge in obtaining the full set of scheme combinations. This arises due to the curse of dimensionality – the possible number of combinations is very large.

3.5.1 Combinatorial Optimization and The Curse of Dimensionality

There are n schemes under consideration. If each component scheme can be either selected (“1”) or not (“0”) this gives rise to 2^n possible project portfolios (with one of these being the do-nothing case). The number of do-something combinations grows very rapidly with n as illustrated below:

Number of Schemes	n	3	5	10	15	20
Number of combinations	2^n-1	7	31	1023	32 767	1 048 575

It could be the case that schemes have multiple levels of implementation, the number of potential project portfolios to be considered rises even more quickly. For example, with 3 levels for each component scheme [not implemented, partial implementation, full implementation] or [not implemented, implemented in 2020, implemented in 2025] or [dual 2; dual 2 with grade separation; dual 3] then we have:

Number of Schemes		n	3	5	10	15	20
Number of combinations		3^n-1	26	242	59 048	14 348 906	3 486 784 400

Additional variables may also be of interest, each with multiple settings e.g. low, medium and high growth forecasts for travel demand and economic growth, scenarios for uptake of new vehicle technologies. These will also be multiplicative factors, giving rise to large numbers of forecasting scenarios under which to assess each of the potential projects.

It is important to recognise that the required number of model runs proliferates much more quickly that our intuition might suggest; this non-intuitive explosion of candidate solutions is an example of “the curse of dimensionality”.

Consequently, for all but the most trivial cases, we cannot “run the transport model” for every possible combination and then select the best alternative. We can only evaluate a small subset of all possible scheme-combinations. The question arises: how can this be done intelligently so as to select a nearly-optimal alternative with the least (modelling) effort?

3.5.2 Heuristics

The *brute force* approach to this optimisation problem would be to compute the valuation function (e.g. the NPV or BCR) for every scheme $\{v(p_i): i = 1, \dots, |P|\}$ and for every scenario, and select the maximum from this finite (but possibly long) list. Better, we would re-run for ranges of values of all model parameters for which we were uncertain and then examine the distributions of $v(p_i)$ and apply probabilistic criteria to select the "best" project portfolio.

Classical exact resolution methods (i.e. enumerative, branch and bound, dynamic programming, linear and integer programming, etc. allow the finding of optimal solutions, but they are often extremely time-consuming when solving real-world problems (i.e. problems with large dimensions, hardly constrained problems, multimodal and/or time-varying problems).

Drawing from Ehrgott and Gandibleuc (2000)[37] a **heuristic** can be defined as a technique which seeks good (i.e. near optimal solutions at a reasonable computational cost without being able to guarantee either feasibility or optimality. Often heuristics are problem-specific, so that a method which works for one problem cannot be used to solve a different one. By contrast, **metaheuristics** are powerful techniques generally applicable to large numbers of problems. A metaheuristic refers to an iterative master strategy that guides and modifies the operations of subordinate heuristics by combining intelligently different concepts for exploring and exploiting the search space. A metaheuristic may manipulate a single solution or a collection of solutions at each iteration. A comprehensive list of 138 references on the theory and application of metaheuristics is presented in (Osman and Laporte, 1996[38, 39].

The literature we have reviewed however has been remarkably sparse in suggesting appropriate heuristics for this problem in the context of practical appraisal.

Cochrane (217 referred to a basic heuristic of incremental drop-in/drop-out as a means of developing a preferred programme. In essence, a drop out analysis would be to test whether a scheme was contributing (sufficiently to a programme. If it wasn't to then exclude it. Repeating the analysis until all schemes within the programme are net contributors. This is akin to a regression analysis in which one regresses the dependent variable on a set of exogenous variables and then gradually drops out variables until all coefficients in the model are statistically significant. The drop-in analysis would be the reverse.

Raith et al. (211 in their case study of investment in Auckland cycleways reduced the complexity of the problem of appraising a new cycle network by considering only pairwise inter-dependencies. They do not offer an argument as to why they exclude from consideration triplet or quadruplet inter-dependencies (i.e. higher order inter-dependencies between three or four schemes. The inter-dependencies are higher for pairs of cycle schemes that are immediately adjacent

---

[37] Ehrgott, M., Gandibleux, X., 2000, Multiple Criteria Optimization: State of the Art Annotated Bibliographic Surveys. OR Spektrum, 22, pp. 425–460

38 Osman I,Laporte G (1996) Metaheuristics: A bibliography. Annals of Operations Research 63:513–623

[39] Metaheuristics include, but are not limited to, constraint logic programming, genetic algorithms, evolutionary methods, neural networks, simulated annealing, tabu search, non-monotonic search strategies, greedy randomized adaptive search, ant colony systems, variable neighbourhood search, scatter search, and their hybrids

to each other – this is due to the spatial proximity and correlations in travel demand between adjacent route sections. The main point of their paper is that by excluding inter-dependencies from the appraisal (including from the demand forecasts) schemes that do not maximise the NPV may be selected. It is therefore necessary to consider inter-dependencies in scheme appraisal.

Haas & Bekhor (2016)[40] suggest running tests to identify schemes which give high levels of benefit and have high levels of synergies with other schemes. Synergies are identified by undertaking a pairwise test and finding if Benefit of A + Benefit of B < Benefit of (A+B). "Benefit" here means using NPV or whatever is the criterion of choice. The difference between the two measures is the level of synergistic benefit. Their heuristic then identifies the schemes that would comprise the programme by firstly identifying the schemes that deliver the highest benefit, and then adding in further schemes based on least cost. They apply this approach to single (stand alone), pairwise and triplet treatments of schemes within the programme, and find that the system of their proposed programme is close to the system time of the optimal programme. The more inter-dependencies that are considered, the better the approximation is: that is considering triplet inter-dependencies is better than pairwise, which in turn is better than stand alone.

In the approach adopted by Haas & Bekhor is that whilst inter-dependencies are considered in the selection of the 'first' scheme, or pair or triplet of schemes' to enter the programme, after that they ignore scheme inter- dependencies. Instead each additional scheme added to the programme reduces system travel time by an equivalent amount.

Interestingly they also find that, in the examples presented, that there are typically many combinations of schemes that (satisfy the budget constraint and) achieve very similar performance levels (optimality). This was also an observation made by Cochrane (2017) who suggested that provided the alternative investment programmes are all reasonably sensible, they may have similar global cost benefit ratios. Thus, solutions found using heuristic approaches may be significantly different in structure (i.e. have different schemes in them) but provide similar aggregate cost benefit results. It is worth noting that the literature reviewed does not offer an opinion or evidence as to why this finding occurs.

In the next section, we turn to the issue that not all of the schemes which may have inter-dependencies with our scheme of interest may be funded (and therefore constructed). That is the likelihood of the interdependency benefits (or dis-benefits) being realised may not be 100%.

3.6 Uncertainty created by interdependence

Appraisal guidance (e.g. the Green Book and the DfT's Value for Money Framework) indicates the need to adequately take account of the risk associated with uncertain outcomes. There are many such risks and uncertainties the treatment of which are embedded in the transport appraisal process. The one

[40] Haas, I., Bekhor, S., 2016. A parsimonious heuristic for the discrete network design problem. Transportmetrica A: Transport Science 12, 43–64.

which is of particular relevance to this project is that the scheme being appraised has inter-dependencies with other schemes which may not get constructed, or are seriously delayed, or are constructed and compete for traffic with the scheme of interest, and so on.

The risks associated with other schemes in the programme not receiving funding may stem from several different sources. Using the typology set out in TAG unit 1.2 they include:

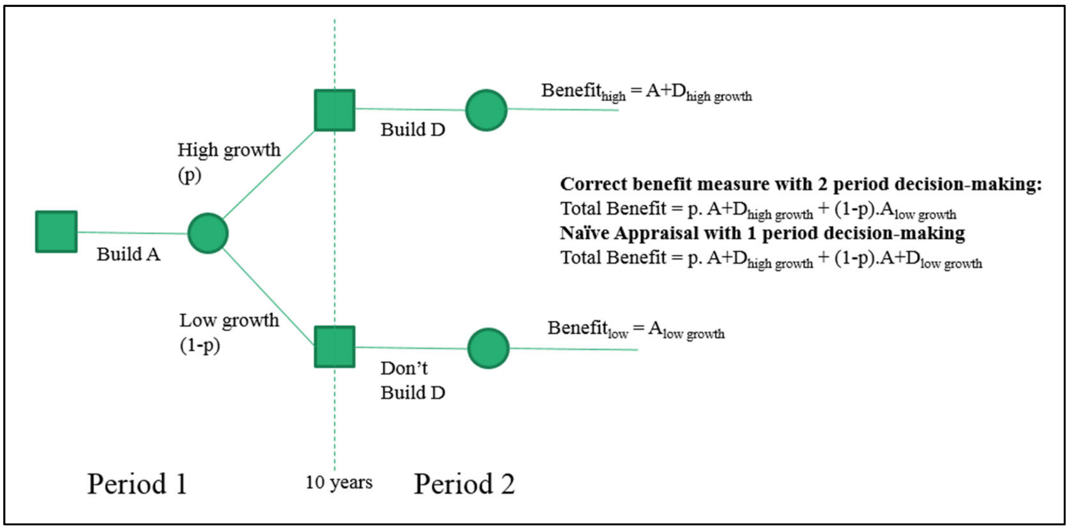
- Policy risk
- Risk on delivering the asset
- Risk on operating the asset
- Risks on demand and revenue

3.6.1 Decision trees and conditional probabilities

Clearly there are many sources of risk and uncertainty, but if for exposition purposes, we make the simplifying assumption that the only reason a scheme may not receive funding in the future would be that information becomes available that suggests the business case has diminished. For example, if we use the earlier example of the programme of schemes A, C & D, with Schemes C and D opening 5 and 10 years after Scheme A. If 5 or so years down the line it is found that traffic growth has not been as high as was expected at the time of the original appraisal the business case for Scheme D may be re-visited. If some of Scheme A's benefits are contingent on the delivery of scheme D this would then undermine the case for Scheme D. This uncertainty can be examined through the use of a decision tree.

In the simple example below, Scheme D is only justified under high traffic growth which occurs with probability p. The total benefit of scheme A is contingent on high traffic growth and the delivery of Scheme D. A naïve appraisal based on 1 period decision-making would however combine the benefits of constructing Schemes A and D under both low and high growth (with the respective probabilities). If Scheme D really is contingent on high growth occurring, then this naïve appraisal would lead to an overestimation of the benefits of scheme A, by including the inter-dependencies with Scheme D when these may not be delivered.

Much more complex decision trees can be constructed. For example, we could assume that both high and low traffic growth could occur in period 2, which may allow Scheme D to be constructed in a new period 3 (20 years after Scheme A opened). We can also consider further schemes and other interactions including that of construction cost uncertainty. The problem can therefore rapidly become highly complex to solve often requiring either the use of computer code or specialist software.



3.6.2 Quasi-Option Value and real options

The quasi-option value is in essence the correction one would make to a naïve appraisal based on a single decision point, so as to derive the correct benefits associated with multiple decision points (Boardman et al, 2011)[41]. The quasi-option value is also known as the 'real option value', and as such has parallels with financial options analysis.

There are limited applications of real options in the transport literature. In their review Byett et al. (2017) identified ten transport related papers. As per our example these papers consider the variable of uncertainty to be transport demand. Flexibility in the system (the option) is either through further expansion of capacity or through the timing of investment decisions. The challenge in the application is to estimate the stochastic properties of travel demand, and in our case how this then translates into the decision to invest or not.

In their case studies Byett et al. had difficulties in parameterising the decision-trees. There is the need for information on the payoffs for each outcome in the decision tree. In our example, these are Benefit$_{high}$ and Benefit$_{Low}$. This will require a lot of modelling analysis as per discussions in earlier sections about the composition of a programme. There is also a need to quantify the uncertainty in the demand growth.

Boardman et al. (2011 p194) advise that if there is insufficient knowledge to explicitly formulate the decision problem then it is better to discuss the quasi-option value (real options) as a source of bias, rather than add an arbitrary sum to the expected net benefits. This is also in keeping with the Green Book and value for money guidance which discusses the use of switching values.

Gathering an understanding of how uncertainties can affect the decision-making is of course important, even if the problem may be complex. Byett et al. drawing together information from several sources therefore proposed the following framework:

---

[41] Boardman et al. (2011) Cost-Benefit Analysis Concepts and Practice. Fourth Edition. Pearson.

[1] Define issue

[2] Estimate status quo and business as usual scenario

[3] Identify key drivers to uncertainty

[4] Create short list of alternatives

[5] Draw decision tree for alternatives

[6] Probe robustness to uncertainties

[7] Crudely estimate indicative payoffs

[8] Establish threshold that favour one alternative over another

This has many similarities to the earlier discussions regarding analysing dependencies between schemes (e.g. through a dependency matrix), and trying to identify the key sources of interdependency and therefore uncertainty.

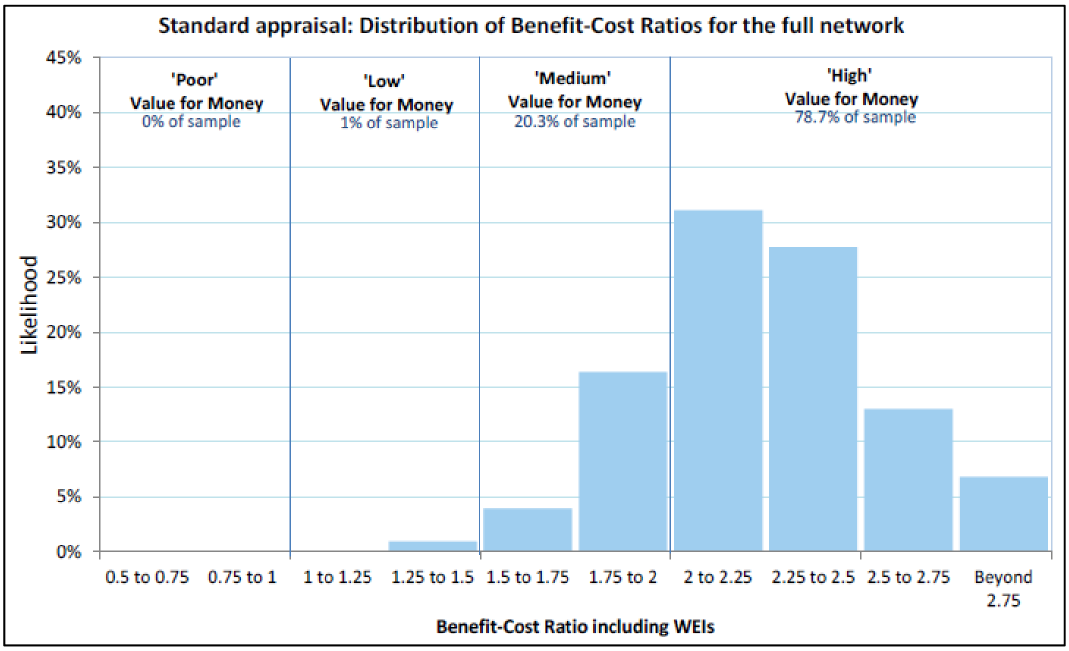
3.6.3 Monte Carlo analysis

A form of Monte Carlo analysis often used to account for uncertainty due to errors in data and/or errors in the forecasting model. The Green Book refers to it and the real options literature also uses it. An example of the use of monte carlo analysis coupled with an analysis of key drivers in uncertainty has been undertaken for HS2. The uncertainties analysed here are short and long term economic growth, values of travel time savings, sensitivity of demand projections to economic growth and fares, sensitivities in the VTTS to changes in GDP and uncertainty in construction costs.

The ensemble approach provides a distribution of results (for each performance indicator) that can help to make a probabilistic forecast, with an appreciation of the spread of outcomes arising from the errors and uncertainties. The ensemble approach is most commonly associated with weather forecasting. The multiple Monte Carlo model runs can cover (i) ranges of parameter values [perturbations] (ii) combinations of possible (discrete) system states [scenario analysis] (iii) different model specifications [multi modal ensemble].

A key requirement of monte carlo analysis is an understanding of the probability distribution of the variable that is uncertain. As a consequence, it is most easily applied to uncertainties which can be measured (e.g. from historic data). These would include for example probabilities of construction costs departing from their estimated values, risks of flooding, avalanche or other naturally occurring events, etc. This requirement limits the application of monte carlo analysis in transport appraisal.

Figure 5: Distribution of BCRs



Source: HS2 (2013 p27) The Economic Case for HS2

3.6.4 Non-quantifiable uncertainty

In the prior sections of this chapter we have set out the treatment of quantified risk through the use of conditional probabilities, which are most easily visualised in a decision tree. If the VfM metrics are viewed as a naïve single decision appraisal metric then an adjustment value, the quasi-option value, can be formulated to correct. The quasi-option value will be significant where new information becomes available over multiple time periods. If no new information is expected to become available over time, or whatever new information that does come to light will not affect the decision, there is no bias in the VfM formula. A single time period decision, as represented by the formula, is adequate.

However, in many circumstances probabilities cannot be quantified and alternative strategies to manage risk in the appraisal is required. Even when they can be quantified there is still a need to manage risk. One of the primary tools associated with the management of risk is through the use of a risk register. In WebTAG this is termed the uncertainty log[42]. The uncertainty log contains information of the nature of the risk, its likelihood, the expected impacts, mitigation measures and who owns the risk. An example extracted from TAG Unit M4 is presented in **Table 3**. Within this TAG Unit the likelihood of transport projects occurring (where probabilities cannot be assigned) are categorised as: near certain, more than likely, reasonably foreseeable and hypothetical. The definitions of these categories are presented in **Table 4**.

[42] See DfT (2017) TAG Unit M4 Forecasting and Uncertainty

Table 3: Uncertainty log for factors affecting supply of transport

Input	Forecast	Description of	Uncertainty	Comments
Increase in Rail capacity **Location Z from 2016.**	2014	Not included (Near Certain so under construction)	Not included (Under Construction)	Near Certain (See Table A2)
	2029	Included	Included	Near Certain (see Table A2)
Road pricing scheme **Location Y from 2013.**	2014	Not included as "Reasonably Foreseeable from Table A2"	Pricing Range as defined by scheme promoter	Reasonably Forseeable (See Table A2) (Business Case Under Construction)
	2029	As above	Pricing Range as defined by scheme promoter	As above

Source: DfT (2017) TAG Unit M4 Table A1

Table 4: Classification of Future Inputs

Probability of the Input	Status	Core Scenario Assumption
Near Certain: The outcome will happen or there is a high probability that it will happen.	Intent announced by proponent to regulatory agencies. Approved development proposals. Project under construction.	This should form part of the core scenario.
More than likely: The outcome is likely to happen but there is some uncertainty.	Submission of planning or consent application imminent. Development application within the consent process.	This could form part of the core scenario [Refer to Section Developing the Core Scenario].
Reasonably foreseeable: The outcome may happen, but there is significant uncertainty.	Identified within a development plan. Not directly associated with the transport strategy/scheme, but may occur if the strategy/scheme is implemented. Development conditional upon the transport strategy/scheme proceeding. Or, a committed policy goal, subject to tests (e.g. of deliverability) whose outcomes are subject to significant uncertainty.	These should be excluded from the core scenario but may form part of the alternative scenarios.
Hypothetical: There is considerable uncertainty whether the outcome will ever happen.	Conjecture based upon currently available information. Discussed on a conceptual basis. One of a number of possible inputs in an initial consultation process. Or, a policy aspiration	These should be excluded from the core scenario but may form part of the alternative scenarios.

Source: DfT (2017) TAG Unit M4 Table A2

4 Identifying scheme benefits and costs

4.1 Introduction

In this chapter, we build on our review of the literature, presented in Chapter 2, by focusing in and developing particular aspects of relevance to the objectives of this study. The primary objective of which is how to address the problem of informing decision makers about the likely value for money category of a specific transport scheme which is part of a programme and which interacts with other schemes in that programme. From a policy perspective a key interest is in if the value for money category would change after inclusion of interdependency benefits.

Putting to one side the treatment of risk for a moment, we have seen in Chapter 2 that the literature on the topic of uses the NPV and BCR formulas as part of the benefit maximisation process in determining optimal investments. These formulas are not adjusted in any manner, and instead the algorithms that are developed in the Network Design Problem literature (and more broadly the Project Portfolio Selection literature) attempt to maximise these criteria. These use linear programming methods of which the knapsack solutions are a subset. Interdependency benefits between schemes are only obtained if the schemes to which they refer are delivered –the transport economics literature on the topic does not therefore split interdependency benefits between schemes.

A scheme's benefit is a function of the state of the network it interacts with. This has led to different benefit measures being proposed in addition to the 'stand alone' benefits. These are incremental benefits and decremental benefits. We have also seen in the literature that pairwise analysis of schemes can be a useful heuristic. In this chapter, we therefore set out how stand alone, incremental, decremental and pairwise benefits relate to one another. The conditions for equivalence and which benefit measure is likely to be greater than the other benefit measures are therefore set out in sections 4.2 to 4.5 of this chapter.

The behavioural changes that give rise to these interdependency benefits are not discussed in the literature. However, the Network Design Problem literature utilises transport models ranging from fixed matrix to LUTI models. The implication of this is that all aspects of behavioural response from re-routeing to land use change can lead to interdependency benefits. We demonstrate from a transport economic perspective why this should be expected in Section 4.6.

The methods used in the literature discussed in Chapter 2 to maximise economic benefit within programmatic appraisal require some form of constraint – even if that constraint is that a BCR of 1.0 is required. This can be formal budget constraint or a constraint imposed by opportunity cost. Benefits are therefore maximised in this constrained environment. We discuss why this analytical process does not fit easily into the transport planning environment within the UK in section 4.6 of this chapter.

A key limitation in the analysis is not the computer processing time of the linear programming algorithms themselves, but the resources required to provide data to those algorithms. This has then lead to the need to develop some heuristics to try to approximate the global benefit maximum through the use of as few transport model runs as possible. The implications for modelling are also discussed in section 4.8.

The nature of programmatic appraisal is that the schemes within the programme will be implemented in the future. As discussed in section 3.6 the transport economics literature provides a method for incorporating uncertainty in the NPV and BCR if the level of uncertainty/risk can be quantified. In many situations, and as we argue in this chapter for our particular area of interest, this level of quantification cannot be undertaken. In section 4.9 we therefore discuss why this is the case and how uncertainty regarding the implementation of other schemes in the programme can be addressed in the appraisal.

In the discussion in this chapter we focus almost entirely on benefits. This discussion can easily be extended to scheme costs and at different points in the text we draw out the implications on scheme costs.

4.2 Independent, complementary and competing schemes and pairwise and higher order interdependencies

If we think about our programme of schemes: A, C and D. Scheme A is the scheme that we wish to assess. It has inter-dependencies with both C and D, which in turn have inter-dependencies with each other. These schemes complement each other therefore the total benefits of the programme exceed the sum of the parts.

We can therefore think of the benefits of the programme as comprising of the benefits of constructing only Scheme A, plus the benefits of constructing only Scheme C, and the benefits of constructing only scheme D plus the interdependency benefits. The *additional* benefits arising from the interdependencies between schemes are labelled correspond to areas A+C, A+D, C+D and A+C+D in **Figure 7**. Interdependencies A+C, A+D and C+D which arise through pairs of schemes are termed **pairwise interdependency benefits**. The interdependency benefit A+C+D is an example of a **higher order interdependency benefit** and in this case is a **triple**.

If the schemes were independent the benefits of the programme would be as illustrated in **Figure 6**.

Figure 6: Benefits from Programme of independent Schemes A, C and D

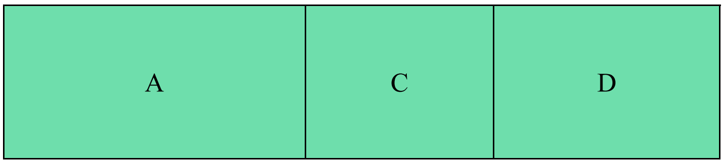
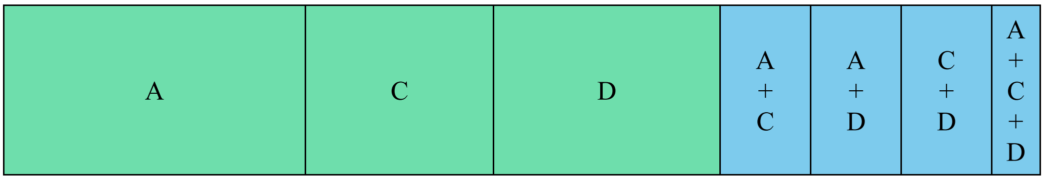
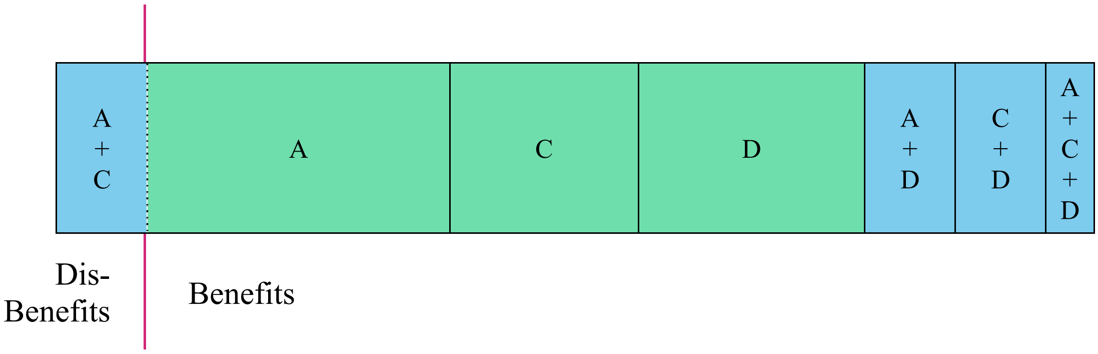


Figure 7: Benefits from Programme of Complementary Schemes A, C and D



If on the other hand Scheme C competed in some way with Scheme A, then the benefit of constructing A and C would be less than the sum of their benefits if they had no inter-dependencies. Analytically we can think of this as a negative synergistic benefit between A and C. In **Figure 8**, we depict the competing effect of schemes A and C with a dis-benefit equal to Area A+C. The benefit of the programme is therefore found by adding Areas A, C, A+D, C+D and A+C+D to each other, before subtracting area A+C.

Figure 8: Benefits from Programme with Schemes A and C competing



This analysis clearly demonstrates that the presence of inter-dependencies – competing or complementary – changes the level of benefit that schemes will deliver.

A similar set of diagrams and discussion can also be associated with scheme costs. If two schemes are complementary in terms of scheme costs then the cost of constructing both of them is less than the sum of the cost of constructing each of them separately. There may for example be a shared piece of infrastructure that is subject to some economies of scope or density in use. If two schemes are competing in costs then the opposite is the case. That is the cost of constructing both schemes is more than the sum of the cost of constructing each of them separately. Potentially one can envisage a situation where schemes are complementary in both scheme costs and benefits, and conversely a situation where schemes are competing in benefits but complementary in costs. An example of the first would be the case where the optimal design standard for scheme C was contingent on the delivery or not of schemes A and D.

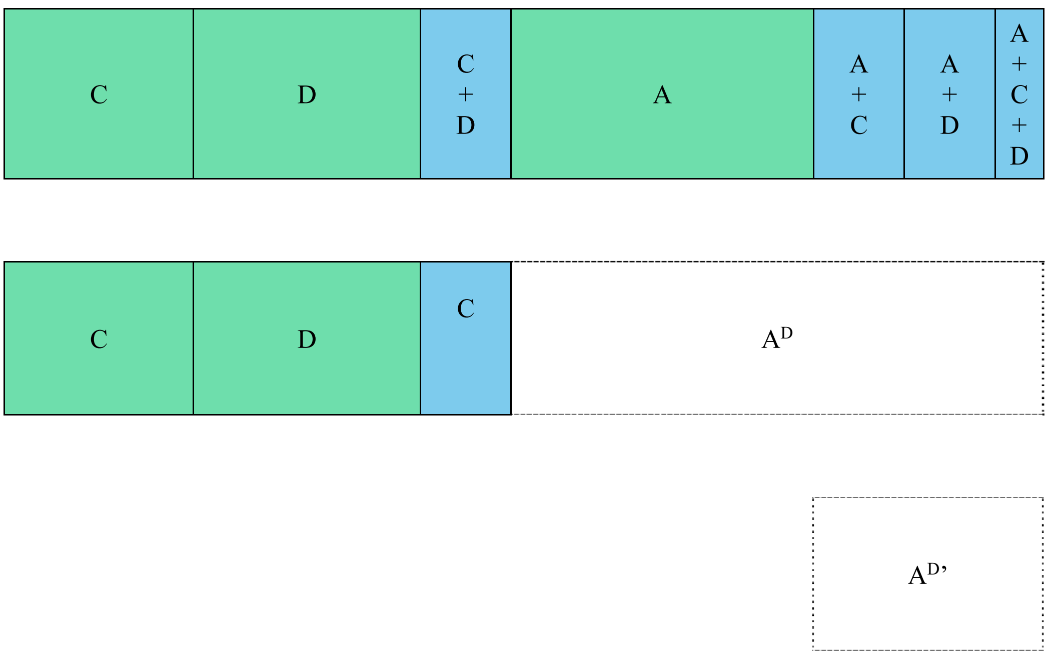
It is clearly important in terms of deriving accurate value for money metrics (the NPV and the BCR) that the scheme benefits and costs used reflect the nature and extent of the schemes being appraised. Each situation will be case dependent and the analysis needs to develop robust estimates of both scheme benefits and costs.

4.3 Decremental analysis

As discussed in the previous chapter decremental analysis is a method of identifying the level of benefit that is attributable to a scheme of interest – say Scheme A. The decremental benefit that Scheme A contributes to the programme is found by comparing the benefits derived by the programme without Scheme A (lower part of **Figure 9**) with the benefits for the full programme (upper part of **Figure 9**). This is depicted by the area A^D.

Area A^D comprises of area A (the benefit of implementing the scheme by itself), and the interdependency benefits: A+C, A+D and A+C+D. We can identify the total interdependency benefits linked to Scheme A by subtracting Area A from Area A^D. This is depicted in **Figure 9** as $A^{D'}$. It is important to note that with a decremental analysis we do not have any information as to what inter-dependencies drive these 'programme level' benefits. That is, we do not know if the inter-dependencies between the schemes are all approximately the same (as in our example), or whether two schemes have strong inter-dependencies, but the third only has weak inter-dependencies. We also do not know if the trio-wise inter-dependencies between all three schemes are large or small relative to the pairwise inter-dependencies.

Figure 9: Decremental analysis of Scheme A



This analysis can also be repeated for Schemes C and D as shown in **Figure 10** and **Figure 11**.

Figure 10: Decremental analysis of Scheme C

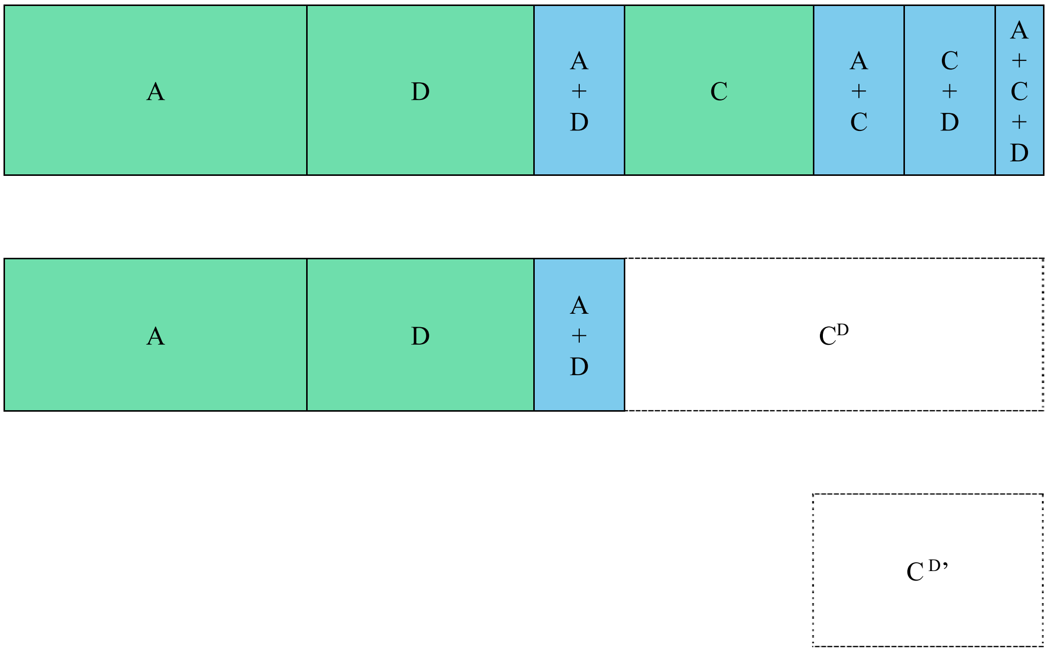
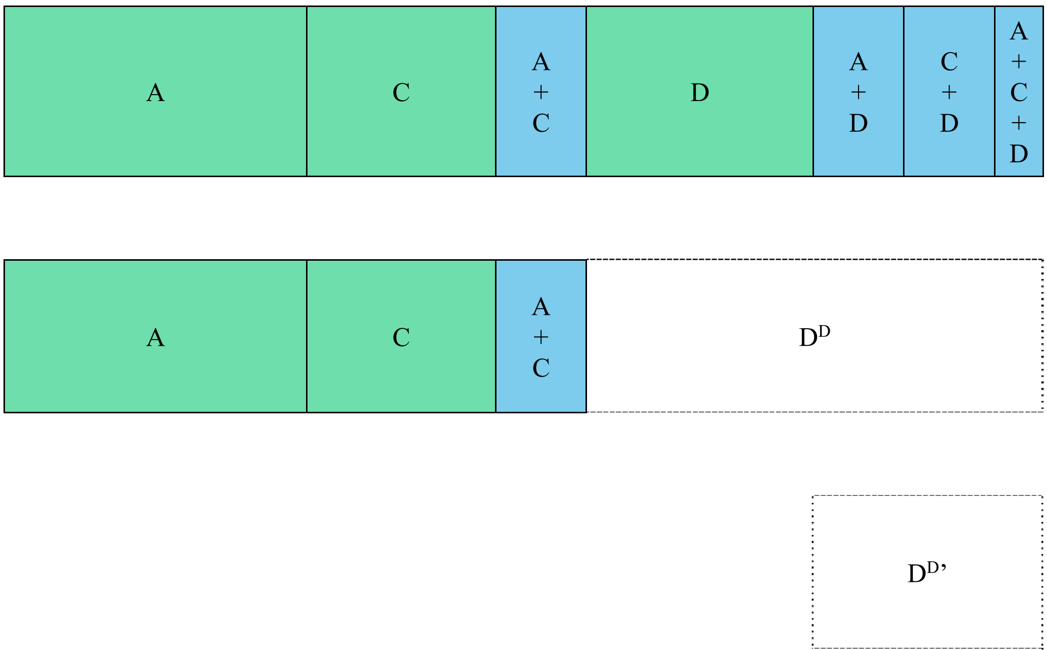


Figure 11: Decremental analysis of Scheme D



We can also see that if we now add the benefits from these three decremental analyses together we would get an area equal to $A^D + C^D + D^D$. This would be an overestimate of the benefit of the programme. The overestimate is by the sum of the areas which appear in two or more of $A^D + C^D + D^D$ (i.e. the overestimate is the sum of A+D, A+C, C+D plus twice the area A+C+D). Thus, we can see that the sum of a series of decremental analyses of complementary programme elements will overestimate the benefit of the overall programme. It is this observation that leads to the concern that interdependency benefits may get double counted within the decision-making process (see e.g. Highways England, 2017)[12].

Conversely if **all** programme elements **compete** then summing the decremental benefits of each scheme in the programme will underestimate the benefits of the programme. This is because once again the error in the estimate is by the sum of Areas A+D, A+C, C+D plus twice the area A+C+D. With the case of all schemes competing this error is negative. If some programme elements complement and others compete then a priori it cannot be certain whether summing the decremental analysis of each scheme in the programme will over or underestimate the benefits of the programme.

This discussion can easily be extended to scheme costs with the same points being made.

4.4 Incremental analysis

The method for undertaking an incremental analysis was discussed in 3.4.1. With a phased construction of work an incremental analysis would identify the benefits associated with the project should later phases not get constructed. It is important that realistic opening years are adopted.

An economic textbook might suggest both selection of optimum scheme opening years and phasing/sequencing of different elements of a programme based on economic return, and in fact the COBA Manual does. A scheme is delayed if the net benefits gained from a delayed opening year exceed those from an earlier opening year.[43]. Within the programme the scheme with the highest NPV should then be constructed first. In reality, though “start dates are often dictated by statutory procedures and resource availability rather than selected on grounds of optimal timing” (COBA manual Part 3 Chapter 4 p4/7). Physical dependency of one scheme on another may also dictate phasing/sequencing, along with other interests such as whether a scheme forms a core element of a strategy or not.

Current governance procedures centre around the Transport Business Case and the Value for Money framework. This, as discussed earlier, considers non-monetised items in addition to monetised impacts and also considers other aspects essential to scheme delivery. In the Transport Business Case for example, the Management Case considers how easy it is to implement the scheme. Thus, delivery considerations (statutory procedures and resource availability), physical dependency and the narrative within which the investment sits all form part of the decision-making and business case. Given this planning context the phasing/sequencing of schemes in a programme should therefore be based on the Transport Business Cases of each scheme. The scheme which gives the best overall Transport Business Case would be constructed first, and so on until the last scheme in the programme.

Thus, if the phasing was Scheme A, C and then D, and the schemes complemented each other, we would get incremental benefits as depicted in **Figure 12**. These are Areas A^I, C^I and D^I. An incremental analysis of the first

---

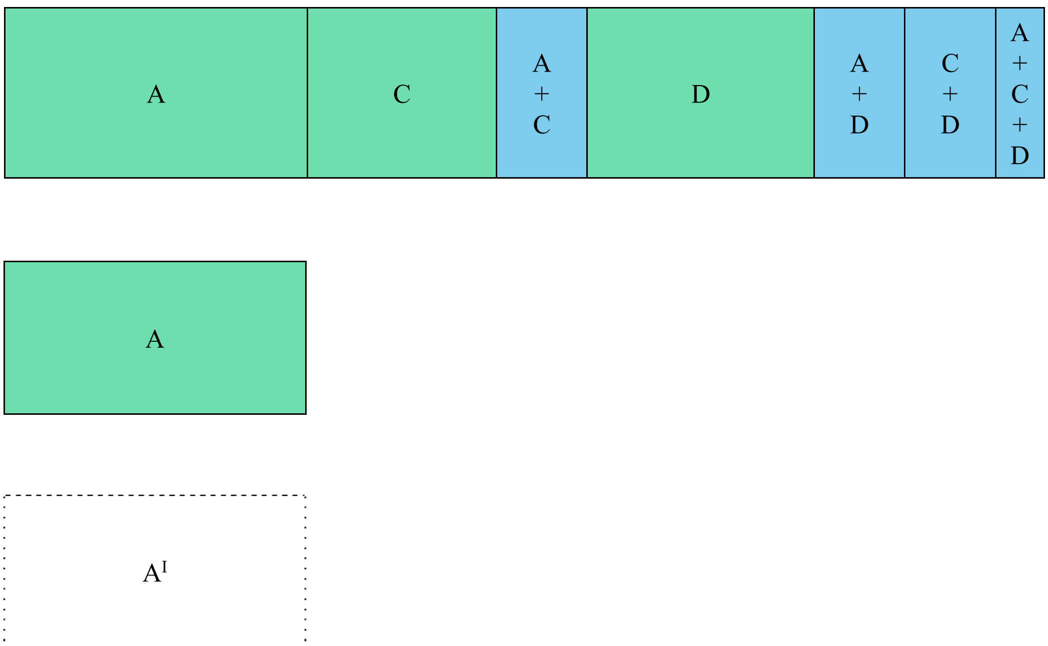
43 See Part 3 Chapter 3 of the COBA Manual.

scheme in the programme only gives the same benefit as if the scheme had no inter-dependencies with any other scheme. The second scheme in the programme delivers benefits associated with the first and second schemes, whilst the third scheme in the programme delivers three sets of interdependencies – the pairwise interdependency with the two preceding schemes and a third order interdependency between all three schemes. With this phasing the majority of the interdependency benefits are only realised once Scheme D has been constructed, however, the interdependency benefits arise as a consequence in this case of the pair or triplet of schemes that interact with each other.

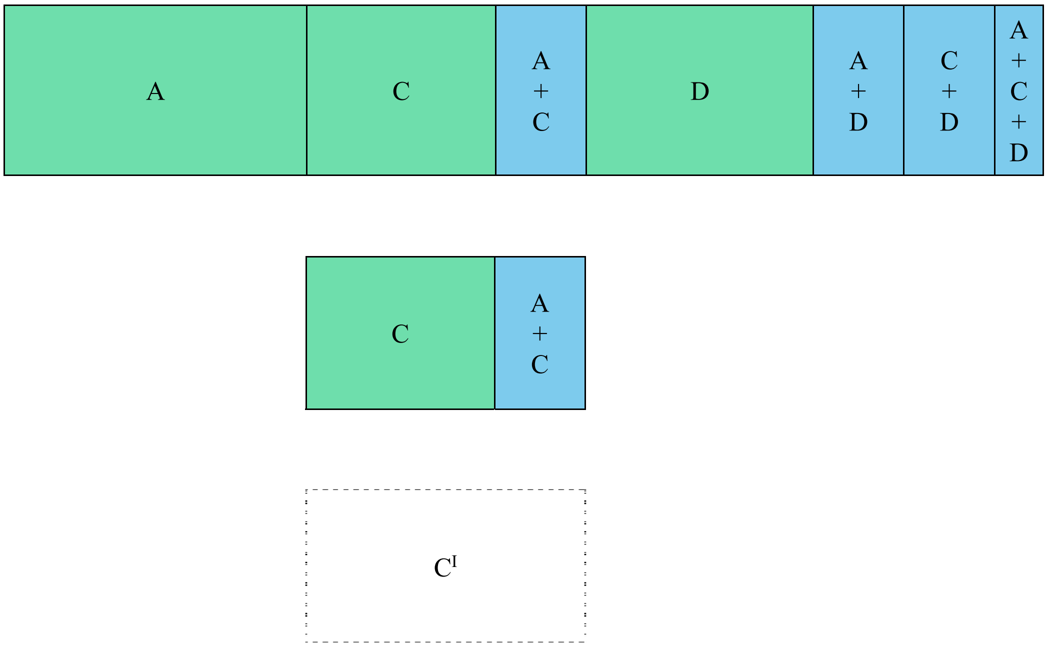
Again, it is important to note that with an incremental analysis we do not have any information as to what particular scheme to scheme interactions drive these interdependency benefits. In our three -scheme example this is particularly relevant to Scheme D, where the incremental benefit of Scheme D comprises of Areas D, A+D, C+D and A+C+D. It is likely we would have information on the size of Area D, and would therefore be able to estimate the sum of Areas A+D, C+D and A+C+D. However, an incremental analysis, like a decremental analysis, does not tell us whether Area A+D is larger or smaller than Area C+D. We would need more information if we wanted to know which scheme inter-dependencies were driving the interdependency benefits.

Figure 12: Incremental Analysis of Complementary Schemes A, C and D (with phasing A, C and then D)

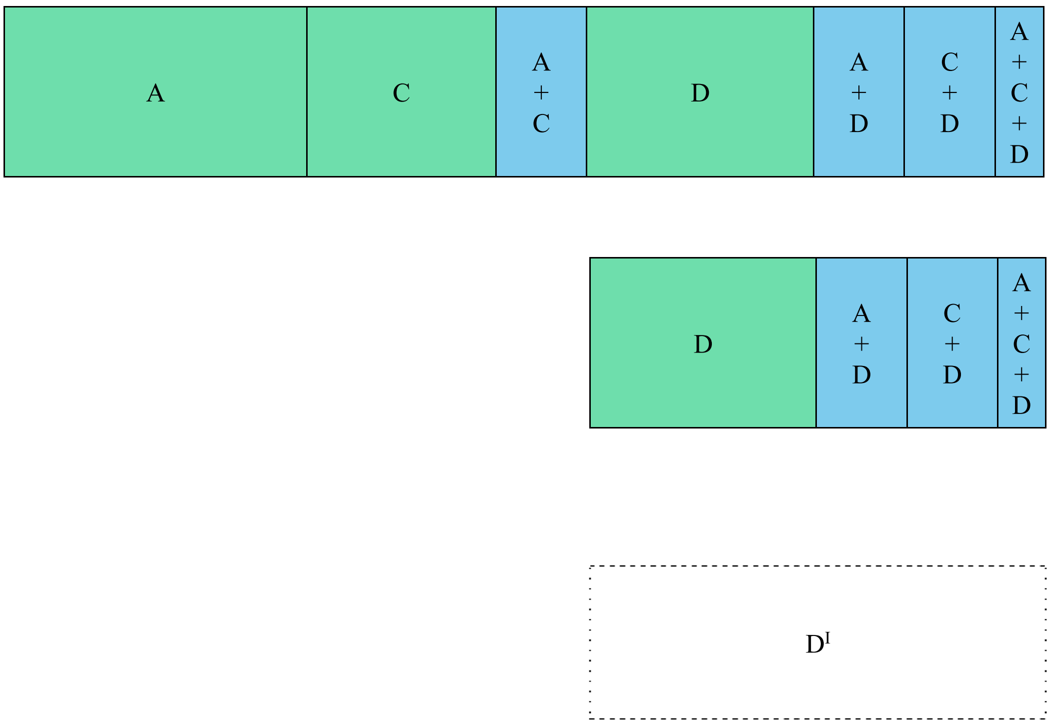
(a) Incremental analysis of A



(b) Incremental analysis of C



(c) Incremental analysis of D



It is also worth emphasising that the results of the incremental analysis are heavily dependent on which schemes precede it. The later the scheme being appraised is in the phasing of the programme the larger the share of interdependency benefits that are attributed to it. It is therefore very important that realistic opening years and sequencing are used. An obvious consequence of this is that schemes which have high levels of interdependency with other schemes, but with an otherwise weak value for money category, benefit the most from being phased later in the investment programme. The greater is the interdependence between schemes, the stronger is the case for appraisal of the programme itself so as to assure decision makers that the programme as well as its individual components satisfy value for money tests.

Once again, this discussion can be extended to that of scheme costs, with similar points being made.

On a more practical perspective when considering the sequencing/phasing of a programme it is important to treat each scheme on a common footing. The standard appraisal period is 60 years, which with a phased programme would imply different terminal end points for each scheme in the programme. To avoid the need to include residual values in the analysis a common terminal end point is often used.[44] The end of the appraisal period of all schemes in the programme is therefore 60 years after the last scheme in the programme opens.

4.5 Incremental vs Decremental

We can see that through the use of 'standalone', incremental and decremental analyses one can obtain three estimates of the economic benefit of a scheme. This reflects the fact that a scheme with inter-dependencies does not have a unique benefit measure, but instead has a benefit measure that is conditional on what else is happening in the network. For the three-benefit measures this conditional aspect varies:

- Stand alone benefit: No other elements of the programme are constructed.
- Incremental benefit: In a phased/sequenced construction of a programme only the schemes that precede our scheme are constructed. Later elements of the programme are not constructed.
- Decremental benefit: All other elements of the programme are constructed – even if other programme elements are phased/sequenced to open later than our scheme.

The relationship between the three measures is illustrated in **Figure 13** for three complementary schemes A, C and D. Looking at Scheme C, we can see for example that the incremental analysis would give a benefit of Area C plus Area A+C, whilst a decremental analysis would give a benefit of Area C plus Areas C+D, A+C and A+C+D. It is also clear that the phasing of the programme influences the exact relationship between the incremental and decremental analyses. The earlier the Scheme is in the programme phasing the larger the difference is between the incremental and decremental analysis.

For complementary schemes, we can see that for early phases of the programme decremental benefits are bigger than incremental benefits, whilst for the last phase of the programme decremental and incremental benefits are equivalent. More generally we can say for complementary schemes that:

- Stand Alone benefits ≤ Incremental benefits

44 See for example the COBA manual Part 3 Chapter 6.

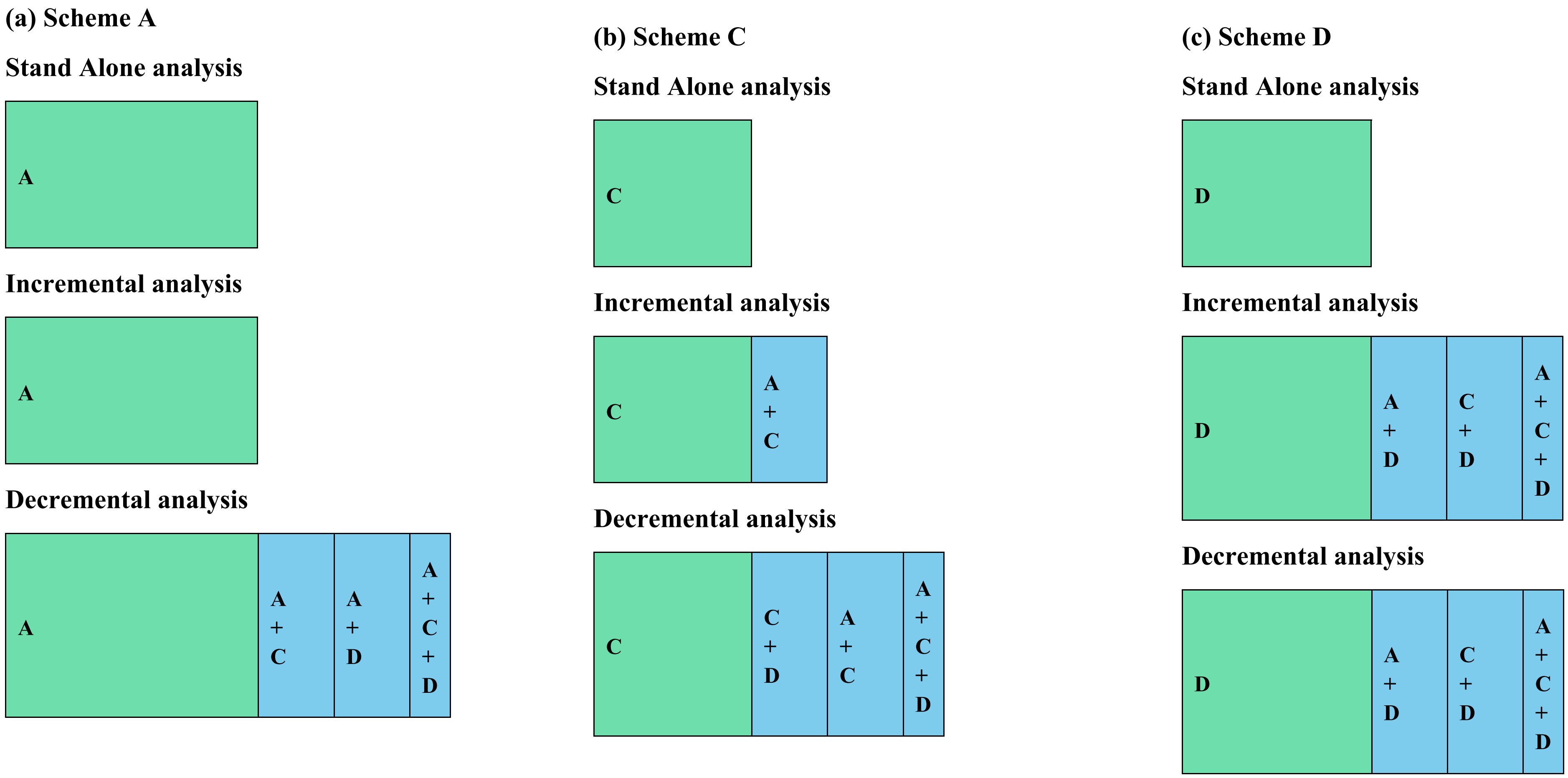
- Incremental benefits ≤ Decremental benefits

We can also observe that presenting **a set of decremental analyses** based on the phasing/sequencing of the programme **gives the same results** as an **incremental analysis of the programme**. This is because the first decremental analysis we would undertake is of Scheme D. Here we can see that the incremental and decremental analyses are the same for Scheme D (the last scheme to be constructed in the programme). The next ‘phased decremental analysis’ would be of Scheme C – but against a programme that does not include Scheme D. This would give the same result as an incremental analysis of Scheme C.

As we have also discussed we also know that summing a set of decremental analyses for the schemes in a programme will overestimate the benefit of the programme. This is not the case of an incremental analysis, where the sum of a set of incremental analyses will give the programme level benefits.

Whilst we turn to the issue of uncertainty in the next section, it is worth emphasising that the decremental and incremental benefits are subject to uncertainty. Arguably the decremental benefits are more uncertain, as the analysis treats the scheme being appraised as the last link in the network. For the benefits to be delivered it requires all other schemes in the network to be constructed. In contrast, the incremental benefits are only dependent on the schemes that come earlier in the phasing of the programme to be delivered.

Figure 13: A Comparison of Stand Alone, Incremental and Decremental analysis for Complementary Schemes A, C and D (Phased A, C and then D).



4.6 The source of interdependency benefits

It is also useful to consider the interdependency benefits within the context of the traditional consumer surplus diagrams. This is because it allows us to draw inferences about the source of the behavioural changes that give rise to these benefits, and also the inter-relationship between the different sets of interdependency benefits (pairs, triplets, etc.).

4.6.1 The case when generalised cost reductions between schemes are additive

Figure 14 shows Areas A, C and D in the traditional consumer surplus diagram. Focusing on a particular origin-destination movement (from Y to Z), in the absence of any other intervention Scheme A lowers the supply curve from the Do Minimum supply (S_{DM}) to the supply curve with only Scheme A in place (S_{DM+A}). The user cost per trip lowers and demand for travel between Y and Z increases from Q_{DM} to Q_{DM+A}. A similar situation can be described for Schemes C and D, should they be the only schemes in the programme that are implemented.

Figure 15 illustrates the situation should only pairs of schemes be constructed. Here there can be three pair combinations: A and C, A and D, and C and D. The schemes complement each other as they increase the demand for travel on each other. That is Scheme A increases the demand for travel on Scheme C, and so on. With a linear demand curve, the cost reductions being additive and scheme phasing of A, C and then D we get the situation shown in **Figure 15**. This would be akin to examining a particular origin destination movement along a route upgrade – with the ends of the route being Y and Z. The main point to draw from this figure is that the interdependency benefit is attributed to the induced traffic generated by the first scheme in the phased construction. Thus, if Schemes A and C are constructed with A phased first, the interdependency benefit Area A+C, is directly related to the traffic induced by Scheme A (that is traffic Q_{DM+A} - Q_{DM}). the same argument can be attributed to the two other potential pairings.

Relaxing the linear demand curve assumption and using a demand curve convex to the origin would result in Scheme C generating more traffic than it would in isolation. With a linear demand curve:

$$Q_{DM+A+C} - Q_{DM+A} = Q_{DM+C} - Q_{DM}$$

But with a demand curve that is convex to the origin we get:

$$Q_{DM+A+C} - Q_{DM+A} > Q_{DM+C} - Q_{DM}$$

The implication here is that interdependency benefits when the demand curve is non-linear are also dependent on additional behavioural responses to those that resulted in the induced traffic we observe from Scheme A.

Figure 14: Consumer surplus of Schemes A, C and D if only one of the three is constructed.

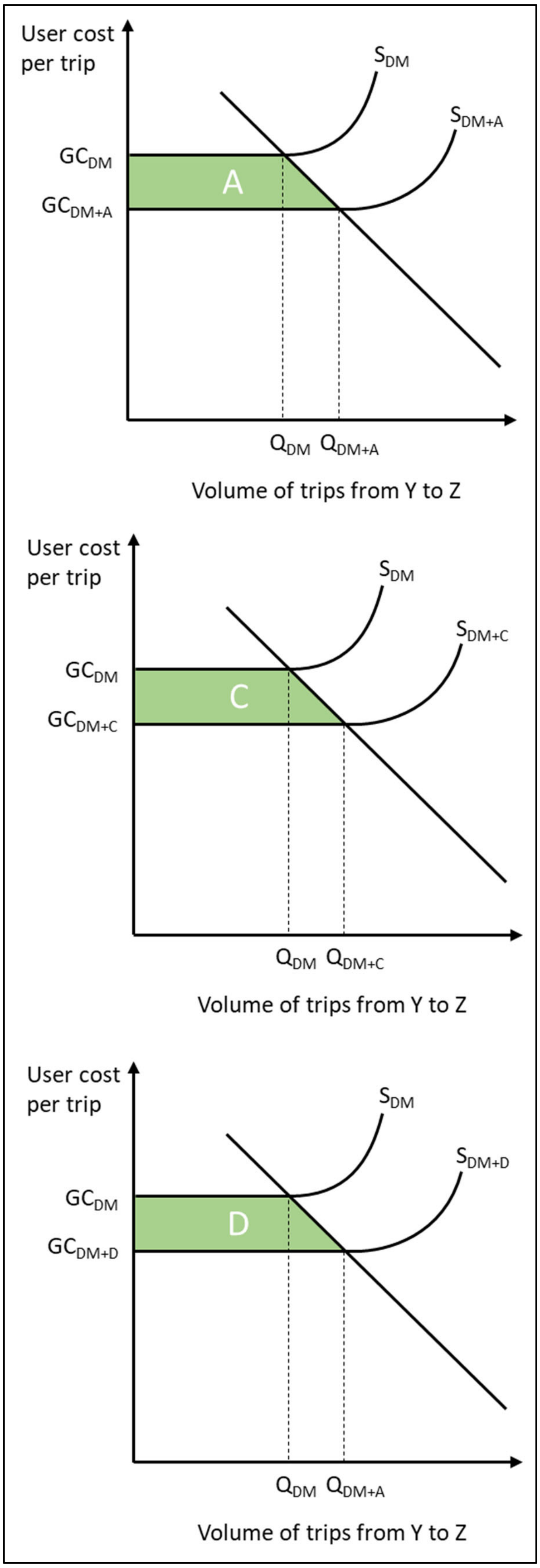


Figure 15: Consumer surplus of Schemes A and C, A and D, and C and D if only one of the three pairs are constructed.

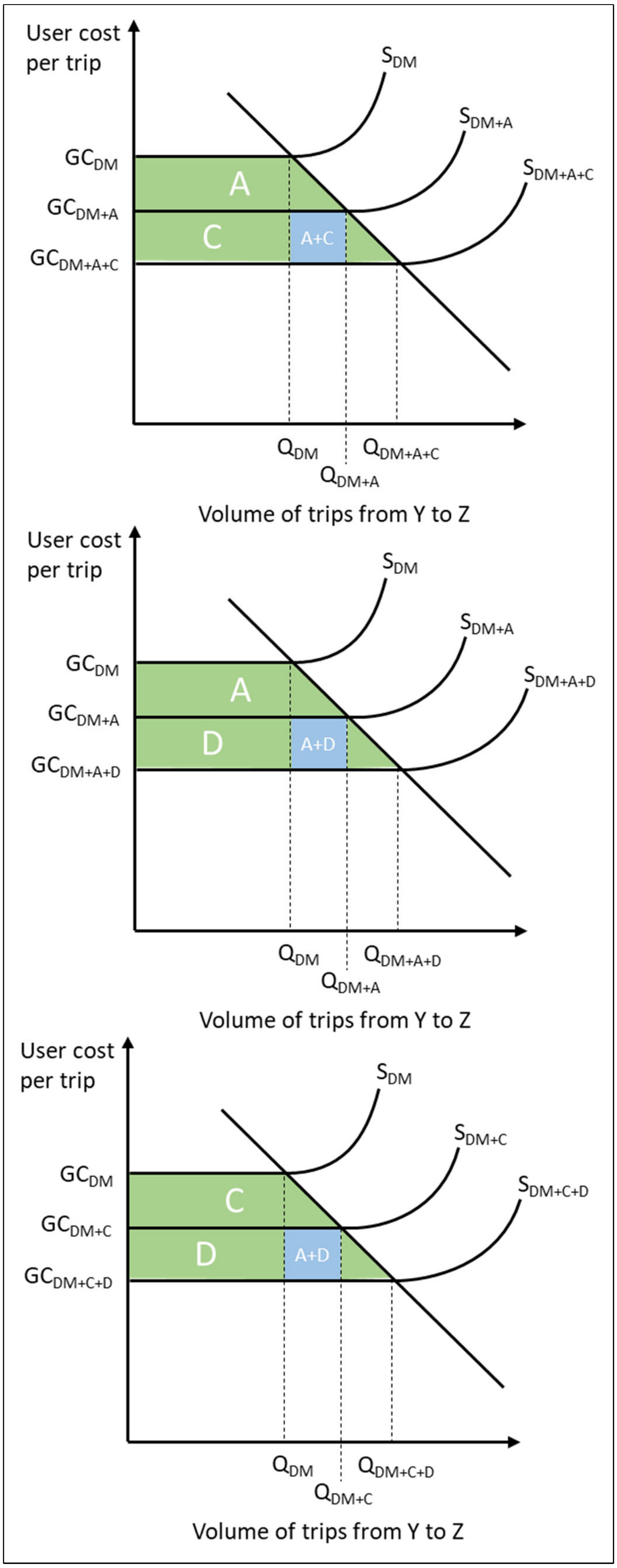
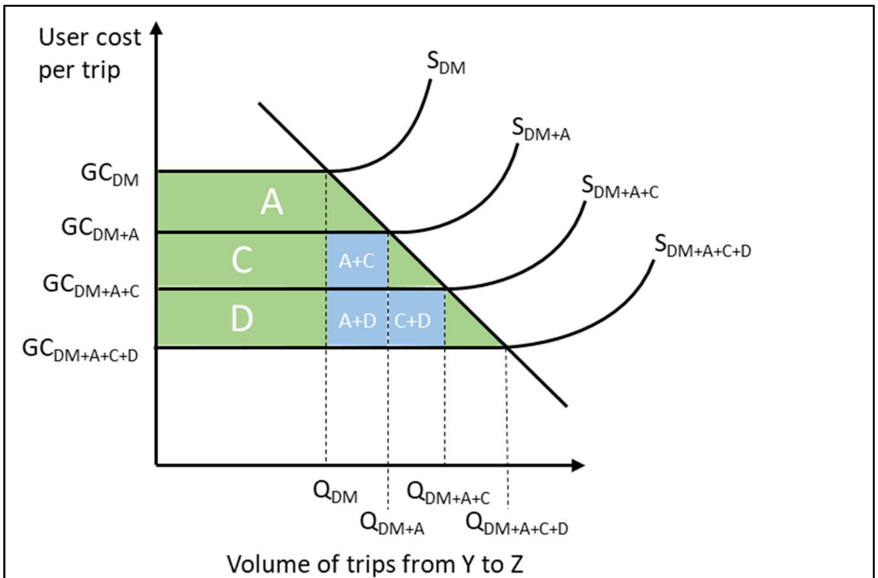


Figure 16: Consumer surplus of the programme comprising of complementary Schemes A, C and D where generalised cost reductions from each scheme are additive



Note: In this example Area A+C+D equals zero. This is a function of the shape of the cost curve and the additive properties of the cost reductions.

Figure 16 illustrates the benefits from a programme level investment in all three schemes: A, C and D. Here we can see that the interdependency benefits are A+C, A+D and C+D. Areas A+C and A+D are a function of the traffic using Schemes C and D respectively that was induced by Scheme A. Area C+D is a function of the traffic that was induced by Scheme C and uses Scheme D. The assumptions of a linear demand curve and additivity of the scheme cost reductions mean that Area A+C+D, which appears in earlier figures, is zero.

Relaxing the linear demand curve assumption would, using a demand curve convex to the origin, result in a positive value greater than zero for Area A+C+D.

One of the insights this analysis offers is that for the situation where generalised cost reductions between schemes are additive pairwise benefits will dominate unless the demand curve is very elastic. For small cost changes, when linear approximations to the demand curve are viewed as acceptable, we would therefore expect the pairwise benefit to be a good approximation to total interdependency benefits. This will be examined in the case study for an empirical situation.

4.6.2 The case when generalised cost reductions between schemes are not additive

There are three particular circumstances when generalised cost reductions created by each scheme in isolation will, when combined in a programme, not be additive. These are for complementary schemes which in combination offer re-routeing options, but in isolation do not, complementary scheme in congestion, and competing schemes in congested and uncongested conditions. We discuss each of these in turn.

4.6.2.1 Re-routeing brought about by complementary schemes

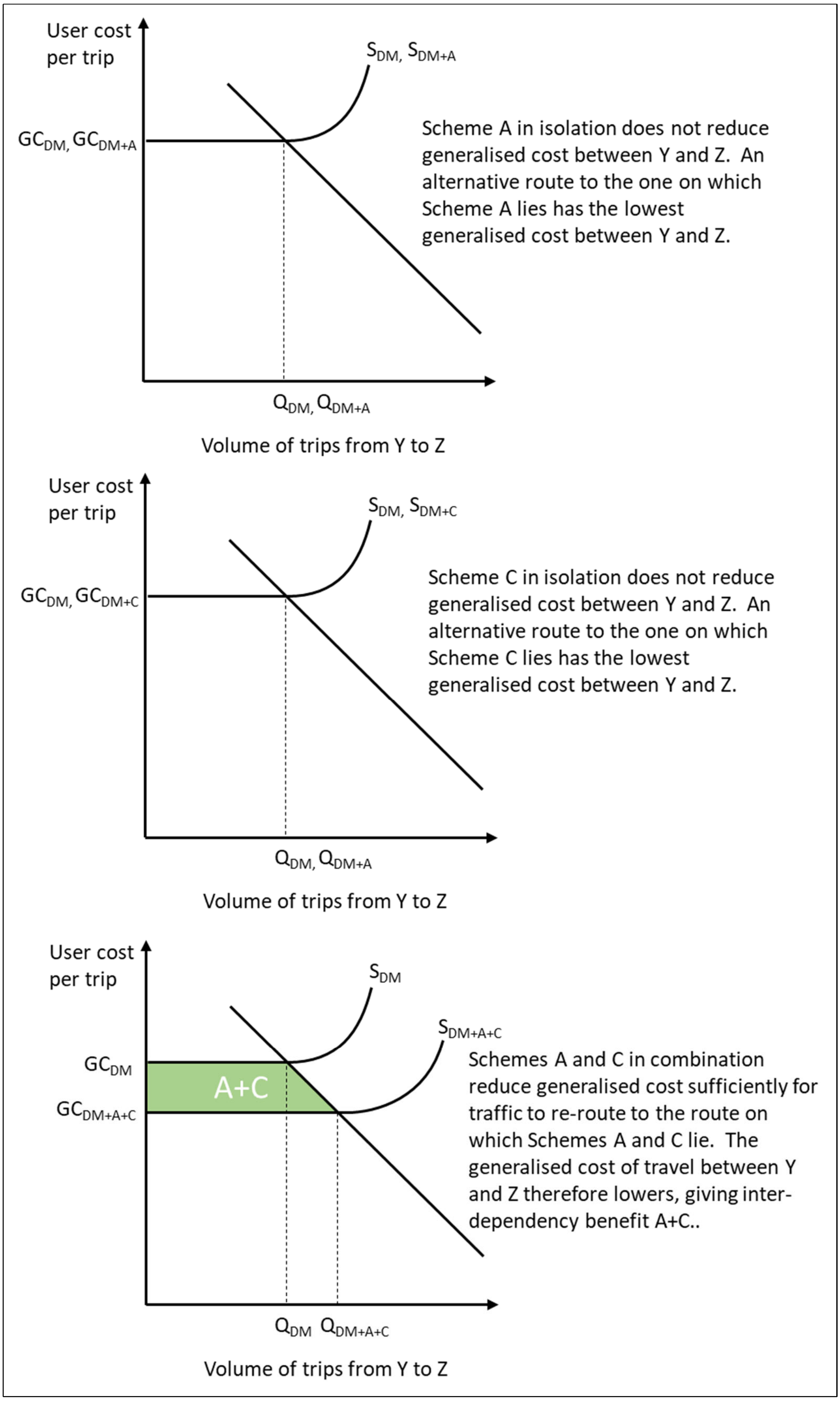
Re-routeing (or reassignment) will also be a relevant response. If Schemes A and C cause re-routeing, which neither A nor C does on its own then interdependency benefits will arise. Arguably as re-routeing is one of the most sensitive behavioural responses to a change in road transport costs, then we would expect significant interdependency benefits arising from re-routeing.

This is illustrated in **Figure 17**. Here neither Scheme A nor Scheme C in isolation make the route along which they lie a viable alternative for traffic travelling between Y and Z. However, in combination they reduce generalised cost on the route sufficiently for traffic between Y and Z to re-route. Clearly any upgrade to the route, from which this traffic came, would compete with Schemes A and C. We turn to schemes that compete later in this section.

The relationship to re-routeing and induced traffic gives us further insights on when interdependency benefits will be relevant to an appraisal. This is because most trips are 'short' distance trips – even on the Strategic Road Network. Only 1 in 4 motorway trips travel more than 25 miles on the motorway, and 64% of vehicles use the SRN A roads for less than 5 miles.[45] We would therefore expect inter-dependencies to be stronger with spatial proximity between schemes – as the amount of induced traffic is likely to fall off the further one is away from a scheme. Therefore, schemes that are adjacent to each other are likely to have higher levels of inter-dependencies than schemes that are a long way apart. But we would caveat that inter-dependencies cannot only be assessed by distance – the sparseness or density of the network will be significant. For example, the screenline for measuring the traffic impact of the M62 across the Pennines was drawn from the A628 at Woodhead to the A66 at Stainmore. Here, long distance re-routeing was an important behavioural response.

[45] DfT (2015) Strategic Road Network Statistics. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/448276/strategic-road-network-statistics.pdf

Figure 17: Consumer surplus of complementary Schemes A and C which in combination induce a re-routeing response



4.6.2.2 Complementary schemes in heavily congested conditions

In heavily congested conditions the generalised cost reductions brought about by complementary schemes, in traffic terms, will not be additive in a programme. This is illustrated in **Figure 18** and **Figure 19**. Here Schemes A, C and D all lie along the same route and complement each other in that they increase the demand along the entire route when implemented. In this example there exists a significant capacity pinchpoint along the route, which is addressed by Scheme D. Schemes A and C lower journey speeds on other sections of the route that are not subject to significant congestion. The influence of congestion here means that the generalised cost reductions from combining schemes in the programme do not equal the sum of the cost reductions when implementing the schemes in isolation.

The benefits from implementing each scheme in isolation are shown in **Figure 18**. If we look at the pairwise combinations with Scheme A in **Figure 19**, we see that as congestion at the capacity pinchpoint worsens through the implementation of the Schemes A and C as a pair. The generalised cost reductions along the route are not additive and the increase in congestion suppresses some of the benefit. The consequence is that the interdependency benefit A+C is negative. This is illustrated in **Figure 19** by the brown area (the loss of some of the consumer surplus that had been associated with implementing Scheme C in isolation). Scheme D on the other hand, by alleviating congestion at the pinchpoint, creates significant additional benefits when combined in a programme with other complementary schemes.

From this we can draw out that complementary schemes that increase congestion on a network will give rise to **negative** interdependency benefits (i.e. the sum of the parts is greater than the sum of the whole), whilst complementary schemes that reduce congestion on the network will give rise to **positive** interdependency benefits (i.e. the whole is greater than the sum of the parts).

Figure 18: Consumer surplus of complementary Schemes A, C and D in isolation and in heavily congested conditions.

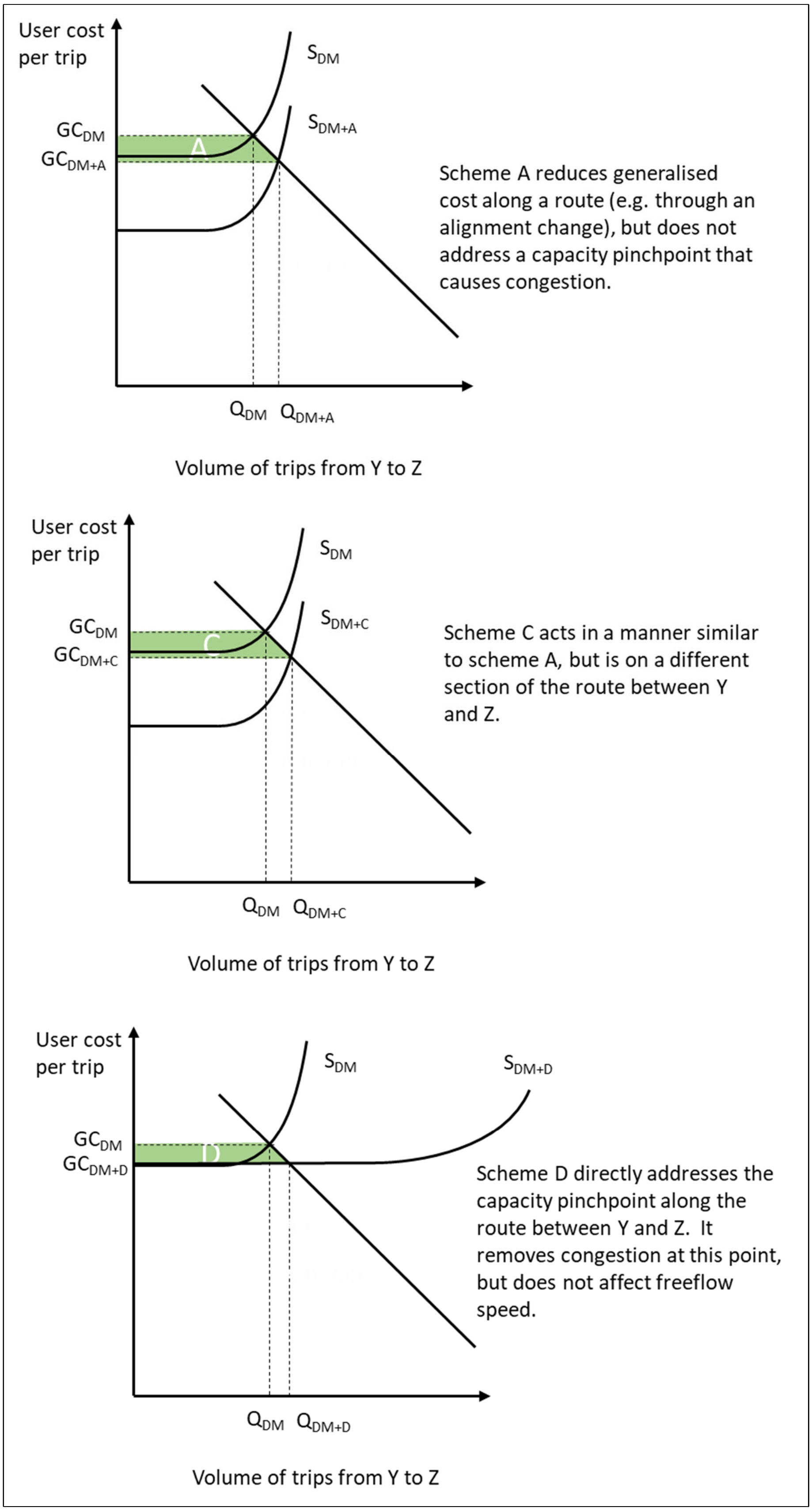
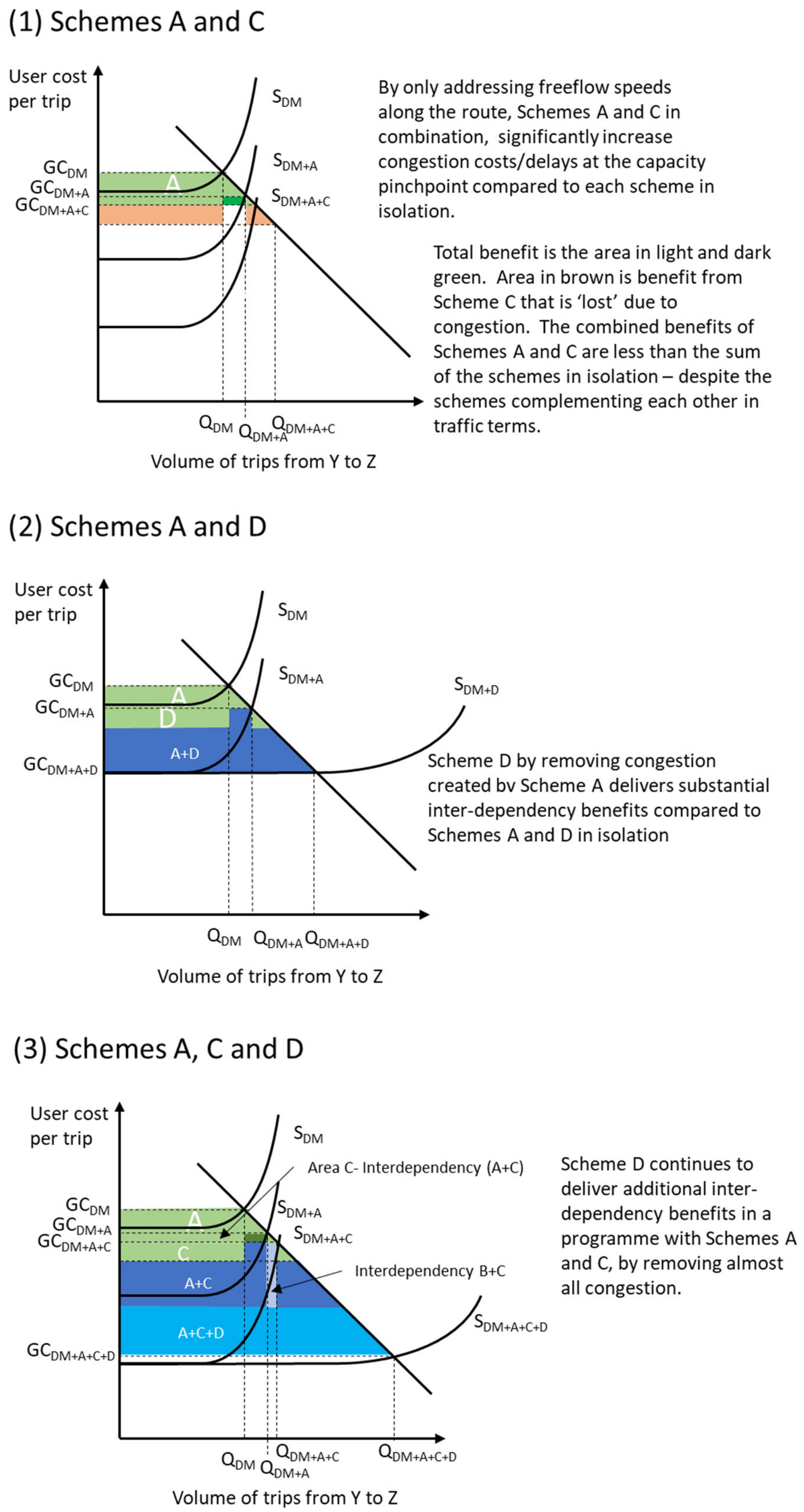


Figure 19: Consumer surplus from implementing programmes of complementary schemes in heavily congested conditions.



4.6.2.3 Competing schemes

Competing schemes abstract demand from each other. That is if Scheme C competes with Scheme A, then the demand for Scheme A will reduce if Scheme C is also implemented. This is easily seen in the context of re-routeing behaviour, where traffic switches from one route to another as the different routes are upgraded. This sort of scenario acts as the example for the situations depicted in **Figure 20** and **Figure 21**.

In uncongested or lightly congested conditions (**Figure 20**) one route between Y and Z dominates with all travellers between this origin and destination using it. Implementing Scheme A in isolation results in all traffic using Route 1, the route in which Scheme A lies. The converse happens if implementing Scheme C in isolation. Scheme C, however, delivers the largest cost reduction and therefore when Schemes A and C are implemented in combination all traffic continues to use Route 2 – the route on which Scheme C lies. Scheme A therefore provides no added value for travellers between Y and Z in addition to Scheme C. In this instance the interdependency benefit for Schemes A and C is negative and is equal (but opposite in sign) to the benefit of implementing Scheme A in isolation.

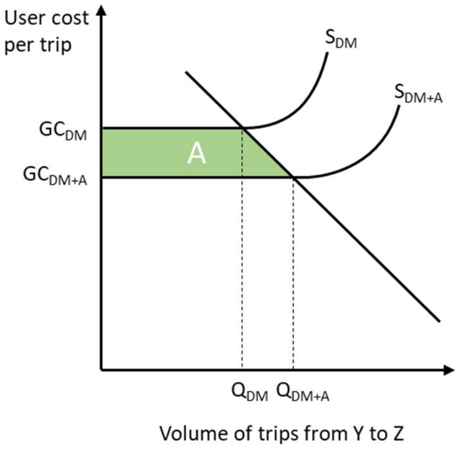
If, however the network between Y and Z is heavily congested in both the Do Minimum and the Do Something, then both routes (Routes 1 and 2) are viable and used routes[46]. In this situation some traffic between Y and Z will use the route on which Scheme A lies and some traffic will use the route on which Scheme C lies. Implementing Scheme A in isolation, will through the interaction of re-routeing and congestion effects, lower the cost of travelling between Y and Z on both routes. The same will occur if implementing Scheme C in isolation. In this congested situation implementing both Schemes A and C will increase capacity between Y and Z and generate additional benefits. These additional benefits are the interdependency benefits A+C. This is depicted in **Figure 21**. It is important to note that for this to occur both Routes 1 and 2 between Y and Z are used in the Do Minimum counterfactual and in the Do Something counterfactuals. This is likely to be the case in an inter-urban network only if congestion is very widespread.

From this we can draw out that in uncongested conditions competing schemes will give rise to **negative** interdependency benefits (i.e. the sum of the parts is greater than the sum of the whole), whilst in congested conditions they will give rise to **positive** interdependency benefits (i.e. the whole is greater than the sum of the parts). If a scheme increases capacity so that congestion drops to a level where one route can then dominate, **negative** interdependency benefits could occur (as the Do Something is no longer sufficiently congested for both routes to be used).

[46] See the principle of Wardrop's Users Equilibrium.

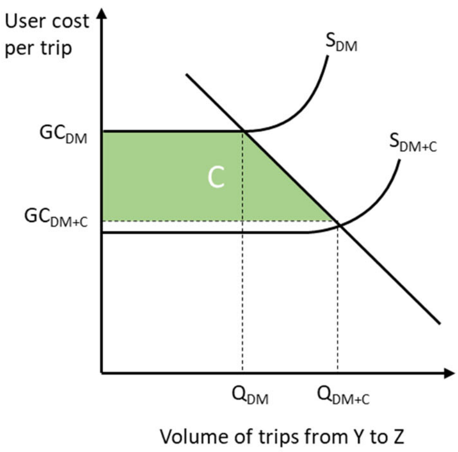
Figure 20: Consumer surplus from implementing competing schemes in isolation and in a programme in lightly congested conditions

(1) Scheme A on route 1



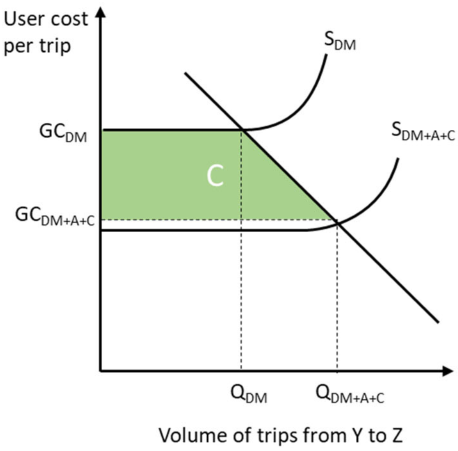
In isolation Scheme A is a viable route between Y and Z, and delivers a user benefit equal to Area A.

(2) Scheme C on route 2



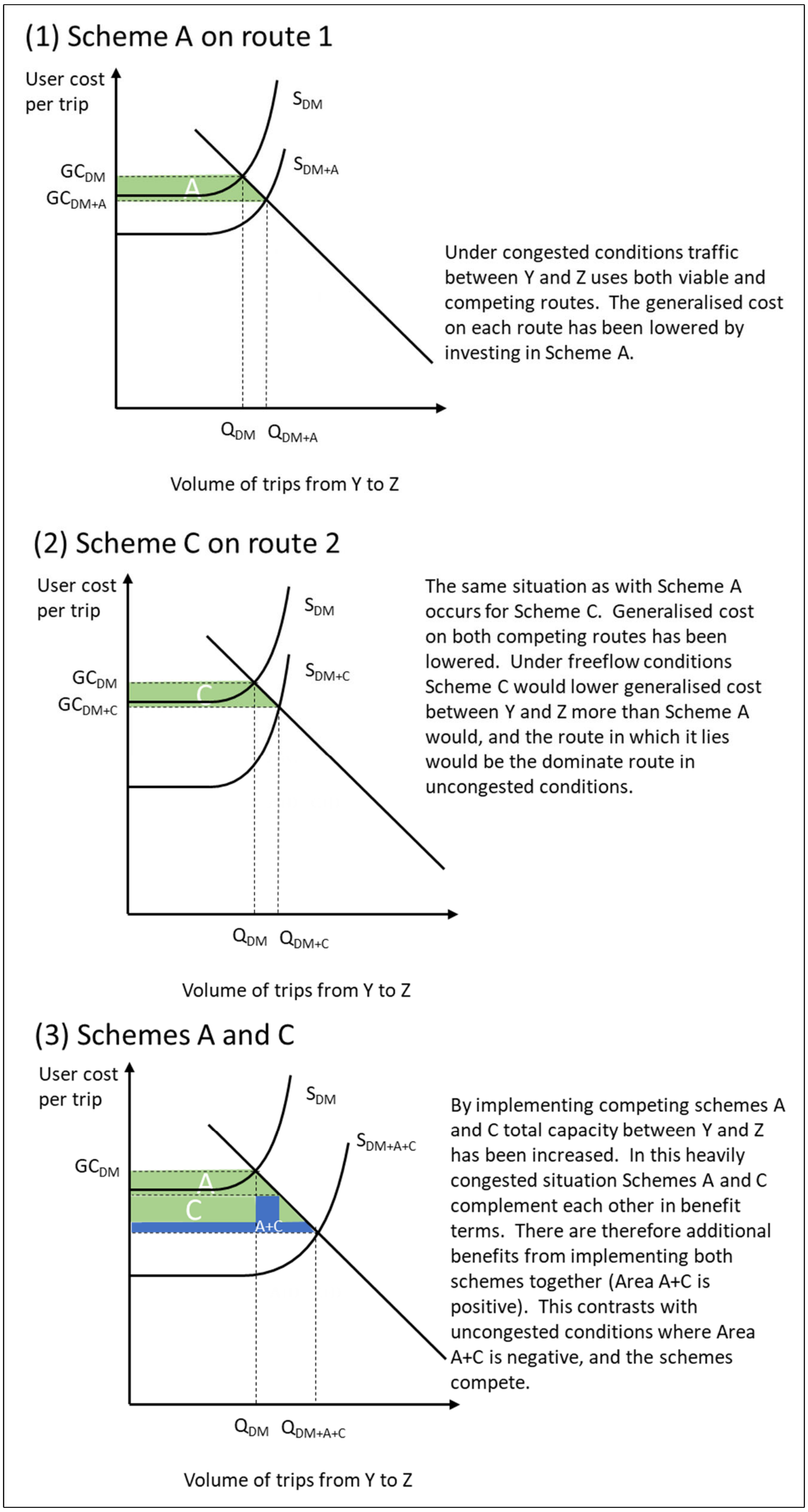
Scheme C is on a parallel route to Scheme A and therefore competes with it. Scheme C lowers user costs between Y and Z more than Scheme A does. In isolation it delivers a user benefit equal to Area C.

(3) Schemes A and C



No traffic between Y and Z uses Scheme A, when Scheme C is in place. Therefore there are no additional user benefits for traffic travelling between Y and Z from implementing Scheme A in addition to Scheme C. Here the interdependency benefit (A+C) is exactly equal and opposite in sign to Area A – i.e. it cancels it out.

Figure 21: Consumer surplus from implementing competing schemes in isolation and in a programme in heavily congested conditions



4.6.3 Behavioural responses

We have seen in the above discussion that the interdependency benefits arise as a result of re-routeing and induced traffic, as well as the level of congestion in the network and how the programme of schemes affects congestion. With respect to congestion **Table 5** sets out whether we expect interdependency benefits to be positive and negative depending on scheme type and congestion.

It is important to realise that, in reality, there will be many origins and destinations. Different network conditions will be prevalent on each origin-destination pair. For some origins and destinations two competing schemes may both be viable (bottom right cell of **Table 5**), whilst for other origin-destination pairs the bottom left cell may be relevant. The same would be true for complementary schemes. It may also be the case that for certain origin-destination pairs schemes may be complementary, but for other origin destination pairs schemes may compete. This analysis therefore is aimed at understanding the problem and the results from programmatic appraisal, rather than forming part of the method for programmatic appraisal. It does of course inform the method in that the potential for both negative and positive impacts depending on congestion levels in the Do Minimum and the Do Something may require a degree of testing in how schemes within a programme combine to address network wide problems.

Table 5: Interdependency benefits and congestion

Scheme types (in terms of travel demand)	Sign of interdependency benefits if network is:	
	Uncongested	Congested
Complementary	**Positive**	Positive if congestion is ameliorated Negative if congestion is worsened
Competing	**Negative**	Positive if congestion remains in the Do Something and both routes using either scheme are viable. Negative if sufficient capacity on one route is created such that that route dominates route choice

The relationship between the interdependency benefits and induced traffic also allows offers us an insight into the behavioural responses that drive the interdependency benefits. In essence they are re-routeing behaviour plus the sources of induced traffic: re-distribution, mode choice, trip frequency and land use change. With respect to induced traffic it is generally regarded that this is the order in which they are most relevant: with re-distribution most sensitive and land use change the least sensitive.

The importance of congestion in determining the sign of the interdependency benefits means that if the level of congestion changes during the appraisal period then the sign of the interdependency benefit may switch from positive to negative or vice versa. This is likely to mean that an interdependency assessment is likely to require more than one modelled year unless the network is expected to remain uncongested.

4.7 A Pairwise Heuristic

As discussed earlier, if a programme is well defined and not too large then the number of scheme combinations may well be tractable for a full analysis. However, if the number of projects is large then some heuristics may well be needed. A practical reality of appraisal is that not every scheme combination can be analysed.

The decremental and incremental estimates of scheme benefits are a starting point. The discussion in the previous sections shows how the benefits estimated by incremental and decremental analyses are comprised and how they overlap. It is, however, important to recognise that the incremental and decremental analyses do not in themselves identify the degree of overlap, nor their composition (in terms of the sizes of the areas A+C, etc.).

Pairwise analysis adds to this incremental and decremental analyses by providing an understanding of the specific interactions between schemes. A pairwise analysis gives an estimate of the 2-way interactions, which for our programme would be: A+C, A+D and C+D. The principal advantage of the pairwise analysis is that it gives quantified information on scheme by scheme inter-dependencies that incremental and decremental analyses do not. Haas and Bekhor also find that pairwise analysis is a good heuristic for determining which schemes should be included in a programme.

To estimate the pairwise benefits (e.g. for Schemes A and C the Area A+C) one:

- Obtains estimates of the standalone benefits of A and C (against the Do Minimum), and the benefits of implementing A and C (with whatever phasing has been determined).
- The pairwise benefit (dis-benefit) is then obtained by subtracting the stand alone benefits from the benefits of implementing both A and C.

A pairwise analysis, however, will not always be sufficient to fully understand all significant scheme inter-dependencies in a programme. The analysis in the previous section shows that the pairwise analysis will perform best in uncongested conditions. In heavy congestion and with schemes that either worsen (relative to freeflow speeds) or significantly ameliorate congestion, significant interdependency benefits (both positive and negative) that diverge from the pairwise analysis may occur. This will be highly dependent on the local context and network conditions. The pairwise heuristic should therefore be viewed as a starting point. A comparison with the sum of the pairwise benefits and the incremental and decremental benefits would identify whether further analysis is necessary to understand the scheme inter-dependencies. If it is then an analysis of higher order interdependencies will be needed. Higher order interdependencies arise if the schemes are appraised in either triples or larger combinations.

4.8 Modelling

The two, key value for money metrics used in transport appraisal in the UK are the NPV and the BCR. As discussed in Chapter 2 the broader transport economic literature identifies that to analytically maximise the economic benefit of a programme there is a need to impose a constraint – even if that constraint is that a BCR of 1.0 is required. This is a financial constraint and can either appear as a budget constraint (e.g. £1 billion) or alternatively as an opportunity cost of investing in that transport scheme. For example, if the opportunity cost is forgoing investing in an alternative government funded project that would deliver a BCR of 2, then a minimum BCR to the marginal scheme in the programme needs to be 2. Whilst there is a requirement on Government to consider opportunity costs of public spending, the problem is not specified in this manner in the UK policy/governance context. Instead, the Transport Business Case – the 5-business case approach to Government spending – is adopted. There may be very good reasons that schemes with high BCRs do not progress to construction (a poor management or strategic case for example). Conversely, there may be very good reasons why schemes with low BCRs progress – very good strategic cases for example. Schemes are therefore considered on their own merits, and those with good overall business cases progress.

To an extent this makes the modelling challenge less onerous than that embodied in the literature on the optimal definition of a programme in the discrete Network Design Problem literature. We are not trying to optimise the programme instead we are interested in understanding the inter-dependencies. This will limit the number of modelling scenarios we need, particularly if we restrict the analysis to pairwise interactions between schemes. Even then, and as discussed in section 3.5.1, the number of modelling scenarios rapidly increases as the number of potential schemes within a programme increases. For small programmes the modelling is quite tractable, but it can quite easily reach a level which presents serious resource constraints on the study, and may also become out of proportion to the extra information it provides.

If we wish to undertake decremental and incremental analysis and be able to understand how the benefits associated with interdependencies arise then, ideally, we would like the minimum following information available on scheme benefits:

- Stand alone analysis for our scheme
- Pairwise benefits of our scheme with all other schemes in the programme
- Decremental and incremental analysis of benefits for our scheme

It should be noted, however, this assumes that triple and higher order interactions between schemes are small. Such an assumption would always need testing in the analysis, and is only likely to be relevant if congestion is limited. If congestion is significant then further model runs associated with capturing the higher order interdependencies (triples, quads, etc.) will be necessary.

For limited congestion situations this will require the following model runs if there are *n* scheme in a programme of which the scheme we are appraising is one of those:

- The Do Minimum
- *n* stand alone scheme model runs
- *n-1* pairwise analyses (our scheme of interest paired with each of the other schemes in the programme)
- decremental analysis on our scheme (2 model runs one of which is benefits of all schemes in the programme)
- incremental analysis on our scheme (2 model runs)

The total number of model scenarios therefore would consist of *2n+4*.

For a scheme which forms part of a programme on a route corridor with 8 different sections this would give the need for 20 model scenarios. This is before one considers additional model scenarios associated with low, central and high growth or analysis on the phasing of a programme. Whilst clearly this is not as bad as the 1 million identified in section 3.5.1 (for a programme comprising of 20 schemes) it still represents a lot of analysis.

Our view is that the more information one has the better the appraisal will be. However, not all of this information needs to be at the same level of detail. That is not all of it needs to be a full 60-year appraisal. Focusing on a reduced number of forecast years and a single growth scenario may provide sufficient information to give a sense of the benefits/dis-benefits that will arise from inter-dependencies with other schemes in the programme. It may also be possible to focus on a single time period within this 'cut down' analysis. However, given the manner in which the size and sign of the interdependency benefits are dependent on the level of congestion in a network, and this will vary by growth scenario and time period, it is likely that only in uncongested conditions will it be appropriate to reduce the number of forecast years and growth scenarios analysed.

The scope of the modelling exercise needs to be fit for purpose. One would expect that interdependency benefits will arise due to the manner that the inter-dependent schemes combine to allow behavioural responses that could not previously occur. For road schemes re-routeing will be the largest response. Model areas therefore need to include all viable alternative routes within their study areas. Variable demand modelling methods are also likely to need to be applied, if it is expected that generalised travel cost changes in the study area will be significant. A key element of this may be the need to include supplementary economic modelling if it is expected that the construction of the programme may have a significant impact on land uses and the local/regional economy. This clearly places significant analytical demands on the modelling and consideration will need to be given how to undertake this modelling in a proportionate manner – for example undertaking variable demand modelling and/or supplementary economy modelling for one or two scenarios and using these scenarios to frame the modelling of the other test scenarios.

4.9 Treatment of uncertainty in scheme funding and value for money conclusion criteria

A key issue in developing scheme by scheme business cases is that the benefits arising from inter-dependencies with other schemes are subject to a degree of uncertainty. If the other schemes upon which the benefits are dependent are not constructed, or their final design differs to that originally envisaged, the expected benefits may not appear, or may be less (or more) than anticipated. In line with economic theory and the Green Book, UK transport appraisal guidance is clear that risks must be taken into account: "a final metric used to assess value for money must account for all relevant risks, uncertainties and impacts" (DfT, 2017 p26, Value for Money Framework).

Given the broad nature of the uncertainties that can lead to the development or not of other schemes in the programme it is unrealistic to attempt to place a probability on the likelihood of an inter-dependent scheme being funded, and a (evidence based) qualitative approach, rather than quantitative, is needed. Economic texts (see e.g. Boardman et al, 2011) support this position as they suggest that qualitative assessments of risk are preferred in situations where it is hard to place probabilities.

The Department's current view is that sensitivity analysis to test the impact of key risks and uncertainties should be utilised:

> When a WebTAG-based assessment is undertaken, sensitivity tests on the high and low scenarios of national demand and values of time are required, as set out in WebTAG Unit A1.3.
>
> Further sensitivity tests should be determined on a case-by-case basis in a proportionate manner. For transport proposals, guidance on this is set out in WebTAG Unit M4. This includes:
>
> - identifying the uncertainties underpinning the appraisal and modelling of the proposal;
> - assessing the likelihood of these risks being realised.
>
> *DfT (2017 p16) Value for Money Framework*

Of particular interest is whether the impact of the uncertainties may change the value for money category.

> As discussed in the Value for Money Framework, sensitivity analysis is recommended to test the impact of key risks and uncertainties. To use the results of sensitivity analysis to inform a value for money category, it should first be considered whether any of the sensitivity tests imply a VfM category different from that suggested by the adjusted BCR (using the 'switching value' approach).
>
> *DfT (2017 p13) Value for Money Supplementary Guidance on Categories*

Clearly the benefits that a scheme may derive from inter-dependencies within a programme are subject to a degree of risk and uncertainty. This risk and uncertainty may vary from one scheme and programme to another: from very low to very high. It will be case dependent. There is a method, sensitivity analysis, for the treatment of risk and uncertainty within WebTAG guidance, a method which is consistent both with overarching appraisal guidance in the Green Book and with economic texts (e.g. Boardman et al., 2011). Thus, in our view sensitivity analysis needs to be applied to the benefits that will stem from inter-dependencies between schemes.

A sensitivity analysis for scheme inter-dependencies needs:

- An estimate of the benefit (dis-benefit) that arises from the inter-dependencies; and
- A judgement as to how likely these interdependency benefits (dis-benefits) are to occur.

This sensitivity analysis places a subtly different focus on the analytical work relative to the decremental or incremental tests previously discussed. With the sensitivity analysis, our primary interest is understanding the extra benefits (or dis-benefits) that may occur if other schemes in the programme were also constructed. We therefore need to be able to attribute benefits to particular interactions. This points towards a pairwise analyses as being strongly relevant in the sensitivity testing. The decremental and incremental analyses are good at identifying the impact of a scheme on a programme, but they are less strong at identifying the impact of a programme (or more pertinently schemes within a programme) on a scheme. They are also not particularly useful at unpicking the sources of the interdependency benefits.

To illustrate if our programme consists of Schemes A, C and D, and our interest is in the appraisal of Scheme A and making a judgement on its value for money category, this would suggest we need to understand:

[1] The pairwise interdependency benefits that arise from interactions with scheme C coupled with a judgement on the qualitative likelihood that scheme C will be constructed.

[2] The pairwise interdependency benefits that arise from interactions with scheme D coupled with a judgement on the qualitative likelihood that scheme D will be constructed.

[3] The triple-wise interdependency benefits that arise from interactions with both Scheme C and D coupled with a judgement on the qualitative likelihood that both schemes C and D will be constructed.

TAG Unit M4 gives guidance on a four-level categorisation of the qualitative likelihood of scheme's progressing: near certain, more than likely, reasonably foreseeable and hypothetical. This has been reproduced earlier in **Table 4**.

An issue arises as to how the Do Minimum counter-factual should be defined in the context of programmatic appraisal. Should it include other elements of the programme? The standard approach is that the Do Minimum counterfactual includes all schemes that are firmly committed. Our view is that this principle should be adhered to. If other elements of the programme are firmly committed then the Do Minimum should include them. If, however, final investment decisions have yet to be made on other elements of the programme then any interdependency benefits that occur need to be treated through sensitivity analysis along with other risk items that may affect the judgement on the final value for money of the scheme.

5 Method for Programmatic Appraisal

5.1 Requirement of method

We have shown in this report that interdependencies between schemes, whether positive or negative, create a problem of non-uniqueness of the scheme benefits. The benefits are contingent on what other policy actions do or do not occur. In this section, we make some suggestions about how to think about and structure the appraisal in such situations. These suggestions have been road tested using a case study to see whether they are recognisable and cover the bases, which is reported in the next chapter.

The method needs to be:

- based in economic theory;
- interlink with DfT appraisal practice as embodied in WebTAG;
- be proportionate and recognise the limitations of practical appraisal, as well as embody the concept of proportional appraisal;
- be based on the position that the crucial level for operational decision-making is the scheme level; and
- promote and ensure transparency, objectivity and a holistic approach in the analysis.

5.2 Overview of method

The underlying principle is that the benefits (or dis-benefits) accruing to a scheme, because it forms part of a proposed programme, are treated as an uncertain benefit/dis-benefit. As such, and along with other factors that contribute to uncertainty, they form part of the uncertainty log[47]. The impact of these other programme elements on the benefits of the scheme can be quantified through sensitivity testing. These sensitivity tests, alongside other sensitivity testing and ancillary analysis, feeds into the decision as to what the final value for money of category of the scheme is.

It is essential that all the schemes considered within the auspices of a programmatic appraisal have been defined through a formal option generation process and have been subject to initial sifting – to ensure that they relate to policy needs and that there are ‘no showstoppers’. The relevant TAG guidance is that contained in The Transport Appraisal Process TAG Unit[48]. In the context of

[47] DfT (2017) TAG Unit M4 Forecasting and Uncertainty. May 2017.

[48] DfT (2014) TAG The Transport Appraisal Process. January 2014.

the RIS this option generation and sifting process is embodied in Highways England's route strategies.[49]

There is also a need to consider the opening years of the different schemes within a programme. These opening years need to be realistic. The phasing of a programme will reflect how good the business cases of the different schemes in that programme are.[50] The better the Transport Business Case of a scheme is the more likely it is to open early in the phasing. There is some circularity in the analysis here, as the programmatic appraisal being undertaken here will form part of the Transport Business Case. However, one input to that process is a set of opening years (and therefore scheme sequencing), which may need to be refined at a later stage once further information is available.

The Do Minimum counterfactual only contains firmly committed schemes. If some of the schemes that comprise the programme are firmly committed then these will form part of the Do Minimum. Other schemes within the programme should be considered within the uncertainty log, as should the estimated opening year.

The modelling that is undertaken needs to be fit for purpose, whilst bearing in minds the constraints on proportional appraisal. Sensitivity tests may be based on a reduced number of forecast years and or behavioural responses, but due consideration needs to be given as to whether this will introduce biases into the analysis. The appraisal period needs to start when the first scheme in the programme is anticipated to open, and end 60 years after the last scheme in the programme is expected to open.

Scheme costs are developed for each of the scheme elements and combinations of elements using TAG guidance, whilst the assessment of benefits (i.e. impacts) is also consistent with TAG processes.

The programmatic method is summarised as a six-step process. The starting point in Step 1 is that there should be something to be learned from the strategic context in which a scheme is being developed and its rationale, which will have been worked up at an earlier stage of the process. Step 1 also contains a stop-/go decision as to whether to proceed with a full programmatic appraisal. The six steps are:

[1] Step 1: Assessment of interdependencies, which includes a stop/go decision as to whether to estimate inter-dependency benefits or whether to proceed with a standalone scheme appraisal;

[2] Step 2: Modelling the benefits;

---

49 Analytically the existence of the option generation and initial sifting process is important as in its absence there would be a need to engage in analysis similar to that adopted in the literature on the discrete network design problem with the inherent difficulties that imposes.

50 Alternative metrics for scheme sequencing can be adopted such as maximisation of NPV, however, none of these are holistic in the sense that the Transport Business Case is. The Transport Business Case in addition to taking into account economic metrics, also considers the strategic need and deliverability. In some situations, strategic needs such as it being a core element of a strategy, may take precedence over ranking by economic metrics *ceteris paribus*.

[3] Step 3: Apportionment of net benefit;

[4] Step 4: Scheme costs and net benefit metrics;

[5] Step 5: Assessment of likelihood of net interdependency benefits; and

[6] Step 6: Reporting and value for money conclusion criteria.

We now describe each of these steps in turn.

5.3 Step 1: Assessment of interdependencies

The key outcomes from this stage of the appraisal are:

- An assessment of whether the scheme being appraised has interdependencies with other schemes; and
- If it does, then a judgement as to whether these interdependencies will give rise to significant enough benefits as to warrant further analysis.

The latter decision will be context dependent. Appraisal guidance elsewhere can assist in that decision as for example the TUBA manual recommends increasing the level of analysis to include intermediate years (through a process known as incremental integration) if the expected error in the benefit estimation is greater than 10%[51].

An assessment of inter-dependencies can be both qualitative and quantitative. In the first instance, a qualitative assessment should be made. Part of this must include the rationale for the scheme and the narrative within which the scheme sits. This will be greatly aided by a series of diagnostics of the kind:

[1] Is Scheme A **the** core element in delivering a corridor or regional strategy (i.e. without this scheme the strategy cannot be delivered or is severely prejudiced)?

[2] Is Scheme A an expensive element involving for example significant bridge or tunnel works?

[3] Is Scheme A a peripheral element of the strategy in the sense that the strategy could survive without it?

[4] Is Scheme A one of several schemes which together make up the strategy— it is difficult to say whether it is more integral to the strategy than Schemes B or C?

[5] How strong are the dependencies between A, B and C?

[6] Is the optimal design of Scheme A likely to be contingent on whether or not Schemes B and C happen?

[7] Is the strategy as a whole fully defined or are there elements of development of the relevant network which are uncertain?

[51] DfT (2014 pp11-3, 11-4) TUBA: General Guidance and Advice. January 2014.

It is also important to realise that how schemes interact with each other will be dependent on the level of congestion (see Section 4.6) that is present in the network – and as a consequence the level of wide area re-routeing that will occur. Empirical work suggests that up or downstream congestion[52] effects can have a strong role in determining scheme interdependency.

In answering these questions, the advice provided in the DfT's draft of package appraisal guidance remains pertinent.

> Practitioners may want to consider developing a matrix setting out the nature of the dependency between different projects in the package. The form of the dependency could be categorised as follows:
>
> - **Costs in construction:** the nature of this relationship can be either negative or positive. In some cases, project promoters may benefit from taking forward more than one project at a time e.g. benefit from economies of scale. In other situations, they may find that there are resource constraints, particularly for specialised skills, to taking forward a number of projects at the same time. This may feed through into higher costs or delays in project opening.
> - **Physical dependency:** projects may be physically dependant on other projects to ensure that the planned outputs can be delivered. For example, the reorganisation of a bus network may be reliant on new bus interchanges being built.
> - **Complementarity:** taking forward some projects may increase the benefits to others (and vice versa) e.g. investment in public transport smartcards may increase the benefits from enhancing a particular bus route. Projects can be complementary not just through an impact on benefits but on costs too. For example, the running costs of enhancing active traffic management may be significantly reduced if a road charging project is implemented at the same time.
> - **Funding (including third party contributions):** projects may be required to deliver funding for capital investment (e.g. from third parties) or to ensure that any revenue costs are sustainable on a long-term basis. Road-pricing and workplace parking levies are examples of this although they will often deliver benefits in their own right.
> - **Substitutes:** sometimes there will be projects within a package that could be viewed as in competition with each other. This does not necessarily indicate that the package has been poorly designed, e.g. it may reflect a varied approach to increasing capacity on a network within certain constraints or it might

[52] Up or downstream congestion can be caused by a scheme generating traffic. This generated traffic then causes congestion problems elsewhere in the network.

reflect distributional considerations with different interventions addressing the needs of specific communities.

DfT (2009 unpublished) Draft TAG Unit 3.X.X Package Appraisal

A dependency matrix will also assist this discussion. **Table 6** presents a dependency matrix for our hypothetical complementary road Schemes A, C and D which form part of a route corridor improvement. It is useful to read this matrix in parallel with an understanding of the uncertainty log associated with each scheme in the programme (see Step 5 of this method). Our interest is in the appraisal of Scheme A. The bottom left half of the matrix has been left empty as, in this instance, the dependency matrix is symmetrical. It will not always be the case that dependency matrices will be symmetrical (see for example the example presented earlier in **Table 2**). Within the programme is a Scheme E which has negligible inter-dependencies with other schemes in the programme. We can also see a Scheme Z (which is in a different programme) that competes with Scheme A. Therefore, whilst Scheme Z is not in the route corridor programme it appears in the dependency matrix.

Table 6: Example of matrix of dependency between schemes

	Scheme A (e.g. Bypass around small market town)	Scheme C (improvement along route)	Scheme D	Scheme E	Scheme Z (e.g. road capacity increases within the town bypassed by Scheme A)
Scheme A		Located in the same route corridor, increasing the attractiveness of the corridor for strategic movements.	Located in the same route corridor, increasing the attractiveness of the corridor for strategic movements.	Negligible	Reduces the level of traffic using Scheme A
Scheme C			Adjacent to each other, making the route corridor more attractive	Negligible	Negligible
Scheme D				Negligible	Negligible
Scheme E					Negligible
Scheme Z					

Note: Bottom left half of the matrix is empty as in this hypothetical context the matrix is symmetrical.

For road investment projects, it is likely that the complementary and competing aspects of dependency will be most relevant. In part, this is because shared costs in construction, physical dependency and funding are often associated with public transport investments. However, one can envisage situations where there may exist some economies of scale in construction (e.g. associated with tunnelling or bridges) in which there may exist diminishing marginal costs to providing extra capacity.

It is likely that the scheme being appraised will already be grouped with other schemes to form a programme – even in only an outline form of different options. This grouping maybe for institutional reasons, for example associated with delivery or for the management of the transport network, rather than just because the benefits of the scheme will be affected by other schemes in the programme. Conversely there may be schemes in other programmes that will impact on the scheme that is being appraised. For example, in the context of road investment programmes being grouped by route corridor, one could envisage a situation where route corridors can compete (act as substitutes for) or complement each other. In assessing interdependencies, it is therefore necessary to look beyond just the programme (e.g. corridor) in which the scheme is placed.

With the interdependencies thus identified the next decision which forms part of this first stage is to decide whether a full programmatic appraisal is likely to materially change the scheme's appraisal results. Whilst clearly the knowledge of experts will be valuable in this regard some quantitative analysis can be very informative. In particular, for complementary schemes, a decremental analysis of the scheme in question will identify an upper bound to the 'programme level' benefits that can be attributed to the scheme.

With reference to our earlier hypothetical example of a programme comprising Schemes A, C and D the decremental analysis for Scheme A is illustrated in **Figure 9**. In that figure Area A is the benefit that would be delivered if no other elements of the programme were delivered, Area A^D is the benefit that would be lost if the programme was implemented without Scheme A, and Area A^{D}' is the benefit that can be attributed to the interactions between Scheme A and other elements of the programme.

If Area A^{D}' is significant relative to Area A then a programmatic appraisal might be expected to add value. TUBA guidance, as already mentioned, implies that errors of less than 10% can be tolerated. This would suggest that if A^{D}' is greater than 10% of Area A a programmatic appraisal should be considered. However, this is clearly a judgemental decision, and the decision to undertake a programmatic appraisal needs to be made on a case by case basis. Part of which has to consider the level of analysis that is needed to undertake the programmatic appraisal, and whether that is proportionate to the scale of the scheme being considered. In some instances, a programmatic appraisal might be quite straightforward and should proceed even if the upper bound on expected benefits is less than 10%, and in other instances it may be quite complex and therefore a decision might be taken not to undertake a detailed analysis even if expected benefits may be more than 10%.

5.4 Step 2: Modelling approach

5.4.1 Interaction between schemes and the role of congestion

Once it has been decided to proceed with a programmatic appraisal the focus of the analysis shifts to the interactions of the scheme being appraised with other schemes within the programme, or in other programmes, with which it has inter-dependencies.

For our hypothetical example this shift represents focusing on the row of the dependency matrix with Scheme A in it. This is reproduced in **Table 7**, we also in **Table 8** re-present an earlier table depicting how inter-dependency benefits can be either positive or negative depending on whether schemes are complementary or competing and whether or not congestion is present in the network.

Table 7: Scheme A and its inter-dependencies

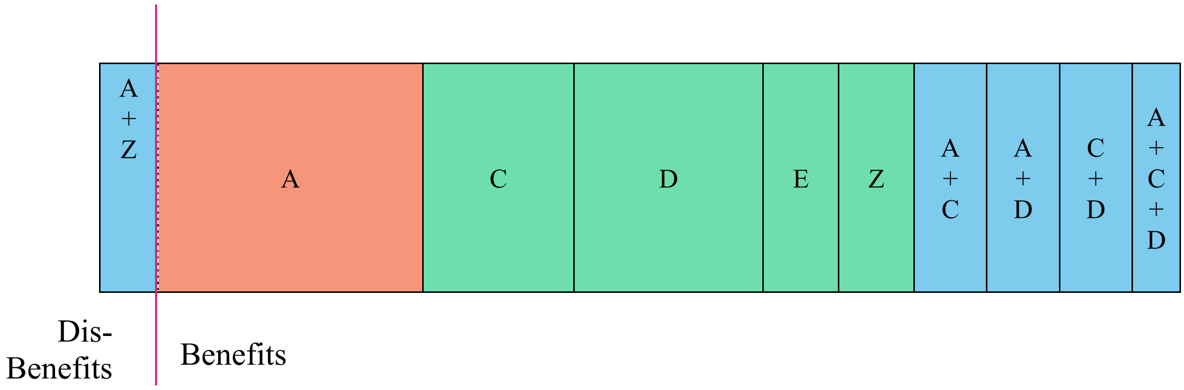
	Scheme A (e.g. Bypass around small market town)	Scheme C (improvement along route	Scheme D	Scheme E	Scheme Z (e.g. road capacity increases within the town bypassed by Scheme A)
Scheme A		Located in the same route corridor, increasing the attractiveness of the corridor for strategic movements.	Located in the same route corridor, increasing the attractiveness of the corridor for strategic movements.	Negligible	Reduces the level of traffic using Scheme A

Table 8: Interdependency benefits and congestion

Scheme types	Sign of interdependency benefits if network is:	
	Uncongested	Congested
Complementary	**Positive**	Positive if congestion is ameliorated Negative if congestion is worsened
Competing	**Negative**	Positive if congestion remains in the Do Something and both routes using either scheme are viable. Negative if sufficient capacity on one route is created such that that route dominates route choice

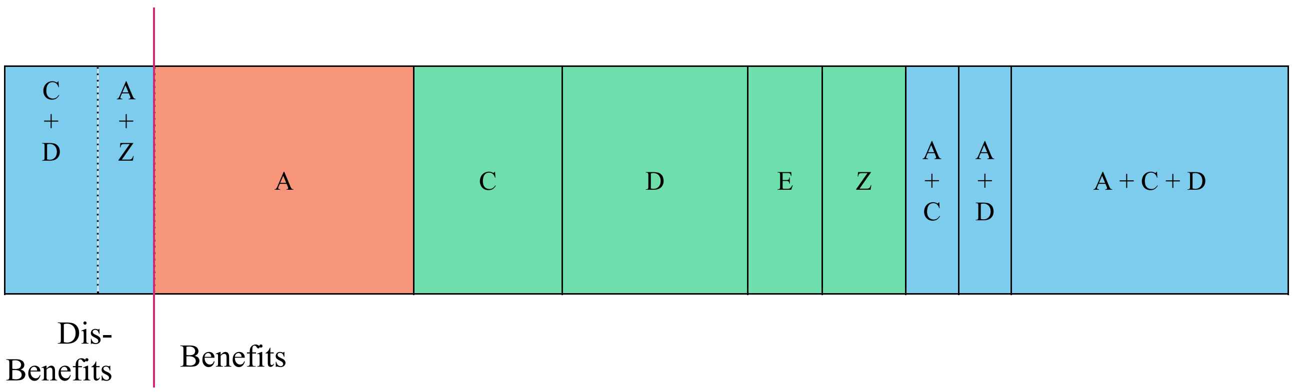
Error! Not a valid bookmark self-reference. depicts the benefits from a programme of complementary schemes which compete with a scheme Z in a different programme and how those benefits are comprised if the network is uncongested. In contrast **Figure 23** shows a congested situation. Here for the same overall programme benefits[53] the construction of pairs of schemes reduces the inter-dependency benefit vis a vis the uncongested situation, or even turns them negative in the case of schemes C and D. The construction of the third scheme in the corridor alleviates all up or downstream congestion in the corridor delivering large triple-wise benefits (A+C+D).

Figure 22: Benefits from Programme with Schemes A, C, D and E including interactions with Scheme Z from a different programme in an uncongested network



Note: Scheme E's interdependency benefits/dis-benefits with other schemes in the programme is negligible and therefore does not feature. Interdependency benefits/dis-benefits between Scheme Z and Schemes C and D are also negligible and do not feature.

Figure 23: Benefits from Programme with Schemes A, C, D and E including interactions with Scheme Z from a different programme when the route corridor in which A, C and D lie is heavily congested.



Note: Scheme E's interdependency benefits/dis-benefits with other schemes in the programme is negligible and therefore does not feature. Interdependency benefits/dis-benefits between Scheme Z and Schemes C and D are also negligible and do not feature.

[53] The sum of the positives and negative inter-dependencies in **Figure 22** and **Figure 23** come to the same total.

5.4.2 Strategic Appraisal

Assessing the impact of other schemes on the benefit of the scheme being appraised is going to place certain demands on the modelling framework.

- The model study area needs to be able to identify wide area re-routeing at a strategic level.
- If cost changes are large the model needs to be able to forecast changes in demand.
- If the expected change to the network is expected to be 'transformational' then some land use of economy modelling is likely to be necessary.

These modelling needs, if accommodated, are often accommodated in a strategic type model. This has the advantage that the programme as a whole and the scheme elements which comprise it could be tested on a single test bed. However, this may then mean that some of the scheme details and impacts cannot be accurately modelled. This might particularly be the case if capacity is currently or expected to be exceeded in one of the counterfactuals – e.g. at grade road junction capacities are exceeded in some future year. In this situation it is important to distinguish between the modelling required for an appraisal of the scheme of interest as a standalone appraisal and the modelling required for the sensitivity tests associated with the risk analysis, that analyse how the benefits of the scheme may change it is included in a larger programme. The core appraisal of the scheme should be based around the best model suitable for that task, which may differ from a, potentially, more strategic model that is needed to assess the sensitivity of the benefits to other elements of the programme.

The DfT's draft guidance on package appraisal contains some useful guidance on modelling which remains very relevant:

> The overarching requirement for all models are that they are fit-for-purpose. In most cases, packages will include investment in more than one mode and/or spread over a fairly wide geographical area. The modelling approach taken will need to be sufficiently flexible so that impacts can be analysed at both a local level (to facilitate standalone appraisal) and at the scale of the package. This is likely to require:
>
> - The model(s) will need to be able to represent a number of different transport interventions and robustly capture the impact of these on all modes and adequately segment demand by time of day and trip purpose.
> - It may not be possible or practical to capture all impacts within the core modelling system. Where appraisal/demand modelling takes place outside of the core modelling system then the appraisal will need to demonstrate a clear and robust procedure for ensuring that the key interactions between projects have been captured. The most significant interactions in most studies is likely to be demand but there may be others e.g. sensitivity of demand to changes in generalised

> cost may vary as a result of what other projects are included in the package.
>
> Where more than one model is being used, either as a result of tiered modelling approaches or a mix of strategic models and more detailed models, care should be taken to maximise the degree of consistency between these models. WebTAG unit 3.12.2 section 6 sets out the requirements for tiered modelling system. The literature also contains an example of the application of tiered modelling to Manchester. The following advice mainly relates to the use of other models in the package appraisal process.
>
> *DfT (2009 unpublished) Draft TAG Unit 3.X.X Package Appraisal*

5.4.3 Reducing the Modelling Effort

As discussed in Section 4.6, ideally, we would like the following information available on scheme benefits:

- Stand alone analysis for the scheme being appraised;
- Pairwise benefits of our scheme with all other schemes in the programme; and
- Decremental and incremental analysis of benefits for our scheme.

For a programme comprising of *n* schemes this requires *2n+3* modelled scenarios. Even for small programmes such as our hypothetical example in **Table 7**, which includes 4 schemes (Schemes A, C, D and Z) which interact, this would give a set of eleven modelled scenarios per growth scenario. For three-growth scenarios this would mean thirty-three model scenarios. If Scheme A were a particularly large scheme that warranted a lot of appraisal analysis, undertaking all this modelling work might be considered proportionate. However, in cases where it is not than the modelling effort could be reduced by:

- Focusing on 1 forecast year if the network is uncongested;
- Using the central growth scenario if the network is uncongested; and
- Grouping schemes together into sub-programmes.

However, given the manner in which the size and sign of the interdependency benefits are dependent on the level of congestion in a network, and this will vary by growth scenario and time period, it is likely that only in relatively uncongested conditions will it be appropriate to reduce the number of forecast years and growth scenarios analysed. For networks in which congestion is prevalent the main mechanism to reduce the number of modelling scenarios will be grouping schemes together into sub-programmes.

In designing these sub-programmes once again the advice provided in the DfT's draft of package appraisal guidance is pertinent.

> The design of sub-packages needs to be carefully thought through and should be guided by the practitioner's understanding of the interactions between projects and the practicalities imposed by the

modelling approach adopted. The following points should be considered:

- If different types of models are used for the project tests (either incremental or decremental) and for the package/sub-package tests, then grouping projects according to the models used can be useful in reducing any bias associated with different models. For example, if a fixed-demand matrix public transport model is used, there may be adjustments required to reflect variable demand responses (e.g. transfer from car). In these cases, the results of these appraisals can be controlled to a sub-package appraisal using a variable demand model.
- Projects contained within a sub-package should be of roughly similar size. No project should account for more than about 30% of the benefits (unless it is to be tested in isolation).
- If complementary projects are placed in different sub-packages, then decremental tests on sub-packages will tend to show a larger gap in benefits compared with the whole package than if complementary projects are placed in the same sub-package. Where there is a degree of substitution between projects (e.g. a new bus route and a tram extension serving a similar catchment area) then the reverse is true. Ideally, projects with strong complementary links should be placed in the same sub-package. Projects with substitution effects may be tested in different combinations of sub-packages.
- Where a project is heavily dependent on another project in the package these should be placed in the same sub-package. Such instances are likely to arise where one project is dependent on another to function fully. For example, if a second city centre tram alignment is required to accommodate more multiple tram extensions they should be grouped together into a sub-package.

DfT (2009 unpublished) Draft TAG Unit 3.X.X Package Appraisal

In addition to these one might also consider grouping projects with similar likelihoods of proceeding together. Such a grouping would assist in the risk analysis.

Through a careful reduction in the number of scenarios being analysed the analysis should become more manageable without overtly compromising the integrity of the results. Effectively these modelled scenarios constitute a form of Alternative Scenario as described in the WebTAG guidance on the treatment of uncertainty[47]. As discussed in that guidance Alternative Scenarios should be subject to a full appraisal and reported. In the context of programmatic appraisal where different scenarios, a full appraisal is considered to be ensuring there exists a holistic approach to scheme impacts (see Step 3 below) even if not all modelled years are analysed. Results might then be scaled to 60-year present values based on some prior analysis.

5.4.4 Congestion and pairwise benefits

Pairwise benefits are a good indicator of total inter-dependency benefits when networks are uncongested. At high levels of congestion they are not. It is recommended that in the first instance the modelling considers pairwise benefits and decremental and incremental analysis only. If the results are indicating that the pairwise benefits are not good indicators of total interdependency benefits (see Step 3 below regarding how to compare decremental and incremental benefits against the pairwise) then it will be necessary to do further analytical work to build up a fuller picture of the role of higher order inter-dependency benefits (triples, quads, etc.). Congestion is likely to be playing a key role and an understanding of the congestion hotspots in the network (and whether they are within the scheme area or up or downstream) is likely to be an important diagnostic.

The output from this step will be pairwise analysis, standalone analysis and any higher order analysis (should congestion be relevant) for each scheme (or sub-programme) plus decremental and incremental for the scheme being appraised.

5.5 Step 3: Apportionment of benefit

The central tenet to the programmatic appraisal is that the most certain benefits from constructing the scheme being appraised are those from the scheme being constructed in isolation. These are the stand-alone benefits. Benefits and dis-benefits arising from inter-dependencies with other elements of the programme are treated as having a higher degree of uncertainty associated with them.

Benefits are attributed by comparing the Do Something scenarios against a Do Minimum scenario. Firm guidance on the definition of a Do Minimum scenario is provided in WebTAG[47]. This guidance indicates that only schemes that are 'near certain' to occur should definitely be included in the 'core scenario'. Schemes which are 'more than likely' might be considered for being in the core scenario, whilst schemes which are 'reasonably foreseeable' or are 'hypothetical' should be excluded from the core scenario.

In a programmatic appraisal context, the different schemes that make up a programme should be categorised in this context: more than likely, reasonably foreseeable and hypothetical. A clear justification for the categorisation and for including schemes from the programme in the Do Minimum that have been categorised as 'more than likely' should be made. Usually only schemes that are classed as 'near certain' will be in the Do Minimum.

By now comparing our model outputs from Step 2 between the different scenarios we can then derive benefits associated with:

- The appraised scheme in isolation;
- The pairwise interdependency benefit (dis-benefit) with each other scheme (or sub-programme of schemes) in the programme;

- The interdependency benefit from interactions between three or more schemes (or sub-programmes of schemes). This can be estimated by subtracting the benefit from the sum of the scheme in isolation plus the pairwise interactions from the decremental benefit.

This can be illustrated with our hypothetical example set out in **Table 7** and **Figure 22**. Here the Do Minimum does not contain any of schemes C, D or Z. None of them are sufficiently certain to proceed to be included in the Do Minimum. The sequencing of the schemes is Scheme D first, then our scheme of interest Scheme A, then Scheme Z and Scheme C simultaneously. This sequencing is based on the Transport Business Cases of the schemes. From our model runs we then obtain:

- The standalone scheme benefit: Area A.
- The incremental benefit of Scheme A. This equals the sum of Areas A and (A+D).
- The decremental benefit of Scheme A. This equals the sum of Areas A, (A+C), (A+D), -(A+Z) and (A+C+D).
- The pairwise benefits between A and the different relevant schemes in the programme:
  - Area A+C; and
  - Area A+Z.
  - Noting that we do not estimate the pairwise benefit between Scheme A and Scheme E, nor between C and Z and D and Z as in Step 1 of the method we considered these inter-dependencies to be negligible. The incremental analysis also gives us the pairwise benefit for Schemes A +D.
- The sum of the benefit associated with higher level interactions:
  - Area A+C+D = Decremental benefit – [A+(A+C)+(A+D)-(A+Z)].
  - Noting that in our example the other higher-level interactions with Scheme C are viewed as negligible: Area A+C+Z and Area A+C+D+Z).

What we wish to achieve is that the model scenarios analysed can explain how the programme level benefits are comprised and attribute these to schemes or combinations of schemes for input to Step 5. For certain network conditions and schemes the pairwise benefits will explain the majority of the interdependency benefits. However, for other networks and programmes it may be found that schemes interact in such a way that they do not. Congestion has an important influence here (see the earlier **Table 5** in Section 4.6) It is therefore important to test how large the higher level interdependency benefits are (that is what the residual term is – by subtracting the pairwise tests from the decremental analysis. If the residual term is found to be significant, consideration should be given to either modelling some of these higher-level interactions explicitly, so as to understand which set of schemes or scheme are driving these benefits, or re-designing the sub-programmes to essentially achieve the same objective.

Finally, it is important that a holistic approach is taken to measuring scheme to scheme (pairwise) interdependency benefits (and dis-benefits). The full benefit measure should include user benefits as well as external costs (safety, carbon, air pollution and noise), as well as wider economic impacts. If non-monetised impacts (e.g. on biodiversity, landscape, townscape and heritage) are also expected to be impacted by synergies between schemes then these should be documented too. An example of this could be a full route corridor improvement that removes more traffic from a built or natural environmentally sensitive area than the sum of the schemes if implemented in isolation. It is worthy of note that this may require a significant amount of analysis.

Having undertaken this apportionment of benefit to the different scheme interactions the analyst is in the position to have a strong understanding of whether the 'interdependency' benefits associated with the scheme being appraised are larger for one scheme in the programme than for others, and if so how much larger. This will then form part of the narrative that supports the overall scheme appraisal, and will also feature in the assessment of risk (in the next step). For our hypothetical programme we can see that the pairwise 'interdependency benefits' are all of a similar magnitude – that is there is no particular scheme between (C, D and Z) that shows more synergies with Scheme A than other schemes, albeit it Scheme Z competes whilst Schemes C and D complement. Noting of course that we consider that Scheme E has negligible synergies with Scheme A.

The output from this step is a set of different benefit measures showing (a) the benefit of implementing the scheme in isolation, (b) the incremental benefit of the scheme within the programme (from the incremental analysis, (c) how the scheme contributes to the whole programme (from the decremental analysis); and (d) how the interdependency benefits can be broken down between the different schemes (or sub-programmes) in the programme. These benefits are contingent on the likelihood of a or some scheme(s) being delivered. The likelihood for this is assessed in Step 5.

5.6 Step 4: Scheme costs and net benefit metrics

For the main scheme scenario and each of the other scenarios modelled, scheme costs need to be developed in line with WebTAG procedures.

For our hypothetical example there is the core scenario (Scheme A as a standalone scheme) and 5 other scenarios.

[1] Scheme A + Scheme D. This scenario is used to capture the incremental analysis and the pairwise analysis of Schemes A and D.

[2] Scheme C + Scheme D + Scheme Z. This scenario is used to capture the decremental benefit of Scheme A.

[3] Scheme A + Scheme C. This scenario is used to capture the pairwise benefit between Scheme A and D.

[4] Scheme A + Scheme Z. This scenario is used to capture the pairwise benefit between Scheme A and Z.

[5] The full programme: Scheme A+Scheme C + Scheme D + Scheme Z
Scheme A.

If there are some cost synergies between schemes, the costs associated with the other scenarios depicted will not just be the sum of the costs of each of the schemes if implemented individually. Our particular interest is whether cost synergies exist. If they do then we adjust the different measures of interdependency benefits from Stage 3 to obtain the net increase in benefits after reflecting cost synergies. As costs form the denominator in the benefit cost ratio, cost synergies will have a different impact on the BCR than additional benefits arising from inter-dependencies. For our hypothetical example, we will assume that no cost synergies exist – that is the cost of implementing more than one scheme in the programme is simply the sum of the respective scheme costs.

It might be the case that scheme costs cannot be identified for some of the schemes within the programme. In which case, it should be assumed that there are no synergies in costs.

The output of this stage of the analysis is firstly a set of scheme costs taking account of any shared costs, and secondly a set of net benefit metrics (these are benefit metrics from step 3 adjusted to reflect if there are any cost savings or conversely cost increases through joint implementation of schemes).

5.7 Step 5: Assessment of the likelihood of net interdependency benefits

In this step of the analysis there is a need to probe the likelihood (or conversely risk) of the interdependency benefits estimated in Step 3 occurring.

This will be a qualitative assessment and would utilise guidance in TAG Unit M4 classifying schemes, where possible, as near certain, more than likely, reasonably foreseeable and hypothetical.

Of particular interest in this step of the programmatic appraisal is whether the majority of the interdependency benefits are derived from projects which have a high likelihood (e.g. categorised as more than likely) of being implemented or a low likelihood (e.g. categorised as hypothetical). As with the treatment of all uncertainty a significant amount of judgement will need to be exercised and the justification for the opinions offered should be documented.

If we look at our hypothetical programme consisting of Schemes A, C, D and E and the potential interaction with a programme containing Scheme Z, we may find that Scheme D whilst not in the Do Minimum is at similar level of design to Scheme A – which we are appraising. The current analysis for it is demonstrating 'Very High' value for money and the opening year is anticipated to be similar to Scheme A. This might be therefore categorised as 'more than likely'. In contrast Scheme C is at a much lower stage of development, there are considerable environmental constraints within the vicinity of the scheme, and early appraisals indicate it falls into a low value for money category. Scheme Z, which forms part of a local authority programme of town centre improvements, is at a very early stage of development with no firm detailed designs. The funding for the scheme is also highly uncertain. Schemes C and Z may therefore be viewed as ‘hypothetical’.

This would be summarised in the uncertainty log as:

- Scheme C: hypothetical
- Scheme D: more than likely
- Scheme Z: hypothetical

We can now categorise the net benefit impacts from Step 5. Returning to our hypothetical example we would expect that the benefit of delivering Scheme A will also include interdependency benefits with Scheme D. The high level of uncertainty associated with Schemes C and Z would imply that the full programme of schemes is unlikely to be delivered – or certainly won’t be delivered in a form or timescale which will impact on the appraisal of Scheme A. This is summarised in **Table 9**.

Table 9: Summary of net benefits and likelihoods

Description of benefit		Classification of likelihood
Net incremental benefit	Area A and Area A+D	More than likely
Net decremental benefit	Areas A and Areas (A+C), (A+D), -(A+Z) and (A+C+D)	Hypothetical
Net pairwise benefit A+C	Area A+C	Hypothetical
Net pairwise benefit A+Z	Area A+Z	Hypothetical
Net higher level synergies	Net decremental benefit – [A+(A+C)+(A+D)-(A+Z)]	Hypothetical

Note pairwise benefit A+D does not appear in the above table as it is the sole determinant of the synergies captured in the incremental benefit.

The output from this step of the analysis is an opinion on the likelihood of the incremental, decremental and different pairwise benefits identified in Step 4 (and higher levels of interaction if analysed) in occurring.

5.8 Step 6: Reporting and Value for Money Conclusion Criteria

The reporting of a programmatic appraisal needs to be closely aligned with that of other aspects of uncertainty. The reporting requirements for this are set out in TAG Unit M4[47].

In addition to this the following should also be reported:

- A narrative describing the programme elements, the context of the scheme within the programme and the inter-dependencies within it;
- A justification for the definition of the Do Minimum as it relates to the programme in which the scheme being appraised sits; and

- A description of the modelling strategy, and if a reduced number of modelled scenarios is being undertake a particular emphasis on how the choice of forecast years and the grouping of schemes into sub-programmes has been made.

In terms of the value for money conclusion criteria, the following should be reported:

[1] The standalone benefit of the scheme. This is the 'core' scenario.

[2] The incremental benefit of the scheme, plus a comment on the likelihood of those benefits being delivered

[3] The decremental benefit of the scheme, plus a comment on the likelihood of those benefits being delivered. For a programme of complementary schemes this would represent the upper bound of the benefits.

[4] For each other scheme in the programme the 'pairwise' and the higher order interdependency benefits that can be attributed to that scheme, plus a comment on the likelihood of those benefits being delivered.

[5] A commentary on whether the inclusion of the 'interdependency' benefits in the analysis could change the value for money category of the scheme,

Items [1] to [4] could be presented in a table similar to **Table 9**.

In addressing point [5] there is a need to be broader in the description than simply setting out the numbers. Here it is important to understand the context of the scheme and its inter-relationship with the programme as a whole. This was analysed in Step 1 of the method.

The way in which the analyst will wish to structure the presentation is context dependent. For example, if the situation is that there is a scheme that is central to the programme, it is important to understand whether the scheme we are appraising (Scheme A) is that central scheme or is one of the more peripheral elements of the programme. If it is the central element of the programme we start with the standalone value of the scheme against the Reference Case. If the business case for this scheme is weak, we know we are dependent on the value of the strategy as a whole, and in this sense the scheme is then dependent on the results of the programmatic appraisal – e.g. as summarised in **Table 10** for our hypothetical example.

Table 10: Programmatic Appraisal Summary table

Scheme	Interdependency description	Sequencing within programme	Opening year	Programmatic appraisal benefit					Reporting of interdependency benefits in other Transport Business Cases
				Description	Interdependency benefits	Scheme cost synergy benefits	Net benefit	Likelihood	
Scheme by scheme synergies within the programme									
Scheme C	Located in the same route corridor, increasing the attractiveness of the corridor for strategic movements.	Post Scheme A	2027	Pairwise A+C	£Xmillion	£0million	£Xmillion	Hypothetical	Business Case has not started.
Scheme D	Located in the same route corridor, increasing the attractiveness of the corridor for strategic movements.	Precedes Scheme A	2020	Pairwise A+D	£Ymillion	£0million	£Ymillion	More than likely	Business case well developed. To be presented to investment board on a similar timeframe to Scheme A
Scheme E	Negligible	Post Scheme A	2032	Pairwise A+E	negligible	£0million	negligible	n/a	Business Case has not started.
Scheme Z	Reduces the level of traffic using Scheme A	Post Scheme A	2027	Pairwise A+Z	-£Zmillion	£0million	-£Zmillion	Hypothetical	Business Case has not started.
Incremental & Decremental									
Incremental (Schemes A + D vs Scheme D)	See above for each scheme	Precedes Scheme A	2020	Incremental Area A^{I}	£Vmillion	£0million	£Vmillion	More than likely	Business case for Scheme D is well developed. To be presented to investment board on a similar timeframe to Scheme A
Decremental (Schemes D, E & Z vs all schemes)	See above for each scheme	Precede and post Scheme A	2020 to 2032	Decremental Area A^{D}	£Wmillion	£0million	£Wmillion	Hypothetical	Business Case for D is well developed, that of Schemes C, E and Z had not started

If the scheme we are appraising is not the core element of the strategy, but is rather an add-on to the core element, it may be the case that it is unlikely to make strategic sense in isolation. It will need to depend on its standalone benefits if it is to proceed independently of A. It is especially important to be clear about this if the timing of scheme development is that this scheme would proceed in advance of the core scheme in the programme. The incremental analysis is therefore critical to the decision-making in this context. Whilst all the Alternative Scenarios need to be considered in the judgement of the final value for money category, there is no escape from making a professional judgement about whether proceeding with the scheme is an acceptable risk if its VfM performance is contingent on a different scheme happening subsequently.

If the situation is more akin to where several schemes together make up the strategy and it is difficult to say whether the scheme being appraised is more integral to the strategy than the other schemes in the programme then the pressure is probably less intense. This is because the overall strategy is not critically dependent on one scheme happening.

In a further case suppose it were found in a particular case that the dependencies between schemes were extremely strong. The diagnostic would be that the standalone VfM of each scheme was low but the VfM of all (or most) schemes together was high. In that case we see no alternative to reporting that the key decision is at the level of the strategy and that all schemes would need to be worked up to a point at which the strategic decision could be taken. This might in itself point back towards a different delivery method, where the schemes in question are in fact combined to form a single larger scheme.

An aspect of programmatic appraisal that is distinct from other elements of uncertainty is that the interdependency benefits ([2], [3] and [4] above) may feature in the Transport Business Case for different schemes. This has to be the case. For example, in our hypothetical example the Area A+D is dependent on both Scheme A and Scheme D. Here it is important to maintain objectivity and transparency. This is a matter of governance. We therefore recommend that not only are the pairwise interdependency benefits reported, but **it is also documented as to whether these benefits have already appeared in previous schemes' Transport Business Cases, or are also appearing or are about to appear in other schemes' Transport Business Cases.** For our hypothetical programme, this is illustrated in **Table 10**.

6 Case Study

This chapter focusses on the challenges of undertaking a programmatic appraisal using a specific case study and the lessons to be learned.

6.1 Case Study description and interpretation

The case study was of a corridor in the UK where there are both a series of projects proposed along the corridor and improvements proposed for routes elsewhere in the corridor but not on the line of route. This seemed a good test bed, since we would expect to find a variety of relevant schemes in a study area, some closely related to the scheme of interest, some less closely related.

The first lesson learned was that in this case, the number of individual projects in the study area was too large for a full analysis of all combinations to be tractable. So individual projects were combined together into five packages (A, B, C, D and E) for comparison with the Do-Minimum. The design standards, alignments etc of each of the packages was taken as given.

The modelling tool used was an existing Strategic Model of a wide area within which the corridor fitted. Effects outside the model area are probably small. Only the results from the strategic model were used; in some real-life cases, the issue of how to interface the strategic model results with local model outputs would arise.

The model was of variable demand form. Trip lengths were variable with generalised cost but trip numbers were assumed fixed. Modal choice was variable but in practice modal shift was only small relative to total traffic in this corridor. The main drivers of the results were wide-area reassignment between routes and changes in the trip length distribution. Overall travel demand was relatively elastic in this corridor and this feature will have conditioned the results to some extent. A fixed matrix version of the model was run to provide model QA and to aid interpretation of the results, but only the variable demand results were used in the subsequent analysis.

In this corridor, there was no one scheme which could be considered to be the lynchpin on which all else depended. So, it is reasonable to view packages A, B, C, D and E as having independent rationale but with some interdependency relationships between them. Three of the packages, A, B and C were laid out along the corridor while D and E were tangential to the corridor on a different major route within the study area.

The prior expectation was that A, B and C would be complementary with each other, so interdependence benefits would likely be positive, while D and E would probably be somewhat competitive with A, B and C by drawing off traffic through strategic reassignment. The analysis was configured with that expectation in mind. It was not possible in the case study to run the model exhaustively for all combinations; actually, fourteen model runs of various combinations of A, B, C, D and E were undertaken, including the Do-Minimum. It is useful to split the interpretation so as first to consider the schemes in the corridor (A, B and C) and then to add D and E where there is more complexity. Scheme C is taken as the scheme of interest to the decision-making process.

The analysis showed that, as expected, A, B and C are quite strongly complementary. Considering the PVB of scheme C against the Do-Minimum as 100, then the PVB of scheme C against the Do-Min plus schemes A and B is 154. So, from this case study, a lesson is that interdependency effects can be material in the sense that they could affect the VfM category of scheme C, contingent on whether A and B are, or are not, assumed to be in the network. We also found that the pairwise heuristic (Do Min plus A plus C versus Do Min plus A and Do Min plus B plus C versus Do Min plus B) was a good predictor of the total interdependency benefit (Do Min plus A plus B plus C versus Do Min plus A plus B). So, along the corridor the results were quite well-behaved and understandable.

Turning now to schemes D and E which were expected to be somewhat competitive with A, B and C (i.e. have negative interdependency impact on scheme C), this pattern was indeed borne out for the early years of the appraisal period. However, beyond around 2040, increasing congestion on the network as a whole changed the pattern of assignment so that schemes D and E became complementary with C in the latter half of the appraisal period. So, another lesson learned is that relationships between schemes may reverse during the appraisal period, suggesting the need for analysis of single years as well as the aggregate over the period. It may not always be obvious what will turn out to be complementary and what competitive.

The pairwise results for C with A and B individually and incremental assessments of C with A and B together indicate a substantial interdependency benefit of 13%, 42% and 54% respectively showing strong complementarity (where the percentage is additional benefit over the stand-alone benefit). The decremental benefit of Scheme C, that is the interdependency benefits arising from adding Scheme C to a package of Scheme A, B, D and E, of just 23% shows the potential substitutability of benefits between schemes that arise if Schemes D and E proceed as well.

Partly because of the unexpected, a further conclusion is that the programme analysis work might need to be configured in stages--- an initial analysis to establish the key relationships and a further analysis to investigate the key relationships more deeply. Ideally, we would have done more work to explain the interactions between the schemes in the corridor and schemes D and E and would recommend further follow up work on this if possible.

There are a number of ways in which a Programmatic Appraisal Summary Table could be devised. From the Case Study, the relevant incremental and decremental values of a project within a programme could be presented. This would then provide the materiality aspect of the picture. A vital input to the decision process would then be the likelihood of various scenarios occurring (e.g. schemes A and B being implemented or not). We have provided for entries on this uncertainty aspect in the Table but have not devoted significant energy in determining the likelihood of the different schemes progressing through any form of qualitative analysis. It has been taken that Schemes A and B are 'reasonably foreseeable' and Schemes D and E are 'hypothetical'.

Based on the uncertainty level ascribed to the schemes, the pairwise, incremental and decremental assessments provide an interesting narrative for the Scheme C's scale of benefit. The likelihood levels suggest that Schemes A and B have a greater likelihood of proceeding than Schemes D and E. Given the 'hypothetical' nature of Schemes D and E, the assessment provides an opportunity to shape how these schemes proceed in the future. A re-design of these schemes may improve the overall performance of a full programme. That is, Scheme C is likely to generate significant interdependency benefits.

Given the relative likelihood of Schemes A, B, D and E, the assessment should provide some comfort that the more likely outcome is for a more significant complementary benefit to occur with the more likely schemes.

6.2 Modelling Challenges

Given a key consideration of the proposed methodology was creating a practical number of scenarios to test, it's important to acknowledge the range of challenges that the programmatic tests can present to modelling teams. The following section outlines a number of these. Some of these are relevant to a modelling practitioner applying the methodology, while others are worth noting in the context of this research study.

Variability of results between years and full appraisal period

Benefits for each scenario within 2026 and 2041 are broadly similar with the 60-year appraisal benefits generally being around 54 times greater than those for a single year. The interdependencies between schemes however, does differ between 2026 and 2041, due to the levels of congestion in each scenario and the levels of induced demand along the corridor. Schemes B and E compete with scheme C in 2026, however in 2041 these are considered complementary and scheme A is considered a competing scheme. At the 60-year appraisal level, all 4 schemes are complementary to C in the VDM assessment.

These results indicate that a single year is not wholly representative of the 60-year appraisal which should account for changes over time. This is likely to vary by geography, scheme and forecast level of congestion. As such it is recommended that a full 60-year appraisal is mandated but clear evidence for not doing this should be provided by practitioners if choosing a single year only. A design year focus for the programme would be preferable than an opening year as the uncertainty will be greater and the operation of the programme is likely to be more complex further in the future.

Setting up model runs for years / scenarios already established within a modelling framework is relatively trivial. The additional analytical time to review scenarios is the key factor driving the modelling timelines alongside the additional model run and 'skimming' time to extract travel costs to drive the economic appraisal. In addition, where new scenarios are run that test the model in a different manner to that under traditional scenarios (i.e. Do Min and the principle scheme tests), there are risks that additional tests cause local instability issues that require some review or adjustment. For a given scenario, the time taken to generate an estimate of the economic benefit, using software such as TUBA, may be a matter of a few hours. This will increase to accommodate additional modelled years although the time scales are not considered to be excessive.

Suitability of the scenarios

The scenarios that have been tested as part of this case study have provided a good sense of the interdependency benefits of C with the other four schemes individually. However, the modelling indicates that there are higher order interdependency benefits which are beyond what has been tested for this case study which result in a negative impact on the programme. The difference in the incremental and decremental dependencies show that at least one of D and E provides a negative impact on the programme when A and B are already delivered.

As part of additional analysis undertaken to support the case study, further scenarios were explored beyond what was initially suggested by the application of the methodology. These scenarios were designed to more exhaustively test the higher order interdependency.

The additional scenarios helped to demonstrate the potential for higher order effects to create a tipping point at which interdependencies may change through the introduction of one or more schemes. The initial methodology helped to isolate the potential schemes in question, and that combined with the existence or not of high levels of congestion in the area of interest does provide a practitioner with a direction to identify potential higher order combinations that would help to inform decision makers on potentially strong or poor scheme combinations.

The quantification of specific combinatory benefits (e.g. the interdependency benefits of A+B+C+D over and above the interdependencies of each of the component pairs or triples) at the higher order, requires significantly more scenarios to be considered, whilst this is interesting as part of the research, practitioners would really only need to consider the specific scenarios where the scale of interdependency benefits may be eroded, such as when less certain (or well understood) proposals are added.

Choice of model for assessing the inter-dependencies

The transport model adopted for this study was of a regional scale and as such was not validated locally for the main scheme. Whilst this was deemed appropriate to cover the geographical coverage of schemes forming the programme, it was noted that specific local impacts, e.g. at junctions between minor and major roads were not incorporated. Typically, for assessing a specific scheme, a 'local' model is developed to focus on the interactions relevant to the scheme in question.

Dependent on the scale of the programme, it is not practical nor reasonable to develop a detailed, validated model to cover a programme across a region. There is consequently a risk that benefits are underrepresented in a coarser regional model. This leads to an obvious question about appropriate scoping and specification of a model for a specific scheme assessment, and, the extent that programmatic effects are likely to be essential as part of the appraisal process.

Use of VDM and model noise

Running VDM for the transport model adopted took approximately 24 hours. Of the 14 runs undertaken to support the application of the methodology, 2 of these would have been run as part of the standalone assessment irrespective of the need for a programmatic appraisal. The other 12 runs required around a week of model run time followed by another week of processing and analysis. Whilst a two-week turnaround for this type of analysis seems reasonable, there are inevitable issues with running a model for new scenarios where responses may identify issues within the model that need resolution (e.g. coding errors).

Due to the combination of schemes and the scale of the region in question, model noise became a problem requiring masking of some movements. A majority of these effects were known issues to the model custodians, while some additional issues were identified that required additional review and some scenarios rerun. Model convergence became a more significant issue for some of the design year runs, particularly where more subtle differences between combinations of scenarios were undertaken. In some instances, stability criteria were more challenging to meet for scenarios which tested the model in a manner not previously considered.

Incorporation of a programmatic appraisal to an appraisal phase of a scheme is likely to add additional delivery risk given these issues.

6.3 Practitioner Overview

This section contains a practitioner overview of the practicality of implementing the 6-step methodology, drawing on the findings of the Case Study.

For reference, the 6-steps are:

- Step 1 – Assessment of inter-dependencies;
- Step 2 – Modelling the benefits;
- Step 3 – Apportionment of net benefit;
- Step 4 – Scheme costs and net benefit metrics;
- Step 5 – Assessment of likelihood of net interdependency benefits; and
- Step 6 – Reporting and value for money conclusion criteria.

Step 1 – Assessment of inter-dependencies

The initial assessment of the inter-dependencies was an important first step to generate a practical number of runs. In practice, there were over 10 schemes considered as part of the programme that were grouped into a sensible number of sub programmes. The consideration of the likely pairwise relationship of the main scheme with those within the programme provides a simple yet logical approach to assessing the likely inter dependency.

Subsequent to the initial application of the methodology, it was considered that additional simplification of the scenarios could have been undertaken. Potentially grouping schemes A and B in particular. The rationale being that both schemes were considered more certain than D and E but also considered likely to be fully complementary. This should be considered by practitioners to try to help minimise the number of combinations.

Step 2 – Modelling the benefits

A detailed discussion of the modelling challenges was outlined in the previous section. This suggests that on the basis that a proportionate number of programmatic scenarios are generated, the modelling can be completed in a reasonable time frame. The key question is the choice of model for undertaking the assessment. The scale of the programme and likely interdependencies will be a key driver of the choice of model. Ideally, locally calibrated models, where good definition in the network and demand around the schemes in the programme, should be adopted, but where this is not available, regional scale models maybe more appropriate for the testing.

As part of the case study, we have not considered how the standalone scheme C assessment would change based on use of a locally calibrated model. It is likely that the increase in modelled interactions would lead to a high estimate of PVB compared with the use of the regional scale model and how to relate the programmatic uplift is an important consideration as part of the appraisal.

Step 3 – Apportionment of net benefit

Apportioning the interdependency benefit was straightforward given the methodology. The pairwise, incremental and decremental tests help to shape additional context to the scheme's economic performance.

Step 4 – Scheme costs and net benefit metrics

This step is meant for programmes that exhibit cost interdependencies, and was not therefore relevant in this case study.

Step 5 – Assessment of likelihood of net interdependency benefits

In this step there is a need to probe the likelihood (or conversely risk) of the interdependency benefits estimated in Step 3 occurring. This is a qualitative assessment and utilising TAG Unit M4, classifying schemes as near certain, more than likely, reasonably foreseeable and hypothetical. Whilst the schemes were classified with different levels of likelihood in this case study, this was not based on any research. In practice the outcome of the programmatic appraisal will be very dependent on this classification and some effort and justification would need to be employed at this stage of the appraisal.

Step 6 – Reporting and value for money conclusion criteria

Based on the outcome of the previous steps of the method, the reporting of the programmatic appraisal in the proposed table and the development of the value for money criteria is quite straightforward.

7 Conclusions

7.1 Summary of Findings

We have set out a six-step method for programmatic appraisal, the first step of which is a decision as to whether to proceed with a full programmatic appraisal or not. This method has been based on a review of the literature and international practice, whilst meshing into the Department's policies and procedures, particularly that set out in TAG Unit M4, and adhering to transport economic principles.

Where interdependencies exist and uncertainty also exists there is no longer a unique value for the expected benefit of any scheme. It is the uncertainty regarding whether a scheme within the programme will go ahead or not that creates this lack of uniqueness. In a committed (i.e. certain) and phased strategy the interdependency benefit is always attributed to the last scheme to be constructed, but in a programmatic appraisal where future elements of a programme are uncertain attribution becomes ambiguous. Where uncertainty exists the interdependency benefit is contingent on both schemes going ahead – it cannot be claimed by both schemes independently or even shared between schemes. This is problematic within a decision making framework that considers each scheme on a case by case basis. It is easier to deal with the combination of interdependencies and uncertainty within an overall strategy appraisal. Though from a decision-makers perspective they may need to be able to make a start on a programme while retaining some flexibility about its future composition – thus uncertainty will always be present even when a programme level appraisal is undertaken.

Where there is interdependency between schemes, as a first step, there is a need for incremental and decremental analysis. The incremental analysis is designed to answer the question: "What is the value for money of scheme A taken in isolation from schemes later in the programme? Does it pass/fail the incremental test?" The decremental analysis is designed to answer the question: "What is the value for money of scheme A if all other schemes are in the network? Does Scheme A pass/fail that test?"

Considering the case of complementarity between schemes, e.g. in a corridor, we expect:

- the decremental value to be greater than the incremental value;
- if the standalone test is passed, the scheme is worthwhile regardless of the related schemes;
- if the standalone test is failed and the decremental test is also failed, the scheme is not worthwhile regardless of the other related schemes; and
- if the standalone test is failed and the decremental test is passed, but the incremental test is failed, the scheme is contingent on the other related schemes that appear later in the programme. Where this is the case, a view

needs to be taken of the likelihood and timing of the other related schemes proceeding.

- Where the interdependence component is very strong, consideration should be given to whether appraisal of the strategy as well as scheme within strategy is required. Where there are interdependency benefits it is difficult to avoid possible undercounting or double counting of the interdependency terms if schemes A,B,C,D and E are appraised separately as schemes within strategy.

Equivalent rules can be stated where schemes are competitive rather than complementary.

When some schemes in the programme are complementary and some are competitive, the rules become more complex, as we have seen in our case study. In this situation the likelihood or not of the other schemes in the programme proceeding becomes essential. In our case study, for example, if the competing schemes D and E that appear late in the programme are unlikely to proceed, whilst the complementary schemes that appear early in the programme are quite likely to proceed, this will have a profound impact on the viability of the scheme vis a vis the opposite scenario. Here the framework in which the results need to be presented is that of the uncertainty analysis contained in TAG Unit M4 (Forecasting and Uncertainty).

In our case study, the interdependency benefits between schemes have been demonstrated to be substantial. Relative to the appraisal of a scheme in isolation, the interdependency benefits can change the absolute TUBA benefit by -12% to +53%. This clearly has the potential to change the value for money category of a scheme by one category and possibly two.

The modelling of all the interactions between schemes adds considerable complexity to the analysis. It is therefore necessary to reduce the modelling burden as far as possible. To this end, a pairwise heuristic can be utilised for uncongested or lightly congested conditions. For more congested conditions we would still recommend starting with pairwise tests and examining how representative they are of total inter-dependency benefits (vis a vis the incremental and decremental tests) before embarking on more model runs. These additional model runs need to be informed by an understanding of how different schemes complement and compete and where congestion is in the network.

Congestion has a strong impact within a programmatic appraisal. This is because congestion can mean that schemes that are complementary in traffic terms can have negative interdependency benefits, whilst schemes that compete in traffic terms have positive interdependency benefits. If congestion levels change over the appraisal period then interdependency benefits may switch from positive to negative, or vice versa. The latter implies more than one modelled future year is likely to be required in a programmatic appraisal.

Finally, in the reporting of the results of the analysis there is a need to be broader in the description than simply setting out the numbers. Here it is important to understand the context of the scheme and its inter-relationship with the programme as a whole. The way in which the analyst will wish to structure the presentation is context dependent. Is the scheme central to the programme or rather peripheral to it? If it is the central element then we start with the standalone value of the scheme against the Reference Case. If the business case for this scheme is weak, we know we are dependent on the value of the strategy as a whole, and in this sense the scheme is then dependent on the results of the programmatic appraisal. If the stand alone business case is strong then the results of the programmatic appraisal might be less important to the decision-maker. Similarly, if the scheme is peripheral to the strategy (are the strategy can proceed without it), then the results of the programmatic appraisal may be less relevant to the decision-maker.

Our case study application of the method demonstrates that real transport networks can be very complex. The combination of high congestion costs, the potential for upstream and downstream transmission of congestion, and variable demand along with the re-routeing of traffic can lead to some complex findings, where schemes that complement as pairs then compete when combined in a larger programme. The implication of this is as follows.

- It is essential that a holistic approach is taken to consider which schemes are tested in the programmatic appraisal. In our case study excluding Schemes D & E which lie in a competing route corridor (and different investment programme) from the analysis would clearly overestimate the benefit of the scheme – as can be seen by comparing the incremental and decremental analysis.
- More than one model year is necessary. As the complementary/competing effects can change through the appraisal period. Basing the analysis on one model year may not be possible.
- The combination of competing and complementary schemes, along with high travel time delays (congestion), may result in additional model runs being required in order to understand the results of the initial pairwise analysis.
- The incremental and decremental benefits remain important indicators of a scheme's economic worth within a programme of investment. The pairwise analysis and further higher order scheme combinations then helps us understand the drivers to these benefits.

7.2 Recommendations

This work has demonstrated that a scheme can have material interdependency benefits when there are other related schemes. This indicates that programmatic appraisal should probably be undertaken in some instances, where the extra analytical effort required is justified by the size of the investment programme.

However, given the relatively small amount of road testing that has been undertaken, we are cautious about recommending immediate incorporation into WebTAG. We would however recommend:

1. that the method is **tested further with practitioners**, with particular consideration of modelling impacts; and
2. further case studies are brought forward to test the method on.

We also recommend that DfT give further consideration to the implications of this report for appraisal of programmes **other than strategic roads** where a range of issues such as cost side interdependency and demand side feedback to public transport provision may be relevant.

In terms of further analytical research we recommend that consideration is given to identifying congestion thresholds where interdependency benefits switch sign from positive to negative or vice versa. We also recommend that efforts are made to address how the uncertainty of other schemes is described: as the two categories in TAG Unit M4 are rather limiting. Possibly both of these research avenues can be progressed through the road testing recommended above.

Appendix A

Interviews with appraisal practitioners

A1 Interviews

A1.1 Introduction

Interviews with practitioners were undertaken with the following individuals.

- Glen Weisbrod, President and CEO, Economic Development Research Group, Boston, USA
- James Odeck, Professor of Transport Economics, The Norwegian University of Science and Technology, Norway
- Jonas Eliasson, Director of Stockholm City Transport Administration, Sweden

A1.2 Interview Questions

The following structure was adopted for the questionnaires.

1. How do your project appraisals take account of inter-dependencies between the project and other potential projects?

   Probe along lines of:

   - How project benefits may go up or down?
   - Shared investment costs (most applicable to rail)?
   - Timing/sequencing of projects
   - How to attribute 'synergy' benefits between projects

2. If one is designing a programme of investment or trying to understand the synergies between projects in a programme the potential combinations of projects are likely to be very high. How are these options sifted down to something more manageable?

   Probe along lines of:

   - Analytical tools. If so any references?
   - Judgemental decisions. How are these judgements made?

3. If one includes 'synergy' benefits within a project appraisal, how is the uncertainty associated with whether or not these benefits will occur accounted for (e.g. if the next phase of the programme is delayed or does not happen)?

   Probe along lines of:

   - *Scenario analysis*
   - *Probability analysis (where do the probabilities come from?)*
   - *Real options/quasi-options*

A1.3 Interview summaries

A1.3.1 Interview 1

Glen Weisbrod started the discussion with an overview of how the planning process works in the USA. In general, there is a two-part process in every state and every metropolitan organisation.

- Stage 1 – System Planning or Corridors
- Stage 2 – Programming

Stage 1 is updated every 5 years and states are required to have a System Plan. States, because of their size, will have a state-wide system, but most also do corridor studies, which are for major corridors connecting cities. Metropolitan Planning Organisations (MPOs) tend to do System Planning whereas states will do 'corridor plans'.

Stage 1 studies must go through a process to identify the purpose and need for transport interventions. When a purpose and need is done for all studies, *they must consider synergies and substitutability*. Studies must also consider multiple modes, meaning that highways studies must always consider alternatives.

When a 'project' is defined, there needs to be a consideration of synergies. If it is to be considered alone, it must have 'independent utility'. If projects are 'dependent' or have 'synergies', there are two studies:

- Tier 1 – Package or Projects
- Tier 2 – Appraisal of Individual Schemes

Tier 1 considers a package of projects to see if a project can stand alone or whether it is dependent upon other schemes. It is about assessing if a project has 'independent utility' and this is done through the Environmental Statement process. Once a project has been shown to be able to stand on its own, it can progress to **Tier 2**.

Stage 2 is the programming process. Every state is required to set out its priorities under a financially constrained environment. Projects are added to a five-year Transport Improvement Plan (TIP). At the state level this is called a State Transport Improvement Plan (STIP). The prioritisation is supposed to be performance-based, but in practice it often isn't as there are separate funding streams for different objectives such as safety, rural and capacity. There are also political pressures.

Overall, the system is quite good for Stage 1, but Stage 2 is not guaranteed to achieve the best performance. It's also worth noting that not all states have a requirement to do a Cost Benefit Analysis, and some instead do Multi-Criteria ranking. There is no specific guidance on 'programmatic appraisal' per se, but Stage 1 has some similarities with this in the Tier 1 step.

A1.3.2 Interview 2

James Odeck explained that in Norway, if they believe that a scheme may have interdependencies, they are appraised as if they are one project. This forms part of the guidance for appraisal in Norway.

In addition, if a practitioner is undertaking an appraisal on project (A), and there is a chance that a particular project (B) might also go ahead, then project (B) should be included in a sensitivity test. I.e. the guidance requires that practitioners assess the impact of a particular scheme going ahead, if it is likely that that scheme will affect the scheme being assessed.

The stage of defining a project is considered to be quite important. It needs to clearly define what is in the do-nothing and what is not.

In Norway there is 10-year National Transport Plan that is updated every 4 years. Every scheme will be assessed (for example, 1,400 projects), and then the ministry will ask for a ranking of all these projects. Economists will undertake this analysis but ultimately it is the ministers that will determine the final ranking.

One interesting example of ‘programmatic appraisal’ being undertaken in Norway is the ‘zero emissions’ studies that are being undertaken in Norway’s ten largest cities. They are developing ‘packages of projects’ and it is challenging to decide which projects to include in the package and then how to apportion the benefits. These studies have involved many model runs.

Another interesting study was undertaken in the mid-90s and used ‘data envelopment analysis’ which is a method used often in productivity and efficiency analysis. A paper was written for the European Transport Conference and showed how to choose the best combination of options for a portfolio of projects. This is effectively a ‘linear programming’ exercise.

A1.3.3 Interview 3

Jonas Eliasson started by explaining that Sweden doesn’t generally undertake programmatic appraisal but noted that it is a topic of interest.

In Sweden it is particularly relevant in the railway sector. There will be a ‘baseline scenario’ and then various projects are appraised by removing or adding them to the baseline scenario. There is debate about whether or not this is the best way to assess timetable improvements but this is how it is done.

In general roads schemes in Sweden tend not to have dependencies although sometimes there will be roads that lead up to a motorway that are complementary to a scheme being assessed (such as a bypass).

In general, there is no formal way of assessing inter-dependencies amongst projects. A baseline timetable is constructed which assumes a number of different investments and then some of these investments are taken away to see what adjustments will still be necessary given that not all the investments can be necessarily be done.

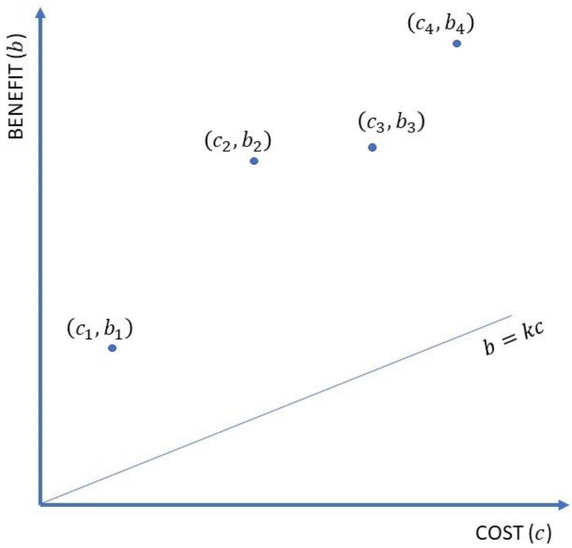
In general, they don't quantify or identify synergy benefits. Rather they calculate the benefits of one project first and if it turns out that more projects are needed in order to meet demand, then a timetable or set of infrastructure projects to meet that demand is developed. Then there will be iterations of removing projects until the 'ideal timetable' or infrastructure is developed. As an example, engineers may start with a project to design a double track railway. Then they may remove some parts of the double track to see if the project will still be worthwhile while saving money. However, often times the time available in the planning process means that not many options can be assessed.

An appraisal of the entire National Transport Plan is also undertaken.

Appendix B

On the equivalence between COBA Incremental Analysis and Minken (2016)

Consider a set of mutually exclusive projects $i \in \{1, \ldots, n\}$ having costs $\{c_i\}$ and benefits $\{b_i\}$. We can represent each project by the point with coordinates (c_i, b_i) in cost/benefit space.

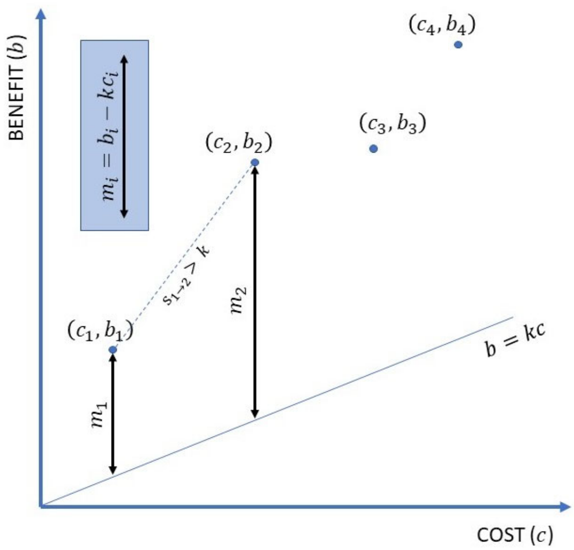


Both COBA and Minken adopt a cut-off k for the BCR. Projects that exceed the BCR cut-off will be "above the line" $b = kc$.

Minken seeks to "maximise the area above k" in the BCR vs Cost space. For project i this area is

$$\left(\frac{b_i}{c_i} - k\right) * c_i = b_i - kc_i$$

In the cost-benefit space this is the vertical distance $m_i = b_i - kc_i$ above the BCR cut-off line.



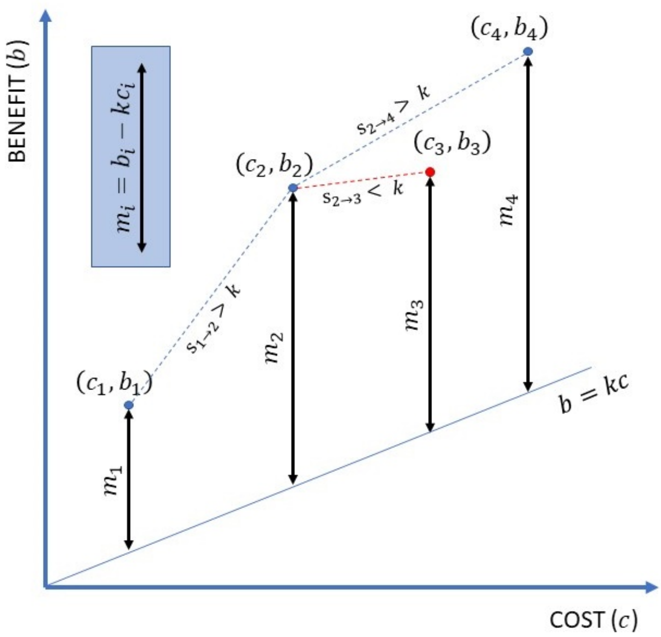
COBA compares projects in order of increasing cost. Without loss of generality, we can assume the projects have already been numbered in this order. The current selected project is updated **if** the incremental BCR, that is the slope from $i \rightarrow j$, is above the threshold k:

$$s_{i \rightarrow j} = \frac{b_j - b_i}{c_j - c_i} > k$$

Hence the COBA incremental algorithm will select the next project under consideration iff $m_j > m_i$. COBA proceeds to "compare to the right" and updates whenever m_i increases, thereby finding max$\{mi\}$. Minken computes all the $\{mi\}$ and then selects the maximum.

Here Minken selects the maximum $\{m_i\}$ which is m_4.

COBA updates from $1 \rightarrow 2$, the rejects (c_3, b_3) as the slope is below k but then updates to select 4.



Appendix C

Summaries and comments on key papers

C1 Practical Appraisal Guidance (Published and Grey)

HMT (2003) Green Book. See Chapter 6: Section 2: "Selecting the Best option"

Summary:

6.3 If a full cost benefit analysis has been undertaken, the best option is likely to be the one with the highest risk adjusted net present value. To the extent that all costs, benefits and risks have been robustly valued, this guideline can be applied with more certainty.

6.4 If there is a budget ceiling, then the combination of proposals should be chosen that maximises the value of benefits. The ratio of the net present value to the expenditure falling within the constraint can be a useful guide to developing the best combination of proposals.

Comment: *The Green Book position is consistent with economic texts – maximise NPV. Texts warn that the use of BCRs can lead to erroneous results – hence we suppose the use of the phrase 'can be a useful guide' has been used. Note that the NPV/cost ratio gives the same ordering as a PVB/cost constraint ordering. One is a transformation of the other.*

HMT (2003) Green Book. Inter-dependencies

Summary:

There is very little mention of interdependencies in the Green Book.

In the section on Appraising Options (p17) the guidance mentioned having cognisance for 'dependencies' when creating options.

In the risk register (risk log) (p80) there is a mention of "inter-dependencies with other sources of risk".

Comment: *The Green Book does not seem to guide us much here in the context of inter-dependencies in programmatic appraisal.*

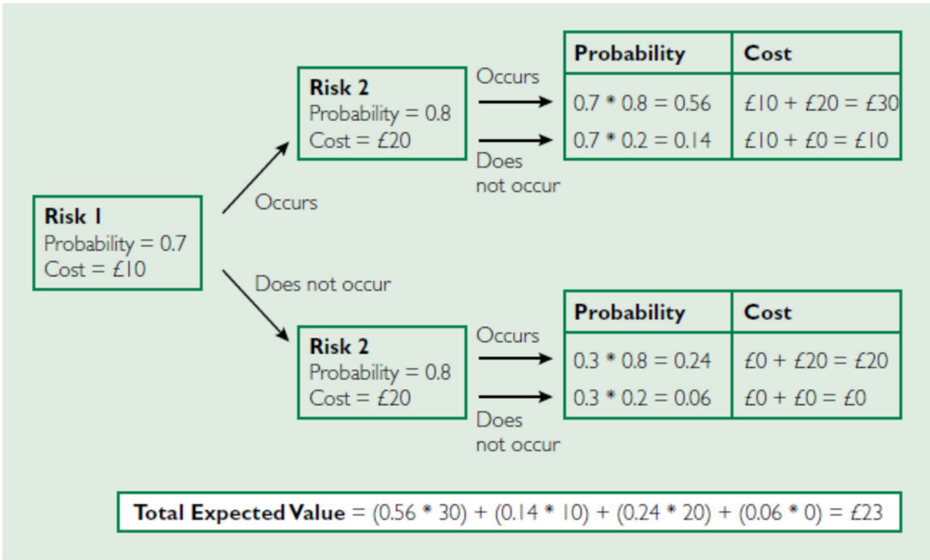
HMT (2003) Green Book: Uncertainty/Risk See Chapter 5 Appraising options & Appendix 4 Risk and Uncertainty.

Summary:

When uncertainty can be quantified in probabilistic terms (often called risk in this situation), then an expected value can be estimated. This is calculated by multiplying the likelihood of the risk occurring and the size of the outcome (see Para 5.66).

Decision trees can be useful in assessing situations in which the probabilities of particular events occurring depend on the previous events. They can be used to calculate expected values in these more complex situations (see Para 5.67).

BOX 14: EXAMPLE – DECISION TREE



Source: Green Book p32

Appendix 4 of the Green Book gives guidance on the management of risk in project development. This includes the development of a risk register and a risk log. Uncertainty associated with inter-dependencies between schemes will feature in this log.

Comment: The treatment of risk in programmatic appraisal is relevant if sections of the programme may not get built. This Green Book decision tree example has many analogies to the use of quasi-option values. The quasi-option value is the value ascribed to learning over time as more information becomes available. Whilst it is labelled as an extra benefit some economic texts say it is only an extra benefit if the initial calculation is undertaken incorrectly (as a one-time period analysis). At the moment, uncertainty really only features in the appraisals in the risk log.

COBA Manual. Section 1 Part 3.2 Incremental Analysis: The choice of route and standards

Summary:

A linear programming method is set out, which maximises NPV subject to a minimum BCR being achieved. The method incrementally tests each increase in capital cost to see if the incremental BCR is above the threshold. The final design option maximises NPV whilst maintaining the BCR above the desired threshold.

Comment: The method is consistent with economic theory with a budget constraint – and the Green Book. It also gives the same result as the Minken *paper (see later). The effect of the approach is that the BCR of the chosen option is not usually the highest BCR (unless the cut off BCR is so high relative to the BCRs of the options that only one option passes the hurdle).*

COBA Manual. Section 1 Part 3.4 The Appraisal of competing and complementary schemes

The scheme in route problem consists of four related issues:

[1] **The determination of the optimal extent of the strategy and its overall economic worth.** Recommends using maximum NPV (assumes there is no budget constraint). [NB If there is a budget constraint one needs to maximise NPV subject to a BCR cut off – see above comments on Green Book and COBA manual incremental appraisal]

[2] **The determination of priority ranking of start dates for sections of the strategy.** Based on BCRs. Highest BCR first. It follows that later sections of the route will have lower BCRs and the overall BCR of the strategy will gradually lower as more sections are completed. BCRs of second section to be determined by including the first section (prioritised) in the Do Minimum. i.e. an incremental BCR.

[3] **The appraisal of the component sections within the strategy.** Use exclusion and inclusion analysis. *Exclusion analysis* compares the benefits of the completed strategy against that of the completed strategy minus the component section under examination. *Isolation analysis* examines the effect of not completing later sections of the route strategy.

[4] **The determination of precise design standards and alignments for each component.** Use of incremental analysis. Needs to be undertaken in terms of exclusion and isolation analysis.

Practical problems:

- Large number of model runs. There is a trade-off between computational ease and robustness of end results.
- Choice of strategy and timing/phasing is interrelated.
- With start dates of different phases spread over a long time (e.g. 20 years) period the end point of the appraisal will be a long time in the future.
- Priority ranking maybe at odds with reality of programming construction.
- Isolation and exclusion analysis may be in conflict.
- High and low growth economic/traffic growth may give conflicting results.

Comment: this is a practical method that has been developed over a significant period of time, albeit it has since fallen by the wayside since the lack of applicability of the COBA software. One issue in the context of the current study in terms of its applicability is the focus on the definition of identifying the optimal strategy – rather than the impact of being in a programme has for the benefits of a project.

Highways England: Programmatic Appraisal – Working Draft (September 2017)

Claims that current existing guidance allows synergistic and competing impacts to be captured, but often repeatedly allocate the total of these to each scheme individually, running the risk of repeatedly claiming the programmatic impacts in multiple project locations (see p6).

Sets out a 6-stage process:

Step 1: assess need for programmatic appraisal. This seems to be a qualitative discussion with no benchmarking tests suggested.

Step 2: scope out the parameters for appraisal. Define study area and sets out some HE procedural issues associated with timescales for undertaking the analysis.

Step 3: appraisal of the whole programme. Gives an appraisal of the whole programme. Individual business cases should mention benefit of whole programme. Key benefits to only be counted once at programme level.

Step 4: decremental programmatic appraisal. Remove the project from the programme and test what the programme level benefits are. Gives an indication of how the project contributes to the programme. Compare to the costs of the project. [This is equivalent to the *COBA exclusion analysis* mentioned earlier]

Step 5: in cases of extreme uncertainty [of programme level funding] undertake incremental assessment. The incremental assessment is that indicated by the COBA Manual (incremental BCR) of adding the project to the programme – but with no other subsequent elements of the programme occurring. [*this is equivalent to the COBA Isolation analysis*].

Step 6. Reporting/Overall assessment. Individual scheme level benefits, programme level benefits and contribution of project to overall programme.

Comment: Guidance seems very much in line with preceding guidance documents. Implicitly the guidance seems to consider that the 'shape of the programme' is fairly well defined already. In Neil Shorten's analogy this would be akin to the RIS1 use of programmatic appraisal, rather than the RIS2 analogy (where the shape of the programme is rather more fuzzy). There is no mention in the guidance of non-road interventions.

DfT Draft Package Appraisal TAG unit (DfT, 2009)

Summary:

This draft guidance note, which was never published, is focused on the appraisal of packages of transport interventions (cross-modal). It is based on COBA guidance and experience in appraising TIF packages. Packages are defined as a set of complementary solutions to address a discrete transport need.

The questions package appraisal should address are: (i) is the package worth taking forward? (ii) is it the right size, (iii) are all the interventions in the package justified?, (iv) is the phasing correct?

The starting point seems to be (as in the HE guidance) that the package is already defined. Schemes are therefore tested using incremental and decremental analysis to understand their contribution to the whole package.

If the number of schemes in the package are small then modelling all variants is expected. If the number is medium then a decremental analysis is expected. If the number is large then some grouping of schemes needs to be undertaken.

The note sets out the need to understand dependency between projects and sets out an example of a dependency matrix.

The note reminds the analyst that some ‘package’ impacts will be felt locally (e.g. air pollution and accidents) whilst others will be felt ‘globally’. There is has an interesting discussion on the issue of shared costs – particularly relevant to public transport which is subject to economies of scope and density [may also be relevant for road schemes where major structures are being constructed].

Reporting: full set of appraisal results for the <u>preferred package</u> and all major <u>individual projects</u>. Includes incremental and decremental tests.

Comment: *A thorough practical treatment of appraisal issues – particularly on the issue of the contribution of an individual project to a package. The main difference with the existing study is that the focus of our study is on how the VfM of a project will change when it is part of a package, the composition of which may or may not be known. This guidance note takes the package as pre-defined.*

Email discussion with Robert Cochrane following UTSG email query.

Summary:

Correspondence with Robert Cochrane following the UTSG email request indicated that:

- In practical appraisal heuristics to cut down the choice set are required to define optimal packages (e.g. warehouse locations/freight hubs).
- There may be multiple optima and/or local optima – the analogy was to a lumpy omelette.
- A practical heuristic is to add/drop schemes [like in a regression analysis – where starting points are known to influence final specification].
- The primary aim in developing a heuristic is to understand the overall lie of the land first using a carefully designed pattern search of options and then check locally.

He also suggests that provided the alternative project baskets are all reasonably sensible, significantly different solutions may have similar global cost benefit ratios, so solutions found using heuristic approaches e.g. incremental add, incremental drop as compared with more complicated methods such as using non - linear programming) may be significantly different in structure but provide similar aggregate cost benefit results.

Comment: it is interesting to see the comment that very different packages may have similar BCRs – though of course this will be case dependent. The need for heuristics was clear due to the large combinatorial problem.

C2 Research Papers (Published and grey)

C2.1.1 TRANSPORT APPRAISAL PAPERS

Raith, A., Nataraj, U., Ehrgott, M., Miller, G. and Pauw, K. (2011) September. Prioritising cycle infrastructure projects. In Australasian Transport Research Forum (ATRF), 34th, 2011, Adelaide, South Australia, Australia. Retrieved from http://www.atrf.info/papers/2011/2011_Raith_Nataraj_Ehrgott_Miller_Pauw.Pdf.

This paper deals with the improvement of cycling infrastructure applied to the Auckland (NZ) region. Construction of proposed cycle infrastructure needs to be phased and requires a means for prioritising projects over time. The existing project selection method uses benefit to cost ratios (BCRs), with high BCR projects prioritised on the basis of a simple rank order. Estimated usage over the life of the cycling infrastructure is a major component of the BCR computation; hence demand forecasting is crucial in this analysis. This paper presents a new demand forecasting model to be used within the existing prioritisation framework. It may, however, be beneficial to prioritise construction of a low BCR project in order to increase connectivity of the cycle network as a whole. This is called the project bundling or portfolio effect. The new demand forecasting method allows a user to estimate demand (and hence benefit) of individual projects and also additional benefits derived from project interdependencies. This paper furthermore proposes a project selection method that appropriately models these interdependencies rather than selecting projects based on BCR ranking of individual projects only. It presents a case study demonstrating this selection methodology. For road and cycleway controlling authorities with budget constraints, this methodology provides a cycleway project selection and prioritisation approach based on whole network benefits, rather than on an individual project basis.

JJL Comment: *This seems a relevant practical application. The approach requires inter-dependent benefits to be assessed and then uses a 'quadratic knapsack' algorithm to identify the optimum investments. It shows that building adjacent sections of cycle track, if there are inter-dependencies, is more worthwhile than building unconnected sections. The analysis requires that all the inter-dependencies are quantified.*

RDC Comment: *Account for interdependencies between component schemes (in potential project portfolios). For each project i compute the costs* w_i *and benefits* b_i *but also compute the additional benefit (or disbenefit)* b_{ij} *for implementing both i and j (over and above* $b_i + b_j$*). Solve this as a quadratic knapsack problem via linearization. Hence consider pairwise interactions.*

Show for a set of example schemes that simple greedy algorithm (implementing in BCR rank order within budget constraint) performs worse than proposed algorithm.

Minken, H., 2016. Project selection with sets of mutually exclusive alternatives. *Economics of Transportation*, 6, pp.11-17.

Abstract: The authors study the problem to maximise the net economic benefit of an investment plan by selecting from a portfolio of candidate projects within a given budget constraint. As is well known, with independent projects the economic efficiency of the entire investment plan is maximised if projects are selected according to their benefit-cost ratio until the budget is exhausted. Often, however, the planning of a project involves a stage where a set of alternative concepts or designs are considered. A best alternative is chosen, and the plan is composed from the pool of all such best alternatives. This procedure violates the assumptions underlying the benefit-cost ratio criterion. In this paper, the authors set out the correct criterion to use. A real-life example from Norwegian transport planning is provided to show how the global setting into which the project is going to compete, matters for the selection criterion to be used.

JJL Comment: *This paper formally sets out the linear programming method that needs to be employed to choose between mutually exclusive projects to maximise NPV. [Note: the COBA manual section on Incremental Analysis employs a variation on this method]. Inter-dependencies between projects need to be treated as a separate project. Thus, A by itself, B by itself and A+B are mutually exclusive.*

RDC Comment: *Considers a set of infinitely divisible schemes where implementing a fraction of the scheme gives you that fraction of the costs and benefits. Considers schemes as independent. Does not acknowledge the problem of too many combinations to consider. Main contribution is to address the issue of mutually exclusive schemes.*

Lambert, J.H., Pinto, C.A. and Peterson, K.A., 2003. Extended comparison tool for major highway projects (No. VTRC 03-CR18,). Virginia Transportation Research Council. Available at: https://pdfs.semanticscholar.org/50f0/acb69eee872664862a8444ba30afba491534.pdf

Under the Virginia Transportation Act signed into law in April 2000, more than $10 billion would have been invested in highway construction, public transportation, airports, and ports during the following 6 years. However, recent budgetary constraints will result in a delay in investing more than $2 billion in road projects for more than a decade. In the current study, a previously developed comparison tool was extended to bring quantitative evidence of safety and categorical evidence of broad motivations to planners, engineers, and the public in comparing the benefits of proposed transportation projects. The extended tool developed in the current study provides visual devices for presenting multifaceted information about project attributes. Policymakers and planners may find the presentation useful in assessing what types of projects are being undertaken and what projects to prefer to others. The extended tool represents project information including cost, average daily traffic, and crash rates for comparison and prioritization of the 1,500 candidate projects that constitute the development plan of Virginia highways. The extended tool is flexible to accommodate applications such as project selection (planning) and programming. Several sources of information include the crash databases of the Virginia Department of Transportation (VDOT) and project plans for districts and localities. The extended tool enables planners to identify principal motivations for various projects based on categories defined by the Transportation Equity Act for the 21st Century. The tool introduces summary reports of criteria including project aggregate costs and counts of projects with particular motivations, facilitating system-level analyses and project ranking. The summary reports can be useful to interpret outcomes of human deliberation or multicriteria rating and ranking processes, some of which are demonstrated in this study in the body of the report and in a substantial appendix. The major innovation of the extended comparison tool is its ability to synthesize the relevant quantitative and categorical information on a large and diverse portfolio of highway investments, bringing more evidence to the table earlier in the planning process. Three case studies demonstrate the application of the extended comparison tool in short-, medium-, and long-term transportation plans. These case studies are the VDOT-Culpeper District Transportation Development Plan (a 6-year plan), long-range financially constrained plans of selected small Virginia localities, and the long-range plan of the Thomas Jefferson Planning District Commission. The incremental data to assess over 100 projects in a VDOT District Six-Year Plan were collected in 90 minutes, providing an advantage over typical methods that can require several hours or more per project. Recommendations are given for implementation of the extended comparison tool and further development of the software prototype.

Comment: Appears to treat all projects as independent. It seems more like a broadbrush/sketch decision-making tool for project prioritisation (of independent projects).

Gühnemann, A., Laird, J.J. and Pearman, A.D., 2012. Combining cost-benefit and multi-criteria analysis to prioritise a national road infrastructure programme. *Transport Policy*, 23, pp.15-24.

Abstract: This paper develops and then applies a novel approach of combining cost-benefit analysis (CBA) and multi-criteria analysis (MCA) within a road infrastructure development programme with the aim to support the effective implementation of transport policy when prioritising projects. By incorporating CBA results into an MCA framework this approach retains the strengths of each appraisal method and provides a procedure for decision makers to create an initial ranking of projects which is consistent between all candidate investments and has a clear link to policy goals. We further develop an approach for an incremental analysis that eliminates mutually exclusive projects and allows decision makers to develop a cost-effective investment programme in compliance with their strategic goals. Stakeholder confidence in the outcome of any infrastructure investment ranking exercise is important and can be enhanced by an understanding of the robustness of the ranking to variations in key inputs to the assessment exercise. Two complementary perspectives on sensitivity testing are outlined which between them facilitate an assessment of the robustness of the project ranking obtained. The applicability of the approach has been successfully demonstrated for the National Secondary Road Network in Ireland.

Comment: *This approach used a 'red lining' system to ensure schemes with non-negotiable negative impacts were flagged. Inter-dependencies between schemes were not assessed – each scheme was treated individually. Incremental analysis, similar to that set out in the COBA manual, was employed. Was able to produce a prioritised set of schemes to make up a programme.*

Salling K.B. & Banister D., 2009, Assessment of large transport infrastructure projects: the CBA-DK model. *Transportation Research Part A: Policy and Practice*, 43, pp. 800-813.

Abstract: The scope of this paper is to present a newly developed decision support model to assess transport infrastructure projects: CBA-DK. The model makes use of conventional cost-benefit analysis resulting in aggregated single point estimates and quantitative risk analysis using Monte Carlo simulation resulting in interval results. The embedded uncertainties within traditional CBA such as ex-ante based investment costs and travel time savings are of particular concern. The methodological approach has been to apply suitable probability distribution functions on the uncertain parameters, thus resulting in feasibility risk assessment moving from point to interval results. Decision support as illustrated in this paper aims to provide assistance in the development and ultimately the choice of action while accounting for the uncertainties surrounding transport appraisal schemes. The modelling framework is illustrated by the use of a case study appraising airport and runway alternatives in the capital of Greenland – Nuuk. This study has been conducted in corporation with the Home Rule Authorities of Greenland.

Comment: *Danish transport investment uses conventional cost-benefit analysis (CBA) converting the virtual impacts into monetary units such as pollutants, accidents, time savings etc… However, these deterministic single point output criteria are based upon "best guess" estimates of each input variable to the model.*

The authors consider a small number of alternative schemes (for a given project) and expand the analysis from single point-based estimates of CBA to interval results (which they call quantitative risk assessment).

C2.1.2 Types of Optimization Problems [from https://goo.gl/omiRqM]

Continuous Optimization versus Discrete Optimization

Some models only make sense if the variables take on discrete values, often integer values, whereas other models contain variables that can take on any real value. Models with discrete variables are discrete optimization problems; models with continuous variables are continuous optimization problems.

Continuous optimization problems tend to be easier to solve than discrete optimization problems; smoothness of the objective and constraint functions means that function values at a point $\boldsymbol{x}$ can be used to deduce information about points nearby $\boldsymbol{x}$.

Nevertheless, improvements in algorithms and advancements in computing technology have dramatically increased the size and complexity of discrete optimization problems that can be solved efficiently.

One or Many Objectives

Most optimization problems have a single objective function, however, there are interesting cases when optimization problems have multiple objective functions.

Multi-objective optimization problems arise in many fields, such as engineering, economics, and logistics, when optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives. For example, developing a new component might involve minimizing weight while maximizing strength or choosing a portfolio might involve maximizing the expected return while minimizing the risk. In practice, problems with multiple objectives often are reformulated as single objective problems by either forming a weighted combination of the different objectives or by replacing some of the objectives by constraints.

Deterministic Optimization versus Stochastic Optimization

In deterministic optimization, it is assumed that the data for the given problem are known accurately. However, for many actual problems, the data cannot be known accurately for a variety of reasons. The first reason is due to simple measurement error. The second and more fundamental reason is that some data represent information about the future (e. g., product demand or price for a future time period) and simply cannot be known with certainty.

In optimization under uncertainty, or stochastic optimization, the uncertainty is incorporated into the model. Robust optimization techniques can be used when the parameters are known only within certain bounds; the goal is to find a solution that is feasible for all data and optimal in some sense. Stochastic programming models take advantage of the fact that probability distributions governing the data are known or can be estimated; the goal is to find some policy that is feasible for all (or almost all) the possible data instances and optimizes the expected performance of the model.

C2.1.3 PROJECT PORTFOLIO SELECTION INCLUDING THE NETWORK DESIGN PROBLEM

Teng, J.-Y., Tzeng, G.-H., 1996. A multiobjective programming approach for selecting non-independent transportation investment alternatives. Transportation Research Part B: Methodological 30, 291–307

Abstract: This article presents a new method for SElecting Non-independent TRansportation investment Alternatives (SENTRA). This method utilizes effective distance heuristic algorithm which attempts to maximize the achieved objectives needed to satisfy available resources. Since transportation investment planning cannot avoid dealing with issues of interdependence among alternatives, this paper will consider four types of investment alternatives: independence, complementarity, substitution and common complementary substitution. Transportation investment alternative selection problem can be formulated in terms of the 0-1 multiobjective multidimensional knapsack problem. Possessing the characteristics of NP-completeness, strict computation is not necessary for the optimal solution, but simple computation for near-optimal solution is expected. The method is proposed in this paper so as to attain the near-optimal solution, which, aside from ranking the selected transportation investment alternatives, can easily perform sensitivity analysis. Finally, an example is presented to illustrate the method.

Comment: *Focus on selecting non-independent transportation investment alternatives. Four types of investment alternatives considered: independence, complementarity, substitution and common complementary substitution. The selection problem is formulated as a multiobjective multidimensional knapsack problem.*

Roland, Figueira, Smet, 2016, Finding compromise solutions in project portfolio selection with multiple experts by inverse optimization. *Computers & Operations Research*, 66, pp. 12-19.

Abstract: This paper deals with project portfolio selection evaluated by multiple experts. The problem consists of selecting a subset of projects that satisfies a set of constraints and represents a compromise among the group of experts. It can be modeled as a multi-objective combinatorial optimization problem and solved by two procedures based on inverse optimization. It requires to find a minimal adjustment of the expert's evaluations such that a portfolio becomes ideal in the objective space. Several distance functions are considered to define a measure of the adjustment. The two procedures are applied to randomly generated instances of the knapsack problem and computational results are reported. Finally, two illustrative examples are analyzed and several theoretical properties are proved.

Comment: *Project portfolios are evaluated by estimating NPV, but this quantity is non-unique, because it requires fixing the rate of return and the period to observe. Hence a group of experts may be hired to assess the shortlisted proposals. The optimal portfolio must maximize the NPV according to each expert (and satisfy budget constraints). This is modelled as a multi-objective combinatorial optimization problem.*

Often there is not consensus and a method to identify the best compromise solution is needed. Typically, his may be to average the expert ratings in some way.

Note that these evaluations are not precise. This paper seeks the compromise solution that represents the minimal adjustment of the experts′ evaluations so that an ideal (consensus) portfolio exists This concept of compromise is closely related to inverse multi-objective optimization.

Carazo, A.F., Gómez, T., Molina, J., Hernández-Díaz, A.G., Guerrero, F.M., Caballero, R., 2010. Solving a comprehensive model for multiobjective project portfolio selection. *Computers & Operations Research* 37, 630–639

Abstract: Any organization is routinely faced with the need to make decisions regarding the selection and scheduling of project portfolios from a set of candidate projects. We propose a multiobjective binary programming model that facilitates both obtaining efficient portfolios in line with the set of objectives pursued by the organization, as well as their scheduling regarding the optimum time to launch each project within the portfolio without the need for a priori information on the decision-maker's preferences. Resource constraints, the possibility of transferring resources not consumed in a given a period to the following one, and project interdependence have also been taken into account. Given that the complexity of this problem increases as the number of projects and the number of objectives increase, we solve it using a metaheuristic procedure based on Scatter Search that we call SS-PPS (Scatter Search for Project Portfolio Selection). The characteristics and effectiveness of this method are compared with other heuristic approaches (SPEA and a fully random procedure) using computational experiments on randomly generated instances.

Comment: *Proposes a model for the project portfolio selection problem simultaneously tackling how to select and schedule (choosing the starting point in time) efficient project portfolios with interdependencies between component schemes.*

Proposes a metaheuristic, an adaptation of the evolutionary method—Scatter Search Procedure for Multiobjective Optimization – to solve selection and scheduling problems in project portfolios.

Farahani, R.Z., Miandoabchi, E., Szeto, W.Y., Rashidi, H., 2013. A review of urban transportation network design problems. European Journal of Operational Research 229, 281–302

Abstract: This paper presents a comprehensive review of the definitions, classifications, objectives, constraints, network topology decision variables, and solution methods of the Urban Transportation Network Design Problem (UTNDP), which includes both the Road Network Design Problem (RNDP) and the Public Transit Network Design Problem (PTNDP). The current trends and gaps in each class of the problem are discussed and future directions in terms of both modeling and solution approaches are given. This review intends to provide a bigger picture of transportation network design problems, allow comparisons of formulation approaches and solution methods of different problems in various classes of UTNDP, and encourage cross-fertilization between the RNDP and PTNDP research.

Heidenberger, K., Stummer, C., 1999. Research and development project selection and resource allocation: A review of quantitative modelling approaches. International Journal of Management Reviews 1, 197–224.

Abstract: This paper reviews the literature on quantitative modelling for research and development (R & D) project selection and resource allocation. The topic has been a subject of operations research for about four decades. Its importance stems from the fact that R & D projects are a core element of corporate renewal, heavily influence a firm's market success and, if not properly chosen and trimmed, may waste large amounts of resources or even ruin the enterprise. Our survey classifies and characterizes the various modelling approaches.

Wang, D.Z.W., Liu, H., Szeto, W.Y., 2015. A novel discrete network design problem formulation and its global optimization solution algorithm. Transportation Research Part E: Logistics and Transportation Review 79, 213–230

Abstract: Conventional discrete transportation network design problem deals with the optimal decision on new link addition, assuming the capacity of each candidate link addition is predetermined and fixed. In this paper, we address a novel yet general discrete network design problem formulation that aims to determine the optimal new link addition and their optimal capacities simultaneously, which answers the questions on whether a new link should be added or not, and if added, what should be the optimal link capacity. A global optimization method employing linearization, outer approximation and range reduction techniques is developed to solve the formulated model.

Archer, N.P., Ghasemzadeh, F., 1999. An integrated framework for project portfolio selection. International Journal of Project Management 17, 207–216.

Abstract: The task of selecting project portfolios is an important and recurring activity in many organizations. There are many techniques available to assist in this process, but no integrated framework for carrying it out. This paper simplifies the project portfolio selection process by developing a framework which separates the work into distinct stages. Each stage accomplishes a particular objective and creates inputs to the next stage. At the same time, users are free to choose the techniques they find the most suitable for each stage, or in some cases to omit or modify a stage if this will simplify and expedite the process. The framework may be implemented in the form of a decision support system, and a prototype system is described which supports many of the related decision-making activities.

Comment: *This paper brings together all stages of project portfolio selection, beginning with strategic considerations that precede our focus. The next stage is to determine mechanisms for project evaluation including NPV, IRR, Benefit/Cost and Risk Analysis. The Portfolio Selection phase involves the simultaneous comparison of a number of projects on particular dimensions, in order to arrive at a desirability ranking of the projects. The most highly ranked projects under the evaluation criteria are then selected for the portfolio, subject to resource availability.*

The problem of reducing the candidate set to a manageable size is not addressed.

Ghasemzadeh, F., Archer, N. and Iyogun, P., 1999. A zero-one model for project portfolio selection and scheduling. *Journal of the Operational Research Society*, 50(7), pp.745-755.

Abstract: A zero-one integer linear programming model is proposed for selecting and scheduling an optimal project portfolio, based on the organisation's objectives and constraints such as resource limitations and interdependence among projects. The model handles some of the issues that frequently arise in real world applications but are not addressed by previously suggested models, such as situations in which the amount of available and consumed resources varies in different periods. It also allows for interactive adjustment following the optimisation process, to provide decision makers a method for controlling portfolio selection, based on criteria that may be difficult to elicit directly. It is critical for such a system to provide fast evaluation of alternatives the decision makers may want to examine, and this requirement is addressed. The proposed model not only suggests projects that should be incorporated in the optimal portfolio, but it also determines the starting period for each project. Scheduling considerations can have a major impact on the combination of projects that can be incorporated in the portfolio, and may allow the addition of certain projects to the portfolio that could not have been selected otherwise. An example problem is described and solved with the proposed model, and some areas for future research are discussed.

Comment: *Defines a linear programming method to identify optimal project portfolio composition within a set of constraints (e.g. maximise NPV for a budget). Seeks optimal start date and accounts for inter-dependencies between projects. Inter-dependencies are here defined as project B requires project A to go ahead or it can't happen. Rather than inter-dependencies that allow benefits of project B to increase if project A goes ahead.*

Leblanc, L.J., 1975. Algorithm for the discrete network design problem. Transportation Science 9, 183–199.

Abstract: This paper addresses the problem of determining which links should be improved in an urban road network so that total congestion in the city is minimized. A nonlinear mixed integer programming model is developed, and strategies for a branch-and-bound algorithm are presented. Particular attention is paid to the computational aspects of large-scale problems, and numerical results are reported.

Abdulaal, M., LeBlanc, L.J., 1979. Continuous equilibrium network design models. Transportation Research Part B 13, 19–32.

Abstract: It is known that the network design problem with the assumption of user optimal flows can be modeled as a 0-1 mixed integer programming problem. Instead, we formulate the network design problem with continuous investment variables subject to equilibrium assignment as a nonlinear optimization problem. We show that this optimization problem is equivalent to an unconstrained problem which we solve by direct search techniques. For convex investment cost functions, the performance of both Powell's method and the method of Hooke and Jeeves is approximately the same with respect to computational requirements for a 24 node, 76 arc network. For the case of concave investment functions, Hooke and Jeeves was superior. The solution to the concave continuous model was very similar to that of the 0-1 model. Furthermore, the required solution time was far less than that required by the corresponding discrete model of the same network. The advantages and disadvantages of the continuous approach as well as the computational requirements are discussed

Magnanti, T.L., Wong, R.T., 1984. Network design and transportation planning: models and algorithms. Transportation Science 18, 1–55.

Abstract: Numerous transportation applications as diverse as capital investment decision-making, vehicle fleet planning, and traffic light signal setting all involve some form of (discrete choice) network design. The authors review some of the uses and limitations of integer programming-based approaches to network design, and describe several discrete and continuous choice models and algorithms. The objectives are threefold - to provide a unifying view for synthesizing many network design models, to propose a unifying framework for deriving many network design algorithms, and to summarize computational experience in solving

design problems. The authors also show that many of the most celebrated combinatorial problems that arise in transportation planning are specializations and variations of a generic design model.

Yang, H., Bell, M.G.H., 1998. Models and algorithms for road network design: A review and some new developments. Transport Reviews 18, 257–278.

Abstract: The Network Design Problem (NDP) has long been recognized to be one of the most difficult and challenging problems in transport. In the past two decades, we have witnessed the development of a vast, growing body of research focused on formulations and solution procedures for the NDPs, which deal with the selection of either link improvements or link additions to an existing road network, with given demand from each origin to each destination. The objective is to make an optimal investment decision in order to minimize the total travel cost in the network, while accounting for the route choice behaviour of network users. In this paper, we present a general survey of existing literature in this area, and present some new developments in model formulations. We incorporate the elasticity of travel demand into the NDP and seek the economic-based objective function for optimization. We also pose the mixed network design problem involving simultaneous choice of link addition and capacity improvement which is considered more sensible for road networks. In addition, we introduce the network reserve capacity concept for a capacity improvement plan, and raise and clarify some interesting issues relating to NDP and Braess's paradoxes. Finally, from the survey and the new proposal made herein, we offer some perspectives on future research

Comment: *Key new developments (i) incorporating elastic demand into the NDP and (ii) posing the mixed network design problem involving simultaneous choice of link addition and capacity improvement. They also introduce the network reserve capacity concept for a capacity improvement plan.*

Haas, I., Bekhor, S., 2016. A parsimonious heuristic for the discrete network design problem. Transportmetrica A: Transport Science 12, 43–64.

Abstract: The problem of selecting the optimal set of transportation projects out of a given set of projects, known as the network design problem (NDP), has been researched for many years. Typical transportation projects are interdependent in their nature, which turns the problem into a very complex one. When a certain objective is sought, an exact solution of the problem can be derived only by enumerating each possible project combination. Therefore, when a large set of possible combinations is involved an alternative approach must be taken. Meta-heuristic methods usually used for this purpose do not make use of the special properties of the given problem. This paper proposes an alternative heuristic that simplifies significantly the solution process. The benefit of a certain combination of projects is inferred based on a subset (pairs or triplets) of projects. The proposed heuristic is tested on simple networks and applied for a real-size network. The paper also discusses the trade-offs between solution accuracy and computation time.

Comment: *Assume every scheme/project gives some benefit, therefore implementing all projects gives upper bound on maximum benefit. A lower bound is given by the best (affordable) individual project/scheme. Now assume each additional project adds equal benefit toward upper bound. Similarly, for pairwise additions.*

A heuristic is developed which does model runs for: no schemes (1 run), all schemes (1 run), each individual scheme (n runs), then considers all possible pairs of schemes (n(n-1) runs) to understand the interdependencies. This approach can be augmented by considering all triples of schemes, which increases computation time but can improve optimality.*

They note in the examples presented that there are typically many combinations of schemes that (satisfy the budget constraint and) achieve very similar performance levels (optimality).

Attention is paid to identification of schemes which induce the Braess paradox.

Almeida, A.T.D. and Duarte, M., 2011. A multi-criteria decision model for selecting project portfolio with consideration being given to a new concept for synergies. Pesquisa Operacional, 31(2), pp.301-318.

Abstract: Project Portfolio Selection (PPS) is a kind of problem found in a variety of practical situations, such as research and development planning. Several different approaches have been proposed to deal with Project Portfolio Selection (PPS). However, the consideration on benefits synergies between projects is little addressed in the literature. The main focus of this paper is on synergy between projects, which is related to the interactions between the benefits of the projects. In this paper, a method has been developed to meet some of the major limitations of existing models: the inadequacy of the treatment of multiple criteria and inter-relationships between projects and the absence of the recognition and incorporation of managers' experience and knowledge, concerning to synergy between projects. The decision model is formulated as a non-linear 0-1 optimization problem, which considers the evaluations of projects and the benefit synergies of these projects.

Comment: *A particular innovation of this paper is the use of a synergy matrix between projects. This synergy matrix is a judgemental one derived by an expert with familiarity with the projects.*

C2.1.4 OTHER INTER-DEPENDENCIES

Maggiore, M. and Ford, K. (2016) NCHRP Report 806: Cross-Asset Resource Allocation and the Impact on Transportation System Performance. TRB.

Abstract: Transportation agencies face a common conundrum—they are often charged with analysing the performance outcomes of investments across different projects, but they lack the tools, methods, and models for the analysis. Moreover, these same tools and methods could help agencies in selecting the best portfolio of projects to yield the greatest improvement in transportation system performance. In Report 806, the National Cooperative Highway Research Program (NCHRP) presents a framework for cross-asset resource allocation that can help achieve optimal system performance. The methodology links transportation planning and budgeting with project selection and programming. Cross-asset resource allocation is a multiobjective optimization problem and the methodology presented involves a multiobjective decision analysis (MODA). MODA achieves a mathematical solution that maximizes the overall score of a portfolio under the given budget or performance constraints. MODA components are discussed along with the development of an Excel-based decision support tool.

Comment: *the project and tool developed does not address inter-dependencies between projects and is more concerned with multi-criteria decision-making methods*

Systematics, C., Inc.,"Development of a Multimodal Tradeoffs Methodology for Use in Statewide Transportation Planning,". Unpublished Final Report for NCHRP Project, 08-36 task 7. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP08-36(07)_PhaseI_FR.pdf

Abstract: Many states are in the process of updating their statewide multimodal transportation plans. In the past, total needs have been usually identified by mode, followed by a tradeoff exercise to financially constrain the plan to a target funding level. These tradeoffs, for program areas like safety, congestion relief, preservation, freight mobility, and alternative modes have generally been made on a policy basis, with little or no technical analysis to aid in the decision. A methodology was developed that can account for cost/benefit analysis, goal/achievement analysis, and performance considerations, thereby improving the decision-making tradeoff process.

Comment: *Inter-dependencies between programmes are assessed in terms of how they contribute to higher level goals. No methodology is presented to formally identify the package composition. The report 'finds' that the task to do so is complex and methods do not exist.*

Tsekeris, T., 2011. Public expenditure competition in the transport sector: intermodal and spatial considerations for Greece. Environment and Planning A, 43(8), pp.1981-1998.

Abstract: The development of transport networks requires public investments, in terms of government expenditure, on several types of (road, rail, port, airport, and urban public transport) infrastructure, including their operational and maintenance services. This paper develops and implements a system-wide spatio-economic model to analyze the expenditure competition among different types of investment in the Greek transport sector. The suggested approach can offer valuable insight into the economies of scale and synergies associated with a particular transport investment. It is also extended to consider how such investment determinants as population concentration, economic growth, and political considerations at the prefecture level affect expenditure allocation to different types of transport infrastructure. The results indicate the statistical significance of scale effects of transport investment, substitution effects of road investment on other types of transport investment, and political factors on different types of transport investment. Airport investment relates to the most significant synergistic effects on expenditures in other types of public transport facilities. Thus, policy makers must take these fiscal externalities into account for the strategic planning and evaluation of infrastructure supply, and coordinate or subsidize public transport projects with significant positive externalities.

Tsekeris, T., 2014. Multi-sectoral interdependencies of regional public infrastructure investments. Socio-Economic Planning Sciences, 48(4), pp.263-272.

Abstract: Public investment decision-making processes involve multiple and interrelated sectoral and regional policy objectives and budget constraints. This paper presents a dynamic spatio-economic model that considers multi-sectoral investment interdependencies using data at the prefecture level in Greece. The expenditure allocation dynamics of most types of regional public investment are found to be competitive with each other. This outcome is attributed to the lack of policy coordination, technological and budget constraints, geographical factors, and equity and political considerations. The investment interrelationships may have a significant effect on future state funding needs and the strategic assessment of infrastructure development at the country level.

Comment: *These papers were supplied in response to the UTSG email request. Their applicability to our study seems limited. The main message is that taking better account of complementarity and substitutability in government expenditure on infrastructure could lead to an improved outcome – which is something our study aims to do.*

C2.1.5 UNCERTAINTY

Bey, R.P. and Porter, R.B., 1977. An evaluation of capital budgeting portfolio models using simulated data. The Engineering Economist, 23(1), pp.41-65.

Abstract: The effectiveness of six approaches to capital budgeting under uncertainty is evaluated. The standard of comparison was a second-degree stochastic dominance model. The research environment consisted of ten hypothetical capital budgeting projects and an existing asset base. Variations in project demand, competitive actions, and technological changes were simulated by changing the shapes of the cash flow distributions. The required net present value distributions were obtained through a simulation and state of the economy methodology. Results of the study indicated that the models were sensitive to the characteristics of the cash flow distributions and that financial managers must exercise considerable care in their selection of a capital budgeting decision model. The mean-semi variance model yielded the most consistent results while decisions based upon the traditional net present value model were incorrect much of the time.

Comment: *This old paper is concerned with uncertainty in the benefit stream. It shows that benefit risk and attitude to risk can affect project portfolio selection. It shows that using a risk adjusted discount rate in calculating the NPV is not as good as explicitly modelling the risks. It is not well cited (Google Scholar gives 6 citations).*

Gabriel, S.A., Ordóñez, J.F. and Faria, J.A., 2006. Contingency planning in project selection using multiobjective optimization and chance constraints. Journal of infrastructure systems, 12(2), pp.112-120.

Abstract: The authors present a multiobjective optimization model for determining an efficient budget allocation for a portfolio of infrastructure projects. The model takes into account both the cost and the priority rank for each project while considering probabilistic constraints related to the available budget. A zero-one multiobjective optimization problem with chance constraints is developed and solved. This approach helps to more accurately take into account competing objectives such as cost and value of the funded projects, as well as budget risk to find a Pareto optimal set of project selection alternatives. The authors present numerical results based on infrastructure projects from a United States governmental agency in which they analyze the Pareto optimal set of solutions for this problem and test the working of the model with several cases that highlight budget contingencies needed in the face of random project costs.

Comment: *Sets out a method to incorporate uncertainty in project costs (e.g. construction) into the NPV maximisation process – such that the NPV of the programme will be maximised at a specified risk of keeping within the programme budget (e.g. 95% chance of staying within programme budget).*

BYETT, A., A. GRIMES, J.J. LAIRD AND P. ROBERTS (2017) Incorporating and assessing travel demand uncertainty in transport investment appraisals. NZ Transport Agency research report 620. Report dated June 2017. http://www.nzta.govt.nz/resources/research/reports/620

Executive Summary: The key issue of this study was to find ways to improve transport investment decisions in the face of uncertainties about future transport needs.

A literature review was undertaken. Fitting for a study of uncertainty, a broad range of research was canvassed, including uncertainties inherent in traffic modelling, approaches to value real options and processes used to address uncertainty, including, in particular, adaptive management.

The research pointed to the presence of pervasive uncertainty, as opposed to measurable risk facing transport planners. In turn, this highlighted the need for approaches that could take into account all uncertainties, irrespective of whether they could be quantified or not. The research showed how real options could be valued and why conditions for accurate valuation will seldom exist for major transport projects. Nonetheless the valuation models do provide insights into what drives value, value that is easily missed in the standard cost–benefit analysis that typically overlooks adaptation. The research showed several processes being used to address risk and uncertainty but no one elegant universal solution.

A key finding was that value does exist in flexibility and more can be done to ensure flexible solutions, where appropriate, are found. A cross-section of examples illustrates and provides insight into this value creation. Similarly, examples show where adaptive management has been used to apply some of the concepts of real options.

If stochastic models are only of limited use in the face of uncertainty, as opposed to risk, then a broader approach to decision making is required. A multi-faceted approach to uncertainty is recommended, which identifies the uncertainty of relevance to the investment decision, ways the investment may be adapted over time to suit the future that does evolve and ways this learning process might be improved by seeking learning opportunities within the investment. This process was applied to three New Zealand case studies – one ex post and two ex-ante.

The study did not find a single definitive answer on how to reduce or deal with uncertainty. Nevertheless, the study has shown that (a) a thorough process is required in the face of large uncertainties rather than adoption of a single go/no-go benefit–cost ratio; (b) learning and adaptation can be of significant value even if this involves a trade-off between interim costs versus reduced incidence of poor returns; and (c) use of one discounted expected value as the basis for a decision criterion does not transparently capture the risk propensity of decision makers.

In practical terms, the recommended solution entails the use of decision trees and scenario planning. Quantitative analysis is used to provide insights but not necessarily dictate the answer. In short, the key recommendation is that more time is taken by decision makers to understand how uncertainty interacts with decisions, and adaptive solutions which provide flexibility in the face of uncertainty are given more prominence.

Comments: *This study reviewed the literature on real option values (quasi options). It is very relevant to this study with respect to the treatment of uncertainty. It shows the benefit of developing infrastructure incrementally (as in a package/programme) as information becomes known further down the line. Computationally use is made of a decision tree, but they found it hard to parameterise. In their opinion, the analysis can usefully feed into the management of risk and project management.*