Cost–benefit appraisal methods for interrelated and interdependent projects/schemes

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Abbreviations

ATAP	Auckland Transport Alignment Project
BCR	benefit–cost ratio
capex	capital expenditure
CBA	cost–benefit analysis
CBD	central business district
DoMin	do minimum (scenario within an appraisal)
GPS	(NZ) Government Policy Statement (on Land Transport)
HS2	High Speed Rail 2 (railway network in UK)
LGWM	Let’s Get Wellington Moving
MBCM	Monetised Benefits and Costs Manual (of Waka Kotahi)
MCR	Major Cycle Routes (programme in Christchurch)
NDP	network design problem
NLTF	National Land Transport Fund (NZ)
NPV	net present value
PI	project interdependency
PV	present value
SACTRA	(Scottish) Standing Advisory Committee on Trunk Road Assessment
TAG	transport analysis guidance (of UK Department for Transport)
TAIP	Transport Agency Investment Proposal
VKT	vehicle kilometres travelled
WEB	wider economic benefit

Contents

Executive summary

A decision as to whether to invest in a transport project requires many pieces of information to be reduced to the core factors that will determine whether such an investment is appropriate or not. Typically, part of this process is a cost–benefit analysis (CBA), and part of this information reduction is to produce a benefit–cost ratio (BCR). When the benefits of a candidate project are expected to vary if or when uncertain future transport projects are also delivered, then one BCR will not suffice to summarise the value-add proposition of the investment. A range of BCRs most accurately describes the uncertain future when project interdependency exists.

This research report sets out a method to consistently and systematically develop a range of BCRs that can be used within the Waka Kotahi decision-making process when project benefit interdependency exists. The method is developed from a search of literature into project interdependency, programme formation and CBA, from an investigation amongst colleagues of current practice and from a sketch model exercise where a 5-project transport model was developed to explore demand growth, congestion and re-routeing effects. The method was then illustrated and tested on a cycleway programme in Christchurch, leading to further refinement and a recommended method to be used for New Zealand transport CBAs.

The practical issues raised by project interdependency are often uncertainty, scale and potentially bias. The benefit of a proposed transport project can increase if complementary future transport projects are also delivered or can decrease if future projects are competing, such as when an alternative route or mode is provided. In principle, the true marginal benefit of a candidate project can be measured by the decremental test, found by modelling all projects with and without the candidate project. In practice, it is often unknown whether future projects will actually be delivered, even when those projects sit within the long-term plans of government bodies. Hence a process is required to establish those future transport projects that are likely to create project interdependency, which can be many, to then estimate the scale of interdependency, which can require much modelling, and to finally present what may be a complex situation to decision-makers in an efficient and transparent manner. Also, the process is required to counter potential behavioural biases that can lead to competing projects being dismissed prematurely, or simply not searched for.

Two key components of the recommended method are to reduce the scale of the transport modelling for a large number of project permutations and to standardise the BCRs to be reported. The core steps within the method are:

1. Identify projects that are expected to be interdependent with the candidate project(s).
2. Group projects for modelling and reporting purposes by the nature of their interdependence and by where they sit within the institutional planning process.
3. Phase the modelling of future project scenarios in a manner to accumulate the information required and at the same time test whether further modelling would materially alter results.
4. Report multiple BCRs in a format that shows the increasing uncertainty about each being attained, albeit the actual level of uncertainty may be unknown.

The advantages of the method are that project interdependency is searched for and taken into account in a manner that is efficient and provides a transparent result to decision-makers. The disadvantages of the method are the reliance on expert judgement at stages within the analysis and that the range of BCRs reported still do not fully capture the range of possibilities. It is contextual as to whether the complexity introduced into the analysis is an advantage or disadvantage – it is definitely more work for analysts and more information for decision-makers to take into account, and this will improve decision-making. Improved decision-making can only be an advantage. However, where projects already have a robust business case,

then the additional information from the interdependency analysis may offer little added value to decision-making.

Abstract

The incremental benefit of a transport project can often depend on if or when other transport projects are also delivered, which in turn can lead to the oft-used standalone benefit–cost ratio (BCR) for a project not accurately measuring its marginal value-add. This research paper explores methods to otherwise measure the incremental benefit when project interdependency exists. This entailed a survey of literature, discussion with colleagues in New Zealand and the UK, the creation of a factitious transport network to test transport interdependency, the development of a practical method to apply to New Zealand transport projects, and the testing of the method with a Christchurch cycleway programme. Two key parts of the method developed are to reduce the permutations of projects to be modelled, by following a defined process, and to report multiple BCRs that progressively record the incremental value of a candidate project as more interdependent projects of decreasing certainty are added as the reference case. For the cycleway programme, a candidate project as at 2018 was shown to have expected complementary and competing effects with other planned cycle projects, both within and outside of the cycleway programme. The net cycleway interdependency effect was complementary, but the additional value was less for those projects that were planned to be delivered beyond the immediate three years. Presenting three BCRs plotted in order of uncertainty was judged to be helpful to decision-making.

1 Introduction

The core issue of interest in this research project is the cost–benefit analysis (CBA) of interdependent transport projects. This involves:

1. selecting a set of (already defined) projects
2. making several runs of a transport model to compare the expected transport outcomes for several future years
3. repeating runs for potentially many permutations of the interventions, especially as the number of interdependent projects grow
4. possibly re-running the model with different underlying assumptions about the operating environment, including associated land use
5. converting all the model outputs into dollars of expected welfare effects
6. presenting, including in summary form, the results to decision-makers (along with other non-monetised benefits and costs).

Not surprisingly, one of the key challenges to analysis of this sort – and hence to this research project – is to reduce the scale of the analysis without unduly compromising the integrity of the results. The methods available to reduce the scale of the analysis will have to be drawn from several fields. The first step is about grouping projects, something that is already done within programme management – what can be learnt here? Computing and choosing amongst many permutations is the stuff of operations research. The primary market approach to a transport CBA is only one way to estimate welfare benefits and costs amongst economic methods. The increased scale of analysis is familiar to analysts of risk and uncertainty. The presentation of complicated results is common to many fields. Each field is likely to have something to offer. And of course, institutional arrangements exist that try to deal with many of these issues already. What are these and how can they be improved? These are all matters the authors have considered in this research report.

1.1 Background

This research takes as its starting point the recent research undertaken by Arup and Institute for Transport Studies (2019) on programmatic appraisal (also reported in Bruce et al., 2019). One of the authors of that study is in this research team. The literature review, in particular, draws heavily on that work but has been expanded in several dimensions: to include literature on programme formation; to strengthen the discussion on risk and uncertainty; and to strengthen the discussion on how practitioners around the world treat interdependent projects, with a particular emphasis on New Zealand practice. In addition to the transport policy and appraisal practice literature, we reviewed:

- the literature on programme definition/formation
- CBA theory on project selection and decision criteria, including the treatment of risk (which is well-established, and there are good treatments in textbooks)
- the optimal design of networks (the network design problem (NDP))
- the broader literature on the optimal selection of projects within programmes (project portfolio selection), which touches on the use of linear programming methods (eg, knapsack routines).

As part of the original work, a set of keywords was used to search the literature databases of Transport Research International Documentation (TRID) and Scopus. Google Scholar was also used. Further papers were identified by utilising citation information. This was supplemented with the CBA texts of Boardman et al.

(2011) and de Rus (2010), and texts on programme formation such as Thiry and Dalcher (2015), in addition to reviews of appraisal guidance in the UK and New Zealand plus interviews with practitioners in Scotland, England, New Zealand and Australia and interviews in the original work with practitioners in the US, Sweden and Norway. The practitioner discussions were conducted under Chatham House rules, and the discussions reported have therefore been anonymised.

1.2 Research questions and project scope

The questions provided to this research team for consideration are as follows:

1. Set out a theoretical framework on how interdependent schemes and packages can be identified and how interdependency benefits can be assessed.
2. Identify and develop techniques and methods to assess the benefits of interdependent transport interventions.
3. Determine how schemes that are interdependent can be grouped into programmes and what the criteria should be for grouping schemes into programmes.
4. Determine how to treat uncertainty of uncommitted schemes.
5. Outline how benefits of schemes should be correctly attributed to ensure that there is no double counting.
6. Outline how the developed methodology be included in the NZ Transport Agency *Economic Evaluation Manual* (now the Waka Kotahi *Monetised Benefits and Costs Manual* (MBCM)).

To paraphrase, the purpose of the research is to develop an economic framework and a practical process to appraise interrelated and interdependent packages of transport interventions so as to assist practitioners in assessing these often complex scenarios. The output of this research is intended to be meaningful and pragmatic methods to include in the Waka Kotahi MBCM.

Primarily this research project is concerned with the measurement of benefits, putting aside that costs can also be interdependent, and is to include consideration of monetised benefits and wider economic benefits (WEBs) that currently are defined within the MBCM, including travel by private vehicles, public transport and active modes, local and national projects and, importantly, the benefit interdependency arising in each case. Out of scope for this project are non-monetised benefits and transformational WEBs.

1.3 Report structure

This report presents the outcome of research into the appraisal of interrelated and interdependent projects. Following this introductory chapter, Chapter 2 sets out the results of a literature review into the issues raised by project interdependency and an investigation of current practices. More detail on three threads of research are provided in Appendices A, B and C. Insights into the nature of transport project interdependency were developed further by way of a sketch transport model, presented in summary form in Chapter 3 and in detail in Appendix D. A method was iteratively developed to identify, measure and report benefit interdependency – Chapter 4 and Appendix E – which was then applied in a case study – Chapter 5 and Appendix F – and then further refined in Chapter 6. Chapter 7 concludes the report and points to areas where further research would be of value. Chapter 6 could also be read as a standalone chapter for those looking for a quicker overview.

2 State of the art

This chapter presents a summary of the literature review. A more extensive coverage of the literature is provided in Appendices A, B and C.

2.1 Interrelated and interdependent projects

The defining characteristic of interrelated and interdependent projects is that total benefits are contingent on multiple future projects that are uncertain to proceed. This adds another layer of uncertainty to the value of the project under consideration and presents challenges within transport CBA methods and how they interface with institutional decision-making.

Projects can be a part of **programmes** and **portfolios**. There is an extensive literature on the definition and formation of programmes and portfolios (see, for example, Martinelli, 2014; Maylor & Turkulainen, 2019; Pellegrinelli, 2011; Project Management Institute, 2018; Thiry & Dalcher, 2015). Projects are our focus of interest, and our interest is in the project's CBA. It is at this project level that the transport business case is developed. Programmes comprise projects, and the projects within those programmes will have some sort of interrelationship: including mode, network type, objectives, or geographic proximity. However, they can also be developed for administrative reasons. There is much variety. Some projects (mega-projects) may be larger than some programmes and comprise many elements. Bringing all this together is the portfolio, which represents the collection of investments.

In transport, programmes typically have *not* been put together to capture all interdependency benefits, albeit some commonality exists between projects. Alternative motivations around programme delivery, including regulation and programme financing, tend to take priority in the programme formulation. Examples within the New Zealand transport sector include:

- programmes centred around road safety (eg, the Safe Network Programme[1])
- the low cost, low risk improvements programmes,[2] which are primarily administrative programmes where the commonality between projects is their small scale (< $2 million) and promotion by local councils
- the state highway corridor programmes.

The Waka Kotahi portfolio then represents the aggregation of its programmes. From a practical perspective, analysis of the interdependency benefits between projects must not therefore be confined to looking within a defined programme but must also look between programmes (ie, at the full portfolio of transport investments that span central government and local authorities). This is particularly the case when programmes may be defined by mode, because modes tend to compete (eg, car versus public transport) but can also in instances reinforce one another (eg, active travel and public transport).

To define interdependent projects, it is useful to first set out the converse. **Independent projects** have benefits and costs invariant to which projects enter the programme, and any such project can enter a programme. They differ from **mutually exclusive projects**, which are projects that cannot all simultaneously enter a programme. Usually, project development requires the consideration of several mutually exclusive alternatives: different route alignments, junction designs, design standards, etc.

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[1] https://nzta.govt.nz/safety/our-vision-of-a-safe-road-system/safe-network-programme/

[2] https://www.nzta.govt.nz/planning-and-investment/planning-and-investment-knowledge-base/201821-nltp/activity-classes-and-work-categories/local-road-regional-and-state-highway-improvements-activity-classes/wc-341-low-cost-low-risk-roading-improvements/

Interdependent projects are projects that are not mutually exclusive but whose benefits and costs alter depending on which other projects are also implemented. To illustrate, if we think of three projects (A, B and C)[3] that lie within an investment programme, and if all projects are independent of each other (ie, no interdependencies), the benefit of Project A can be found by appraising it against a Do Minimum (DoMin) with none of the other projects in the programme, or with Projects B or C included – the result is invariant to the project mix. The same would also be true of the appraisal of Project B and Project C. The programme benefit, if these projects are truly independent, is the sum of the project benefits, and could be depicted as in Figure 2.1. Here the green rectangles represent the benefits delivered by each of the three projects individually. If, however, any of these projects exhibit interdependencies, the benefits of the programme A plus B plus C do not equal the sum of the benefits of A, B and C appraised individually.

We can therefore think of the benefits of the programme as comprising the benefits of constructing only Project A, plus the benefits of constructing only Project B, and the benefits of constructing only Project C plus the **interdependency benefits**. These *additional* benefits arising from the interdependencies between projects are labelled corresponding to areas A+B, A+C, B+C and A+B+C in Figure 2.2. The interdependencies A+B, A+C and B+C that arise through pairs of projects are termed **pairwise interdependency benefits**. The interdependency benefit A+B+C is an example of a **higher-order interdependency benefit** and in this case is a **triple**. In Figure 2.2 all projects are **complementary** to each other, as their interdependency benefits are all positive. This might be the case if A, B and C are projects in series along a corridor, designed, for example, to relieve three successive pinch points.

If, on the other hand, Project B **competed** in some way with Project A, then the benefit of constructing A and B would be less than the sum of their benefits if they had no interdependencies. This might be the case if projects are in parallel corridors. Analytically, we can think of this as a negative interdependency benefit between A and B. In Figure 2.3, we depict the competing effect of Projects A and B with a dis-benefit equal to area A+B. The benefit of the programme is therefore found by adding areas A, B, C, A+C, B+C and A+B+C to each other, before subtracting area A+B. A similar set of diagrams and discussion can also be associated with project costs.

It is worth mentioning a further dimension to this grouping of projects at this stage. We can imagine for simplicity two possible states of the world. In the first, there is a defined long-term plan for the region or corridor, within which we are appraising Project A in the firm knowledge that B and C will be delivered later. In the second, we are appraising Project A in the knowledge that B and C are possible future projects but with no knowledge of whether they will ever be delivered, even if they exist in plans. We will return to this issue of uncertainty of project delivery.

In the meantime, if our interest is in the CBA of Project A, then two important benefit measures arise. These are the **decremental** benefit and the **incremental** benefit. The decremental benefit of Project A is the added value of Project A to the overall programme. It is equivalent to a drop-in/drop-out test used in econometric modelling when trying to identify a parsimonious model specification. With reference to Figure 2.2, the value of Project A under a decremental test would be the sum of areas A, A+B, A+C and A+B+C.[4] If Project A competes with other elements of the programme, then the interdependency benefits (A+B, A+C and A+B+C) may be negative, and the benefit of A is reduced. If it is highly complementary, then these interdependency benefits may be large and hence A may add little to the programme. The incremental benefit, on the other

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[3] For convenience, Project A has been shown as having the largest standalone benefit.

[4] If the proposed investment programme consists of Projects A, B and C and the CBA is of Project A, with Project B proposed to open 5 years later and Project C 10 years later. The decremental test of Project A would therefore be against a DoMin that included Project B opening in 5 years and Project C in 10 years. This analysis takes it as certain that Projects B and C will go ahead.

hand, is the benefit derived from adding Project A to a defined 'reference case'. Classically in CBA this is the DoMin, but in an interdependency analysis we would also be interested in the added value of Project A, if B already existed or if C already existed. Thus, the incremental benefit of Project A against a reference case of Project B would be the sum of areas A and A+B but now showing as one number.

Figure 2.1 **Benefits from programme of independent Projects A, B and C**

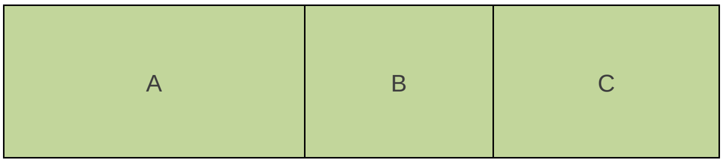


Figure 2.2 **Benefits from programme of complementary Projects A, B and C**

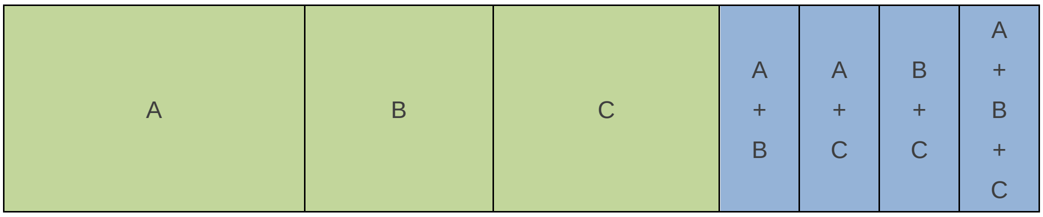
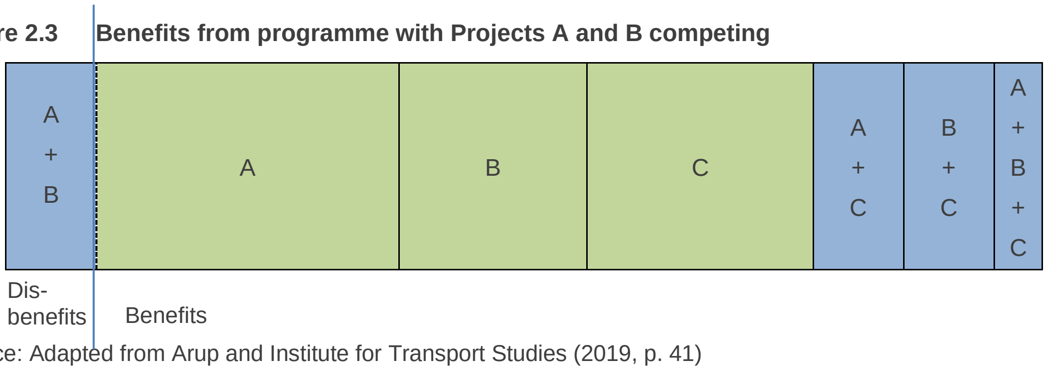


Figure 2.3 **Benefits from programme with Projects A and B competing**



Source: Adapted from Arup and Institute for Transport Studies (2019, p. 41)

2.2 Economic appraisal

2.2.1 The project cycle

Good practice in transport investment decision-making requires the development of transport investment projects that address identified problems or weaknesses in the transport system and also meet broader economic and social goals. As a result of this, it has become conventional to think of a 'cycle' of decision-making that starts with objective-setting (based on an assessment of need and goals) and proceeding through to option development and then ex-ante appraisal. This is followed by implementation and evaluation that feeds back to lessons learnt (see, for example, Nellthorp, 2017, for a broader discussion). The ex-ante appraisal typically takes the form of an option-sifting process to go from a long list of options to a short list, followed by a more detailed appraisal of the short list. CBA techniques usually form part of the latter detailed appraisal, but can sometimes be part of the option-sifting process.

Typically, we find that CBA methods are applied in the mid to late stages of the project cycle. This is because in a transport context CBA requires significant data inputs, including transport demands and network time and service quality (see, for example, the MBCM (Waka Kotahi, 2020c) and other equivalent transport appraisal guidance in Australia, the UK, Europe, etc). This typically limits its application to those projects with a reasonable degree of definition and that typically have made it on to a shortlist of potential projects. More qualitative methods are utilised earlier in the appraisal process to make the case for the investment and to sift from a long list of potential projects to a shortlist. Given that project interdependencies will be relevant at all stages of the appraisal process, this points towards the need to incorporate analysis of project interdependencies at the qualitative stage as well as in the CBA stage of the appraisal. However, this analytical constraint does not prevent programme-level CBAs. In fact, the cumulative impacts of investments on the wider economy and the environment are likely to point towards the need for programme-level CBAs (Polasky et al., 2011; Standing Advisory Committee on Trunk Road Assessment [SACTRA], 1992; Waka Kotahi, 2019).

We can therefore see three contexts to the appraisal of interdependency benefits:

- in a qualitative option generation and sifting stage
- in a programme-level appraisal
- in a project-level appraisal.

Arguably the interaction across sectoral programmes (eg, de-carbonisation) is best dealt with in the early and more qualitative stage of the appraisal. This research is concerned with the stages of the appraisal in which the CBA is applied, which in the main this will be at the project level, but occasionally it may be at the programme level. Either way the appraisal process needs to account for interdependencies throughout.

2.2.2 Decision criteria

Decision-making with CBA is concerned with maximising net present value (NPV) across all the Government's investments (Boardman et al., 2011, pp. 13–14; de Rus, 2010, pp. 131–132). The textbook position with *perfect foresight* (ie, under conditions of certainty) leads to the following set of decision rules when government budgets are constrained.

Project-level decisions:

- *Independent projects:* Benefit–cost ratio (BCR) > return of the marginal project in the government investment programme (across all policy sectors)
- *Mutually exclusive projects:* Incremental BCR > return of the marginal project in the government investment programme (across all policy sectors)
- *Interdependent project:* A decremental test – if delivery of the full programme is certain. That is, treat other projects in the programme as pre-defined in the DoMin, then calculate return. Decision criteria as per either independent or mutually exclusive projects as relevant.

Interdependent project selection for inclusion in a programme:[5]

- *Where no programme budget is specified.* Treat each potential project combination as mutually exclusive. Use the mutually exclusive project selection criteria to choose the optimum project combination.
- *Where the programme budget is finite.* As above, but an iterative search is required to meet the programme budget constraint.

Mutually exclusive and programme optimisation type decisions require linear programming methods based around knapsack routines to identify the preferred project(s) (Kellerer et al., 2004; Minken, 2016). In practical terms these algorithms are difficult to implement due to the need for pre-defined BCR thresholds representing the marginal return on a government investment.

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[5] When projects are independent, the project-level decision criteria are sufficient to define a programme.

Returning to the decision criteria, there are two key practical issues.

First, the decremental test requires the other interdependent projects to be pre-defined and certain. This is often not the case, so we are left resorting to a series of incremental tests.

Second, no government we are aware of defines the marginal return on a government investment that can be used as part of these tests. Invariably, the CBA, the non-monetised impacts (including fit to national policy objectives), and an understanding of uncertainty and risk form the basis as to whether a project enters the government's investment programme. If codification of thresholds is provided, it is often as a requirement to have a BCR > 1 (ie, NPV > 0). This gives the space to accept projects with low monetised benefits but large non-monetised benefits (Mackie et al., 2014). Waka Kotahi (2020a) and the UK Department for Transport (2017) go a step further and set out value-for-money thresholds, but these are used in a descriptive way rather than as a threshold that is required to be passed for investment. This practical difficulty currently represents an impasse where judgement and institutional rules are being used to decide, say, whether to proceed with a costly Project A, which is of high value but is contingent on B and C, but B has significant adverse non-monetised environmental impacts and there is uncertainty as to whether C will actually be delivered.

2.2.3 Decision-making with risk and uncertainty

A key feature of project interdependencies is that other projects in the portfolio may not be implemented. The interdependency benefits are therefore risky or sometimes simply uncertain.

Taking the risky situation first, risk within a CBA decision-making framework is dealt with in a probabilistic manner using expected values. The expected value is obtained by summing the product of the benefits from different potential future states and their probabilities.

When probabilities in one period are conditional on what occurs in previous periods, a more flexible framework than this basic expected value procedure is required. This is often termed *decision analysis* (Boardman et al., 2011, p. 174), but is also known as *decision tree analysis* (for a review, see Byett et al., 2017). These decision trees can easily become complex, and as a consequence software exists for their application. Byett et al. (2017) give several transport examples.

The key feature with multi-time-period decision-making is that it offers the *option to learn*. Delaying investment decisions until new information becomes available reduces the uncertainty, possibly eliminating it. The expected value of information gained by delaying an irreversible decision is called a *quasi-option value*. The learning can either be exogenous (ie, imparted to the decision-maker through a form of passive learning) or it can be endogenous (a form of active learning). Whilst some analysts consider the quasi-option value to be a separate benefit category, it 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, p. 190). Quasi-option values are also known as 'real option values', and as such they have parallels with real options analysis and financial options analysis.

The riskiness of the benefits should form part of the decision.[6] This gives rise to the certainty equivalent concept, discussions around the pooling of risk over many individuals, and broader discussions around discount rates[7] (Arrow & Lind, 1970; Boardman et al., 2011, pp. 173, 217; de Rus, 2010, p. 157). An

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[6] The exception would be where the decision-maker and all those impacted by the project are risk neutral. Then only the expected value is of interest.

[7] An alternative to using certainty equivalents is to adjust the discount rate to reflect the riskiness of the investment. The downside of this is that benefits in later years of a project are discounted more heavily than those in the early years, when in fact it may be that the early years are more risky.

underlying feature of the analysis that supports such decision-making is an understanding of the potential distribution of benefits. This is in addition to the expected value of benefits. A risk-averse decision-maker prefers a certain lower income over a higher 'expected' risky income. Underlining the importance of this is the comment by the National Audit Office (2013) in the UK on the proposed High Speed Rail 2 (HS2) investment that the Department for Transport failed to communicate the uncertainty to the BCR by quoting point estimates and not ranges.

In the context of interdependent projects, a depiction of the distribution of benefits can only be obtained through a probabilistic analysis – that is, if the future is risky rather than uncertain. To our knowledge, this has not been undertaken in practice due to the difficulties in attributing probabilities to the likelihood of alternative interdependent projects going ahead. However, research is lacking as to what extent such probabilities can be derived. In the absence of such research, the impact of uncertainty around which projects will be present in future years can only be undertaken through a mixture of *scenario analysis* and *sensitivity analysis*. Scenario analysis would involve dropping interdependent projects in/out of potential future scenarios. Sensitivity analysis would involve adjusting their implementation date (opening year) and design standard (eg, single carriageway, dual carriageway, motorway).

This inability in practice to attribute probabilities to the different potential future network configurations implies that it is the treatment of uncertainty within the decision-making process that is more relevant than risk for the assessment of project interdependencies. Uncertainty, in contrast to risk, is where probabilities cannot be associated with outcomes. As a policy area, this is most pertinent to the treatment of the environment and climate change (see, for example, Polasky et al., 2011). It could also arise when a series of interventions are required in a road network that are to be phased over years or possibly decades, say a series of road sections leading to a potentially expanded bridge, but because of institutional funding arrangements it may be uncertain whether future planned phases will actually be delivered.[8]

In the face of uncertainty, as opposed to risk, there is little that can be added analytically to the CBA, which ultimately is underpinned by calculus. Instead, authors (eg, Polasky et al., 2011) argue that uncertainty is best dealt with by a mixture of decision theory (ie, decision-tree analysis), scenarios (eg, based on thresholds), adaptive management strategies that look closely at the decision-making process, and/or the use of sensitivity testing/scenarios to reveal when thresholds would be crossed. These approaches are not directly related to CBA, but would guide the governance and decision-making framework within which the appraisal and the CBA sit. How these can be brought into an analysis on interdependency benefits needs further consideration.

In practice we see scenario analysis being utilised. The Waka Kotahi MBCM does not make specific mention of different network scenarios but does identify scenario testing and the use of multiple DoMin as tools for understanding uncertainty (Waka Kotahi, 2020c, p. 31). In the UK the transport analysis guidance (TAG) is more explicit, recommending scenario analysis in assessing the impact of uncertain future transport network developments (Department for Transport, 2019). Our discussions with UK practitioners also identified that the Department for Transport is piloting a method using several DoMin scenarios. This method establishes three conditional incremental benefit estimates by using three DoMin scenarios: with all committed projects included (the standard DoMin); then with the 'highly probable' projects added as well; and then with all projects under active consideration. This creates three incremental benefit tests and three BCRs. The likelihood of each scenario occurring needs to be described qualitatively.

An alternative approach to addressing uncertainty in the configuration of the future transport network is to undertake investment decisions at a programme or portfolio level. Our discussions with practitioners

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[8] Note, this is a situation that can also lead to gaming, to the extent that programme proposers leave the more contentious project until last, by which time there is little opportunity to re-jig the programme to avoid said project.

identified the following examples. In Scotland, the Strategic Transport Projects Review analysis led to an identification of the projects that would form the basis of investment from 2012 to 2032. This gives a degree of commitment to different projects. Additionally, it has also led to the identification and commitment to route improvement strategies. The Scottish A9 Perth to Inverness corridor is an example. Here there is a commitment to upgrade the road to dual carriageway throughout its length. This reduces the uncertainty associated with project interdependencies within the route corridor to more of a timing-related issue. In countries where national transport plans are developed (eg, Norway and Sweden), the national transport plans also give a high degree of certainty, particularly over the early project years, which are often the most important in terms of project benefits (due to the effect of discounting).

2.2.4 Separating interdependency benefits

We turn now to the question as to whether interdependency benefits, such as A+B, B+C, A+C and A+B+C (in Figure 2.2), can be divided between projects. For example, can interdependency benefit A+B be divided between Projects A and B, with a portion allocated to each? To answer this, we need to consider the project selection criteria summarised earlier. This selection criteria (and comparable knapsack routines) do not permit attribution of interdependency benefits between interdependent projects, whilst maximising NPV. Project selection for entry into a programme is dependent on the added value of the project in maximising the programme-level benefits. In fact, an advantage of programme-level appraisal is that it circumvents the desire by policymakers of attempting to allocate interdependency benefits between projects when undertaking project-level appraisals. Examples of programme-level appraisals in practice include the identification of strategic investment priorities in Scotland and the use of 5- and 10-year investment plans in Norway and Sweden, as just mentioned above.

Whilst we cannot split interdependency benefits between projects, when undertaking an interdependency analysis we can distribute pairwise, triples and higher-order interdependency benefits between projects through the use of an incremental test and on the basis of a programme’s phasing. Thus, if Project B is expected to follow five years after Project A and five years before Project C, then an incremental test on Project B would allocate interdependency A+B to Project B. However, interdependency benefits B+C and A+B+C would be allocated to Project C along with benefit A+C.

2.2.5 Thresholds and non-linearities in the benefits and costs

Another factor that makes the assessment of interdependency benefits challenging is the prevalence of non-linearities in the benefits and costs of interdependent projects – that is, the way that Project A interacts with and is interdependent with Project B is dependent on whether Project C is implemented or not. It is not just a case of looking at whether Project A is interdependent with Project B, and whether it is interdependent with Project C, and whether Projects B and C are interdependent. It is the presence of thresholds that create these non-linearities and thereby the analytical challenges.

With respect to WEBs, *threshold effects* and the unlocking effects of transport investments have been long-recognised (eg, SACTRA, 1999). In this context small transport investments can lead to large economic outcomes. However, threshold effects can also lead to the opposite, as large transport investments may lead to limited changes in economic outcomes if at an insufficient scale. Venables et al. (2014, Appendix 4.1) identify the ‘lumpy’ or non-marginal nature of the private sector investments that follow a transport investment as the source of these threshold/unlocking effects and in a theoretical framework identify the associated WEB. The context for Venables et al. was a dependent development. The existence of threshold effects has implications for interdependency benefits. Take Projects A, B and C. Each project on its own may be insufficient for development to occur, but development will occur in any pairwise combination if the threshold has been exceeded. However, the completion of the third project (to provide the full programme), may not create any additional development, as it is of an insufficient scale to cross an additional threshold.

Similar arguments are at play with the environment (Polasky et al., 2011; SACTRA, 1992), but here environmental thresholds act as costs. Again, any two of Projects A, B or C may be insufficient to cross an environmental threshold (eg, water pollution), but the addition of the third crosses the threshold and creates irrevocable environmental damage. Safety measures are another. Looking at safety in particular, motorcycle training and protection are strongly complementary, but are not necessarily additive between the different safety measures (Morrison, 2018).

With respect to time saving related user benefits, we see two distinct thresholds that are relevant: one related to congestion and the other to re-routeing. When the network is not congested, then theory suggests a simple pairwise analysis captures all interdependency benefits, but if congestion is present on the network (eg, a downstream bottleneck), then a sum of the pairwise interdependency benefits is unlikely to give an accurate measure of the interdependency benefits. Modelling of the higher-order interactions becomes necessary (Arup & Institute for Transport Studies, 2019, Chapter 4). A theoretical consideration also identifies that projects can switch between being complementary or competing in response to congestion (see Table 2.1). At a point in time a threshold is reached and re-routeing occurs, changing a complementary situation to competing. In congested urban networks with many used routes this is unlikely to be relevant, but it may be in sparse rural networks.

Table 2.1 Interdependency benefits and congestion

Interdependent project	Type of interdependency if network is either:	
	Uncongested	Congested
Induces traffic on project being appraised	**Complementary**	**Complementary** if congestion is ameliorated. **Competing** if congestion is worsened.
Abstracts traffic from the project being appraised	**Competing**	**Complementary** if congestion remains in the Do Something and both routes using either project are viable. **Competing** if sufficient capacity on one route is created such that that route dominates route choice.

Source: Adapted from Arup and Institute for Transport Studies (2019, p. 62)

Two main points arise from this discussion. The first is that any interdependency analysis must be cognisance of threshold type effects. The second, and following from this, is that if threshold effects are likely to exist (and in the main they will), then to get a full understanding of all interdependency benefits, all potential project permutations must be modelled (eg, for three projects (A, B and C) these would require modelling the DoMin plus seven scenarios: A; B; C; A+B; A+C; B+C; A+B+C). It is a topic of this research project to explore when the modelling analysis could be reduced without unduly diminishing the understanding of interdependency benefits.

A final point is that interdependency benefits for each benefit category may move in different directions. The presence of threshold effects, and non-linearities in the functional forms of the benefit categories (eg, congestion effects, accessibility function in agglomeration economies, safety impacts), means that context will always be important. If a full picture of interdependency benefits is required, this would suggest that there will also be a need to consider each benefit category individually.

This understanding from theory is supported by practical experience, though this experience is limited. Further work – as follows in this report – is therefore needed to understand the congestion tipping points regarding when user benefits flip from being complementary to being competing (and vice versa). This practical understanding is also of interest because if we know when the interactions between projects are well-behaved, we can use a simplified modelling strategy based around a pairwise analysis.

2.3 The curse of dimensionality and transport modelling

A key difficulty faced in practice is the sheer number of project combinations that need to be analysed to obtain a full picture of the potential interdependency benefits arising from a project. This is known colloquially as the curse of dimensionality. To illustrate: if there are two decision options for each project (build or not to build) then there are 2^n possible project combinations (including the DoMin), where n is the number of projects that could be considered as part of the investment programme. Thus, if there are 7 route sections, there are 127 project combinations plus the DoMin. If two different infrastructure standards were also available for each section, then this would increase to 3^n possible project combinations (including the DoMin), which for 7 potential route sections would lead to 2,187 possible combinations. Adding in potential variations on phasing or timing of project combinations and different demand growth scenarios increases the potential combinations further. This rapid proliferation of project combinations is an example of the 'curse of dimensionality'.

The curse of dimensionality is a familiar challenge for those considering 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) (Leblanc, 1975). The intention of this field of research is to efficiently identify the optimal network, and therefore it has strong parallels to the problem of optimally defining an investment programme. A brute force method would require the analysis of every potential project combination, but the curse of dimensionality makes this an onerous requirement even with access to modern computing power. To be more efficient, a search algorithm is required to identify the global optima. However, the problem is well-known to be non-convex – that is, there are typically many local optima making it very difficult to determine the global optimum (Liu & Wang, 2016). 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.

In search of a heuristic that would approximate an NDP global optima, Haas and Bekhor (2016) proposed identifying the interdependency benefit that arises from pairs of projects. Their heuristic then identifies the projects that would make up the programme by firstly identifying the projects that deliver the highest benefit, and then adding in further projects based on least cost. They apply this approach to single (standalone), pairwise and triplet treatments of projects within the programme, and find that the total network travel time of their proposed programme is close to the total network travel time of the optimal programme. The more interdependencies that are considered, the better the approximation is. However, Arup and Institute for Transport Studies (2019) found that this heuristic fails where congestion is large. This may then suggest that for immediacy, more qualitative techniques may be required for the analysis of project interdependencies – certainly in terms of narrowing the options down that are analysed with transport modelling and CBA.

2.4 Discussion

A key challenge with the CBA of projects with interdependencies is a need to consider firstly how to identify project interdependencies that are relevant to the decision-making around project selection whilst minimising the analytical effort. Secondly it requires a treatment of risk and uncertainty. Limitations on modelling capabilities and data (project definitions, probabilities, etc) mean that some approximation will be necessary – certainly given the current state of knowledge.

As a way of structuring the problem and reducing its scope, we can think of a typology of projects. Consider that we have two types of projects: enabler and peripheral. Enabler projects permit investment programmes to be developed around them (eg, missing links), whilst peripheral projects are just part of the overall investment programme. Some of these projects will have good value for money in a standalone capacity and others will have poor value for money. We can depict this in a two-by-two matrix as in Table 2.2. It is primarily for projects that exhibit poor value for money (and have a high cost) and where the decision to invest is contingent on demonstrating a robust CBA that there is a need to quantify the interdependency benefits, and these interdependency benefits will need to be large to justify a significant change in the categorisation of value for money. Arguably this is most essential for the 'enabler' project (top left of the matrix) as these are essential for the programme. Even in this enabling, high-cost project situation, it may still be that some early-stage modelling and a narrative may suffice – this will depend on the nature of the interdependency. Marginal peripheral projects can be substituted for other peripheral projects, re-designed or phased to occur later in the programme when, for example, demand may have increased. This way of thinking also points towards the advantage of a programme-level CBA in addition to a project-level CBA, albeit the extra analysis increases the cost of analysis.

Clearly within this line of thinking there is a subjective decision that must be made about what size of interdependency benefits are needed to change an investment decision from reject to accept. What is a significant amount of interdependency benefits in this context? There is also a need to consider what constitutes an enabler project or a peripheral project and whether there should be any other project categories.[9] If looking to give assurance to decision-makers whilst minimising analytical effort, it would also suggest the interdependency analysis focuses on the key benefit categories that drive these benefits. For an active travel project this might be health-related benefits, whilst for a road capacity project it might be travel time savings.

Table 2.2 Interdependent project typology

	Poor value for money	Good value for money
Enabler project	Quantification of interdependency benefits necessary in the economic case to justify programme and project progression.	CBA in economic case is adequate for project progression supported by narrative argument in the strategic case, including that benefits are resilient to competing projects.
Peripheral project	Quantification of interdependency benefits may be needed.	CBA in economic case is adequate for project progression supported by narrative argument in the strategic case, including that benefits are resilient to competing projects.

If interdependency benefits become critical to the decision as to whether to select a project or not, then it becomes important to model them. Whilst desirable and seemingly intuitive to base an interdependency analysis on pairwise benefits, the existence of thresholds and non-linearities in benefits and costs means that such a strategy may lead to incorrect decisions being made. Context is important. This research will therefore consider the circumstance in which such a pairwise analysis may be applicable.

Even with pairwise analyses, some systematic strategy is required to prune the project combinations to be analysed to something more manageable. For example, under what circumstances can we group projects together? Under what circumstances can we disregard a project as not being sufficiently interdependent with our project of interest? Such a strategy will resonate with the adaptive management methods referenced earlier and would likely require a mixture of analytical analysis and expert judgement. Alternative strategies would be programme- or portfolio-level appraisals, as per the previously mentioned Scotland, Norway and Sweden examples, or a multiple DoMin project-level appraisal as, for example, being piloted by the

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[9] The Request for Proposal refers to union, dependent association and dominant effect project combinations, which could be viewed as subsets of the two categories depicted in Table 2.2.

Department for Transport in the UK. A better understanding of these alternatives is required to take the CBA of interdependent projects forward in practical terms.

Once interdependency benefits are determined to be important, it also becomes necessary to understand the level of risk and uncertainty to which they may be subject. If there is no uncertainty, then the decremental benefit measure gives a measure of the added value of the project to a programme or portfolio. However, if there is no certainty as to what other projects will be implemented, then the interdependency benefits will be risky or uncertain. There is a general recognition amongst practitioners that such risks and uncertainties need to be conveyed to decision-makers. However, our review has not identified any established methods for this. The textbook position for risky outcomes is through some form of probabilistic analysis, but the evidence base is devoid of any probabilities that can be attributed to future network definitions (ie, the likelihood of other projects in the portfolio going ahead). The standard method to treat this uncertainty then becomes through the use of sensitivity analysis and scenario analysis, and the consideration of thresholds (eg, passing a value-for-money category). How best to then communicate the results of these scenario analyses to decision-makers is seemingly unresolved. Again, drawing something from adaptive management methods may provide insights.

As an alternative to this project-level risk analysis, institutional approaches that permit project selection decisions at a route corridor level or at a national or regional plan level have merit. Such higher-level analyses reduce uncertainty as to what other projects will be implemented, and therefore reduce the level of risk analysis required relative to institutional frameworks that make decisions at a project level.

Finally, whilst this research is concerned with the CBA of interdependent projects, it is clear that interdependencies would ideally be considered at all stages in the project appraisal cycle, even for the stages where CBA is not routinely applied (namely at the early optioneering stages).

3 An exploration of project interdependency benefits

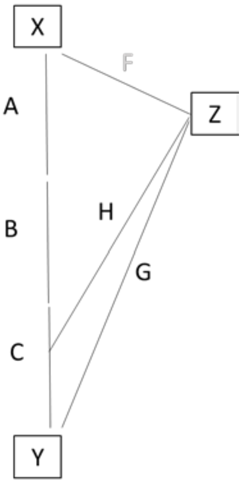
This chapter discusses the results from a factitious sketch network that was created to enable full modelling of all project permutations for a range of demand scenarios – 160 runs in total as it turned out. This modelling led to insights discussed below. Such a large number of runs for a standard traffic model would not ordinarily be viable. How the number of runs might be reduced to a tractable level is considered in Chapter 4. More detail on the sketch model results is available in Appendix D.

3.1 Introduction

The literature reviewed in the previous chapters leaves several gaps about the nature of project benefit interdependency that we wish to explore before embarking on method development and the case study. Primarily in this part of the analysis we are interested in exploring the interaction between induced demand and congestion and the impacts of re-routeing on interdependency benefits. We are also interested in exploring issues at the interface between analysis and decision-making – primarily presentation of results (tabular versus graphical), programme-level appraisal versus project-level appraisal, and the treatment of uncertainty within those appraisals.

This chapter therefore describes a sketch network created to explore these particular gaps, and the results that come from applying it. The sketch network is not meant to be a complete modelling system, but is an investigative tool that helps illuminate and helps frame certain aspects of the problem in advance of moving on to the method development phase. At proposal stage it was envisaged that these explorations would be undertaken in a spreadsheet, but we have opted to use a more sophisticated approach in the use of the SATURN network assignment model. However, the analysis remains high level (commensurate with the spreadsheet approach initially proposed) and framed around answering a handful of research questions.

Figure 3.1 Sketch network



The sketch network (Figure 3.1) contains a small number of complementary and competing road projects (Projects A, B, C, G and H) between three nodes (X, Y and Z). To ensure there was a full range of congestion in the analysis, five different demand scenarios were modelled (a base demand of 500 vehicles/hour times 0.5, 1, 2, 3 and 4 – these have been labelled Demand Scenarios 0.5, 1.0 etc). The demand model itself is unimodal and of a single time period but allows re-routeing and also includes an elastic demand curve. The use of the elastic demand curve allows a number of behavioural responses on traffic flows (and vehicle kilometres travelled (VKT) on the upgraded links to be captured in aggregate, even though they are not modelled explicitly. These include all the induced traffic effects of:

- trip re-timing
- re-distribution
- mode choice
- land-use change.

While covering a wide range of situations, this still leaves many more not considered, such as re-timing and re-distribution within the network. Likewise, benefits/costs that would occur off the transport network modelled (eg, through reductions in overcrowding on public transport services, changes in land use) are not captured. The implication is that all other benefits are zero. This does not alter the conclusions reached here but is a reminder of the complexity of real-world interactions and the modelling that we may use to reflect and inform these complexities in a tractable manner, all transport models being simplifications of reality.

An elastic response was implemented with an elasticity of 1.0 to travel time costs. Induced traffic effects (one of the main sources of interdependency benefits) are therefore relatively high in congested conditions and/or when transport costs change significantly. The projects induced traffic at levels between 1% (Projects A and B) of base network travel demands and 69% (for the most congested scenario with all projects: A, B, C, G and H). The network has also been designed to be sensitive to re-routeing at high levels of congestion, and for certain projects. For these projects re-routeing effects can have a significant impact on traffic flows on the project links – at similar levels to induced demand. For other projects re-routeing has a minimal impact. The network therefore allows a number of different situations to be explored, in a controlled manner. Again, the particular results are dependent on the network features and demand parameters and are purely illustrative.

3.2 General

A couple of general insights are quickly apparent when analysing the effects of multiple projects.

Sketch Lesson #1. Many model runs are required if all project interdependencies are to be fully measured.

Not of any surprise, the five projects generated 32 model runs (ie, 2^5). Running five demand scenarios requires 160 different model runs to provide a full description of all project and demand permutations. This would not usually be viable and would be even higher for more than five projects.

Sketch Lesson #2. Graphical representation of benefit measures is required to improve communication.

Bringing together the results from 160 model runs proved challenging. Appendix D contains tables of key results, but it was necessary to represent these numbers in graphical form to quickly assess and communicate the results. Graphs are preferred in this summary chapter.

3.3 Programme-level analysis

Two key questions are:

- To what extent might the full benefit of a programme be estimated from a partial set of model runs?
- To what extent is any error in benefit measurement related to congestion?

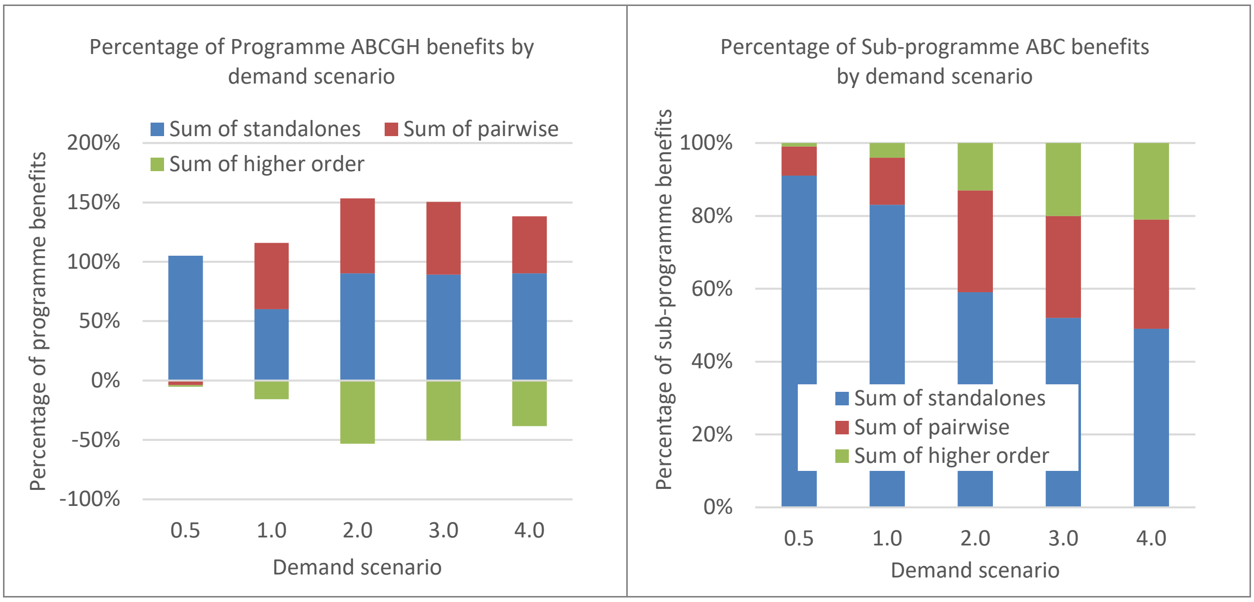
Two ‘programmes’ of key interest in the sketch network exercise were the full programme of Projects A, B, C, G and H, being a mix of complementary and competing projects along two parallel routes, and a sub-programme of Projects A, B and C, being complementary projects along a single route.

Sketch Lesson #3. A model run that includes all interdependent projects is required to accurately estimate the full benefit of a programme when project interdependency exists.

The benefits of the full ABCGH programme would have been underestimated by up to 40% if project interdependencies were ignored by simply summing the standalone project benefits (see Demand Scenario 1.0 in the first graph in Figure 3.2). The programme benefit would have been over-estimated by up to 53% if the estimate was the sum of standalone and pairwise benefits (Demand Scenario 2.0), where the pairwise benefit is taken to be the marginal benefit of combining two projects (eg, benefit of combined AB less sum of standalone benefits A and B).

The benefits of a simpler ABC sub-programme entailing a 2-node, 3-section, 1-route network would have been underestimated by up to 51% if estimated using standalone project benefits only and by up to 21% if estimated using standalone and pairwise benefits only (both Demand Scenario 4.0 in second graph in Figure 3.2).

Figure 3.2 Composition of benefits for Programme ABCGH and Sub-programme ABC



These results serve as a warning that the modelling of all interdependent projects together may be necessary for programme appraisal. The conditional nature of this conclusion arises because measurement errors of this magnitude are sometimes acceptable (eg, when the programme BCR is large) and/or the conditions imposed on this sketch network are not representative of all programmes (it is possible that ignoring interdependencies could produce even larger errors as the sketch network was not set up to establish the outer boundaries of programme benefit error).

Sketch Lesson #4. The level of congestion was not the only primary determinant of interdependency.

One issue of interest was to establish whether interdependencies increased with congestion, as to be expected when project interdependency results from operating on the steep part of the supply curve.

The sketch network did not reveal any one-to-one relationship with congestion. Programme measurement error (ie, if not all interdependencies were taken into account) was minor in the uncongested Demand Scenario 0.5, but the relationship between measurement error and congestion was not uniform (see again Figure 3.2). For the full ABCGH programme, the measurement error actually declined at high levels of demand. For the simpler ABC subset, the measurement error did increase as demand, and hence congestion, increased, but the extra error was only marginal when moving to more extreme congestion.

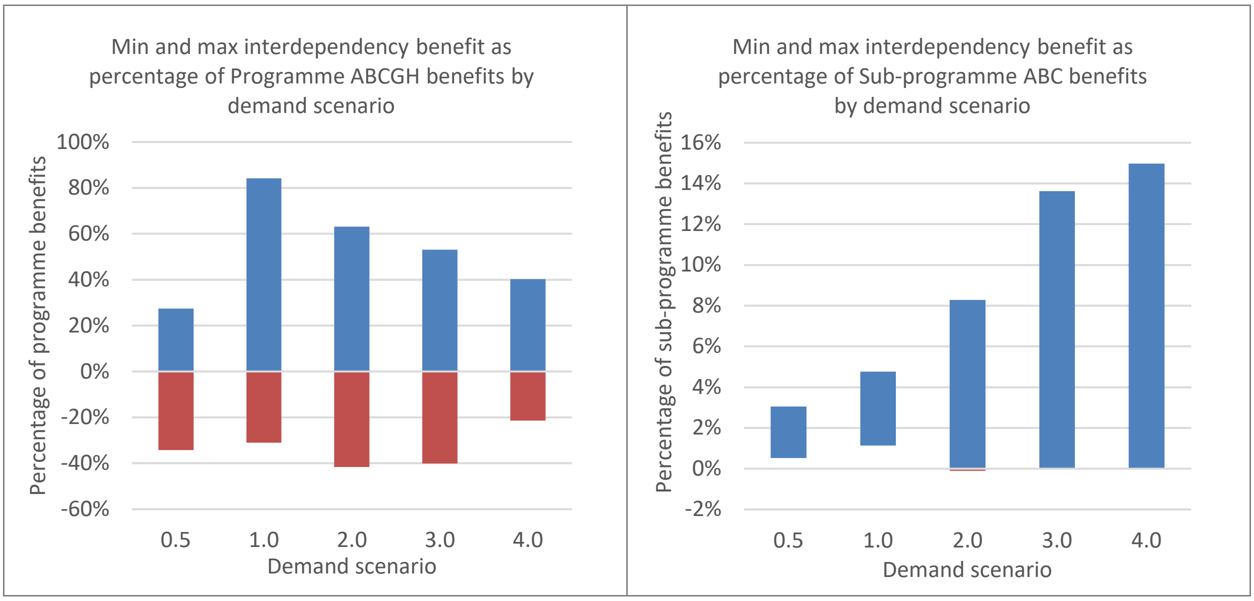
Sketch Lesson #5. Project interdependencies can be large, can be both positive and negative, and can change from positive to negative as demand changes.

Further to the previous lesson, the project interdependency terms varied considerably in magnitude and sign between demand scenarios in the full ABCGH programme where competing Project H was influential. The maximum interdependency within the sketch modelling was a CH pairwise benefit in Demand Scenario 2.0 equivalent to 84% of the ABCGH programme benefit for that scenario (see left-hand graph in Figure 3.3).

The minimum ‘benefit’ was the CGH triple (ie, benefit of project mix CGH less benefit of components C, G, H, CG, CH and GH) that was −42% (ie, a dis-benefit) of the Demand Scenario 2.0 programme benefit.

Some sign change in interdependency also occurred within the simpler ABC sub-programme, but the magnitude of these changes was not material. Likewise, the range in interdependency benefits was much narrower (see right-hand graph in Figure 3.3, noting narrowed *y*-axis scale).

Figure 3.3 Minimum and maximum project interdependencies for Programme ABCGH and Sub-programme ABC



Sketch Lesson #6. Interdependency influences the likely investment path as demand grows and more funding becomes available.

One consequence of changing interdependency is that the optimal project mix will change between demand scenarios. To put this in a more practical perspective, a 60-year horizon was assumed whereby demand growth was assumed to be 2.0% per annum for each of the starting-year Demand Scenarios 0.5, 1.0, etc and project costs were assumed to be such that 4 of the 5 standalone projects had a BCR of 1, a situation often of interest to this type of analysis (Project G was assumed to have a standalone BCR of 2.5, both to bring its costs into line with the other projects but also to test if this higher BCR survived closer analysis). Optimal programmes were then calculated for various programme budgets and for different starting-year demand scenarios, some shown below in Table 3.1.

Table 3.1 Optimal programmes by starting-year demand scenario and budget ($m), with benefits fully calculated (left) and partially estimated using standalone and pairwise only (right) – differences highlighted

Budget ($m)	Demand scenario	
	0.5	2.0
$500	AB	AB
$1,000	AB	AB
$2,000	AB	ABG
$4,000	AB	ABCH
$7,000	AB	ABCH

Budget ($m)	Demand scenario	
	0.5	2.0
$500	AB	AB
$1,000	ABH	ABH
$2,000	ABG	ABG
$4,000	ABCH	ABCH
$7,000	ABCGH	ABCGH

This exercise illustrated the interaction between benefit interdependencies, demand growth, budget and also benefit measurement error. For example, if project interdependencies were fully measured, a low budget would have only seen a programme of AB delivered, irrespective of demand. A non-constraining budget would have delivered a programme of AB at low levels of demand and ABCH at high levels of demand. However, if programme benefits were derived from standalone and pairwise benefits only (ie, from only a subset of model runs) the respective optimal programmes would have been AB (low budget) and ABCGH (non-constraining budget). Incomplete programme benefit measurement would have implied in this case a wasteful, or at least premature, inclusion of Project G within the emerging programme.

These results show, first, that erroneous programme benefit measurement can lead to sub-optimal programmes and, second, that a phasing of projects could be established to take advantage of the changing nature of project interdependency. For example, in this case, it would have been prudent to delay Project G, initially a competing project with a high BCR, until such time as demand increases to justify the extra network capacity provided by Project G.[10]

Sketch Lesson #7. Path dependency issues point towards programme-level analysis being required to be able to develop the optimal development of a network.

Aligned to above, it is also a risk that a chosen investment pathway may be sub-optimal if the true nature of the project interdependency is not understood. For example, Project G was part of the optimal programme at a mid-level budget, but the existence of Project G may have prevented the establishment of Project H if extra funding became available later, as is sometimes the case.

The ultimate optimal set of projects, including the optimal phasing of projects, was not explored further with the sketch model due to the many permutations that are possible. It was shown that the optimal project mix was sensitive to assumptions about monetised interdependency benefits, levels and growth rates of demand, project costs, programme budgets and programme time frames. However, the optimal project mix is also likely to be sensitive to construction interdependencies, non-monetised benefit interdependencies and the timing of funding availability. Analysing this complexity to derive an optimal project mix remains a matter for further research.

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[10] In this factitious example, no *cost* interdependency might be assumed between Project G and other (ABC) projects (albeit that they might exist with Project H). In practice, for other analyses, the potential for such cost interdependencies will almost certainly require at least consideration along with that of benefits.

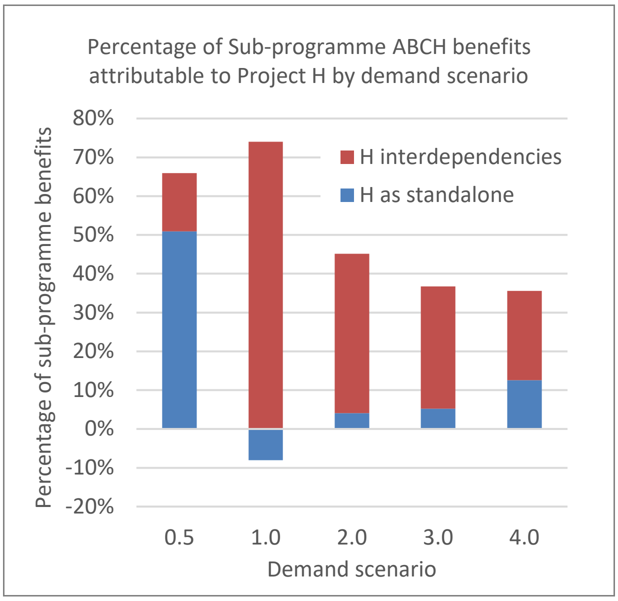
3.4 Congestion, re-routeing and the pairwise rule

The previous section discussed the extent and some potential consequences of not fully measuring project interdependency benefits. In this section we explore reasons for project interdependencies and discuss the implications from the sketch network analysis on the interaction between induced demand and congestion, and the impacts of re-routeing.

> *Sketch Lesson #8. The standalone measure only provides a true measure of a project's benefit when there is no interdependence.*

Our analysis clearly indicates that standalone benefits did not always capture the full extent of project benefits. The previous section mentioned the maximum interdependency benefits of 53% at the *programme* level. However, at the *project* level, interdependency benefits could be much more extreme. For example, if Sub-programme ABC was already in place, then the marginal benefit of adding Project H would be around 30% more than the standalone benefit of H under Demand Scenario 0.5 (see Figure 3.4, which shows the benefits of Sub-programme ABCH are 51% due to the standalone benefit of H and 66% if the interdependencies with H are also brought into account – a rise of 30%), whereas the incremental benefit of H is 11 times higher than its standalone benefit under Demand Scenario 2.0.

Figure 3.4 Effect of Project H added to Sub-programme ABC for alternative demand scenarios



> *Sketch Lesson #9. The standalone benefit of a project can significantly overstate its true benefit when a competing project is likely.*

Conversely, competing projects could also cause negative interdependency benefits at the project level. This would occur if Project H was added to ABC in Demand Scenario 1.0 above (shows as a negative interdependency benefit). The right-hand graph of Our analysis clearly indicates that standalone benefits did not always capture the full extent of project benefits. The previous section mentioned the maximum interdependency benefits of 53% at the *programme* level. However, at the *project* level, interdependency benefits could be much more extreme. For example, if Sub-programme ABC was already in place, then the marginal benefit of adding Project H would be around 30% more than the standalone benefit of H under

Demand Scenario 0.5 (see Figure 3.4, which shows the benefits of Sub-programme ABCH are 51% due to the standalone benefit of H and 66% if the interdependencies with H are also brought into account – a rise of 30%), whereas the incremental benefit of H is 11 times higher than its standalone benefit under Demand Scenario 2.0.

Figure 3.4 shows a situation where the incremental benefit of Project G (being the sum of the standalone and interdependency benefits) is less than the standalone benefit in all demand scenarios. More extreme examples are discussed below.

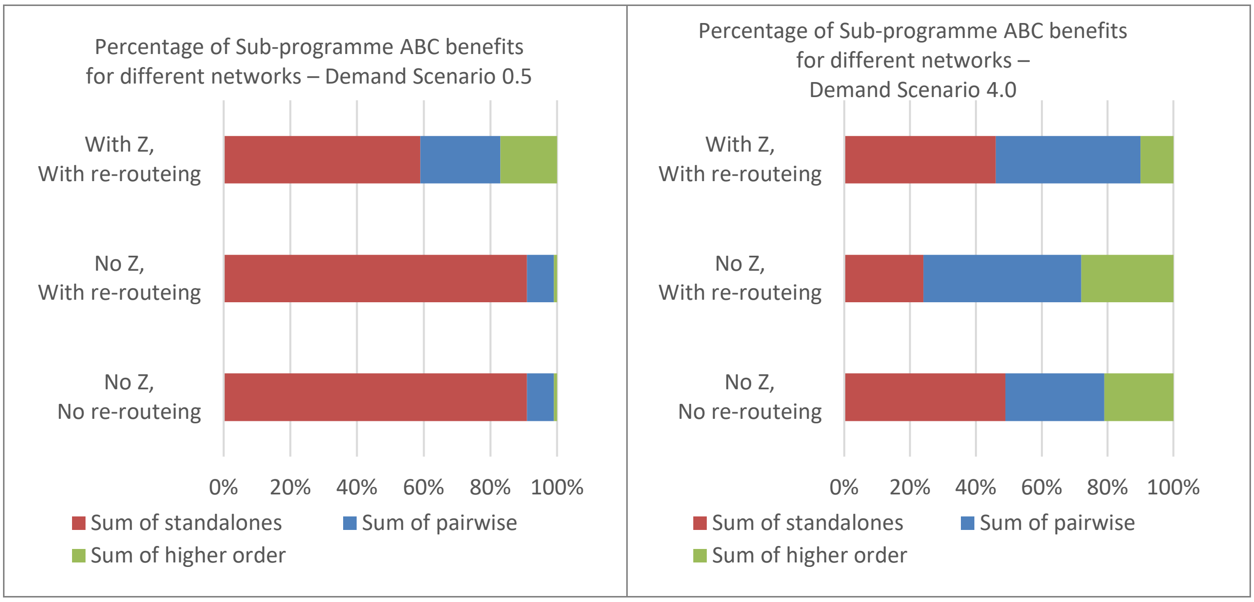
The sketch network was not set up to explore the limits of interdependency benefits, and we would be very cautious about suggesting such extreme levels of interdependency benefit. However, what the network shows is that where induced demand and re-routeing impacts are large, then interdependency benefits can also be large.

Sketch Lesson #10. The pairwise measure of interdependency benefits captures the majority of the interdependency for the complementary projects when there is no re-routeing and no congestion.

The combined standalone and pairwise measures of benefits did capture 96–99% of the total benefits from complementary Projects A, B, and C at low congestion levels (see Demand Scenario 0.5 in the left-hand graph of Figure 3.5). Even with congestion (right-hand graph) the pairwise error would have only been 21% when heavily congested, as long as re-routeing did not occur, though it is unclear whether this level of error with congestion is specific to the sketch network considered. Note, adding the pairwise to the standalone benefits reduced any programme measurement error considerably as completely ignoring interdependency benefits (ie, standalone only) would have led to programme benefit errors of up to 76%.

Low levels of congestion in this sketch network were considered via Demand Scenario 0.5, which had links operating at less than 50% volume to capacity ratios (link demand flows of approximately 500 vehicles/hour). Conversely, at Demand Scenario 2.0 the urban links were running at around 70% of capacity and congestion levels were sufficient to lead to a breakdown in the pairwise rule.

Figure 3.5 Composition of benefits for Sub-programme ABC with another node (Z) and re-routeing available, for alternative demand scenarios



Sketch Lesson #11. The pairwise measure of interdependency benefits is likely to be inadequate when project re-routeing occurs.

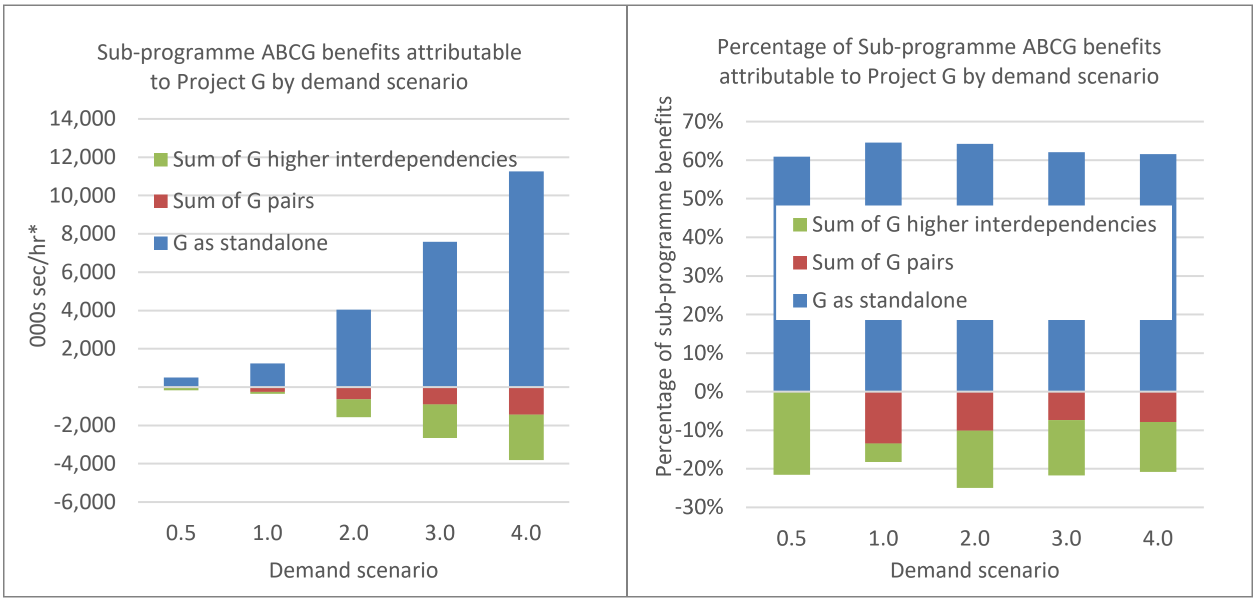
In the simple ABC sub-programme (as shown above in Figure 3.5), the ability for traffic to re-route meant that an assessment based on standalone and pairwise benefits would have understated the programme benefit by up to 28% more than had re-routeing not been possible. In the full ABCGH programme (see earlier Figure 3.2), where re-routeing was common, the standalone/pairwise analysis would have led to programme measurement error of up to 53%.

A closer look at how Project G affects the ABC sub-programme reveals the effects of competing projects. The standalone benefit contribution of Project G and all its interdependency effects are shown in Figure 3.6. The disconcerting figures were the large positive standalone effects of Project G being partially offset by large reductions in the benefits of Projects A, B and C, being up to 25% of the sub-programme's benefits. As it turned out, the benefits of a sub-programme of ABCG could have been reasonably estimated using all standalone and pairwise benefits only; the difference between this partial measure and a complete programme benefit measure was at most 11%, but this cannot always be assured when netting large numbers.

In sum, we find that there are significant competing effects arising from the re-routeing effect of Project G on Projects A, B and C. These are not fully captured in the pairwise analysis (as shown as green column segments in Figure 3.6). For the pairwise rule to hold triples, quads, etc, interdependency benefits should be close to zero. This was only the case where re-routeing did not occur.

Combined with the previous lesson, we therefore conclude that the pairwise rule is only adequate at low levels of congestion *and* where re-routeing effects are limited.

Figure 3.6 Effect of Project G added to Sub-programme ABC for alternative demand scenarios

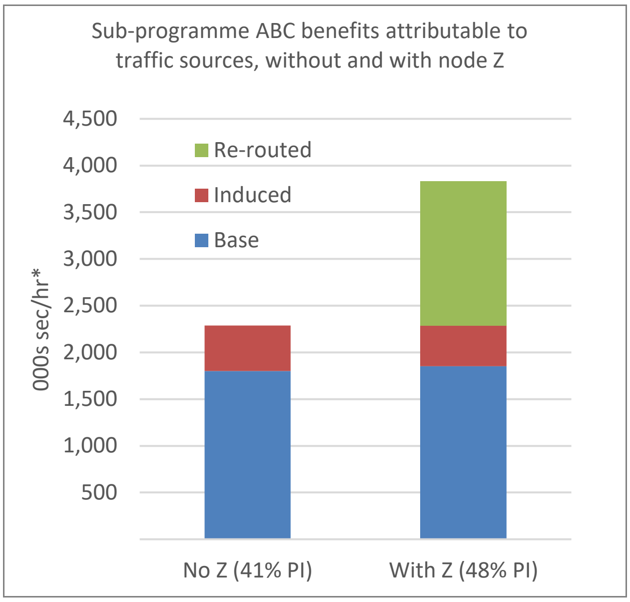


* 000s sec/hr = thousands of seconds of travel time savings per representative hour

Sketch Lesson #12. Induced demand can play an important but ambiguous role in interdependencies, leading to positive interdependency benefits if congestion is ameliorated, but also potentially *exacerbating congestion, thereby dampening down interdependency benefits and in extreme situations potentially leading to negative interdependencies.*

We have identified that induced demand is a key driver to positive interdependency benefits. An example of the effect of induced traffic can be seen by comparing the ABC sub-programme benefits under two network scenarios: one with no traffic generated from the third node Z and hence no re-routeing, and the second being a network that allows re-routeing to/from node Z. Project interdependencies made up 41% of the sub-programme benefits in the former and 48% in the latter network, under Demand Scenario 2.0. The major change between the two network situations was a 67% increase in sub-programme benefits, entirely due to re-routed traffic (see Figure 3.7) – and hence also the increase in interdependency benefits.

Figure 3.7 Traffic composition of Sub-programme ABC benefits, without and with the ability to re-route (Demand Scenario 2.0)



* 000s sec/hr = thousands of seconds of travel time savings per representative hour

However, in congested networks the theory reviewed identified that if bottlenecks are present elsewhere in the network, then induced demand can exacerbate congestion, turning positive interdependency benefits into negative ones. We have been able to reproduce this in our sketch network. An extreme example of this network congestion effect is Braess's paradox, whereby the negative costs of the additional network congestion are so significant that the project gives rise to net negative user benefits. Again, examples of Braess's paradox are evident for certain project combinations and certain demand scenarios in our sketch network.

Sketch Lesson #13. Re-routeing plays a large role in the interdependency effects and was more significant at higher levels of congestion.

Our sketch network only gave rise to re-routeing effects in congested conditions. Analysis indicates that, within this sketch model study at least, re-routeing is a significant contributor to interdependency benefits. For example, re-routeing effects contribute half of the Sub-programme ABC interdependency benefits. Compared to induced demand, however, interdependency benefits arising from re-routeing are likely to be easily eroded by competing schemes that serve the relevant origin–destination movements more directly. The uncertainty this may generate for project-level benefits is discussed further in the following section.

3.5 Project-level appraisal

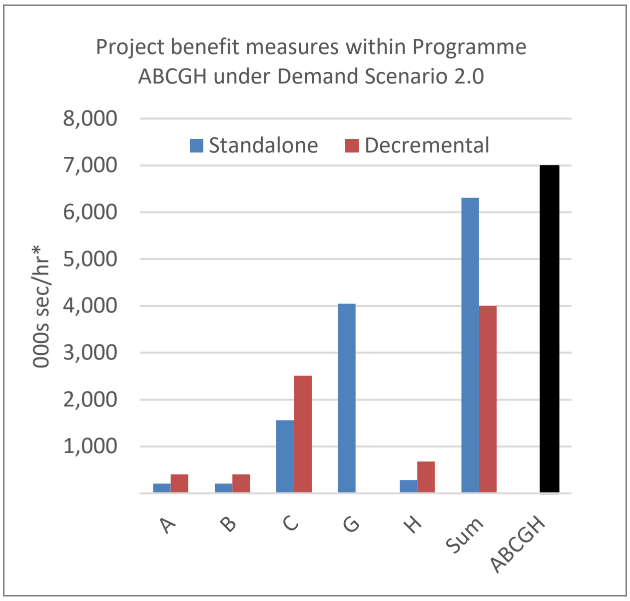
Extending the previous sections, the discussion now turns to the measurement and attribution of benefits to individual projects. As a reminder, many of the results discussed are only possible because a full set of project permutations was modelled.

*Sketch Lesson #14. The decremental measure gives a true measure of the marginal benefit of **one** project **if** all the others were committed.*

A typical question is: What is the value to a programme of an individual project? If all other projects within a programme are certain to proceed, then this question can be answered by calculating the benefit of a programme with and without the project in question. This is the decremental benefit, which is the same as the incremental benefit of adding the project in question to all other projects combined. In the sketch network, for example, the decremental benefit of Project A is the same as the incremental benefit of Project A if Projects B, C, G and H are already in place – shown as 404,536 seconds of travel time savings per representative hour (sec/hr) in Figure 3.8. When interdependencies exist, both figures will differ from the standalone benefit (standalone Project A benefit in the graph is only 208,996 sec/hr). The decremental benefit of each project in the sketch network differed from its standalone, with the marginal value of Project G (ie, given all other projects existed) declining to zero in Demand Scenario 2.0. To recap, though, the decremental benefit is only the appropriate measure of a project's marginal value when all other projects are certain.

Note, the sum of the decremental benefits of the five projects did not equal the total programme benefits (shown in the graph as the right-hand black column). Nor did the sum of the standalone benefits. Neither sum provides the appropriate figure for the benefit of a programme when project interdependencies exist.

Figure 3.8 Standalone and decremental benefits of individual projects within Programme ABCGH for Demand Scenario 2.0

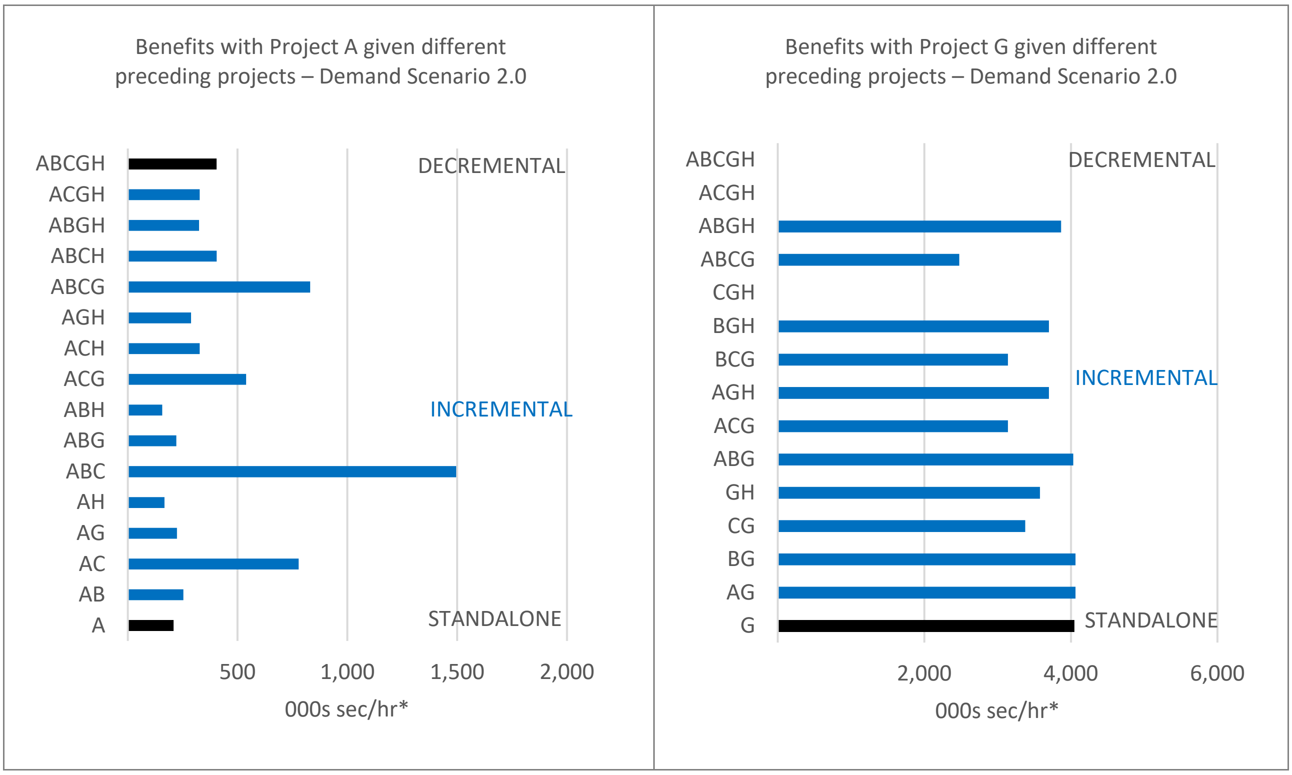


* 000s sec/hr = thousands of seconds of travel time savings per representative hour

Sketch Lesson #15. The incremental measures can vary significantly. These different measures depend on the ordering of projects and give an indicator of how project interdependencies vary.

When a full programme is not yet committed, then the marginal benefit of each project is provided by the incremental benefit measure, which will differ when project interdependencies exist depending on which projects form the 'before' set of projects (typically referred to as the reference case). Figure 3.9 shows the range of incremental values of Project A as A is added to the full set of permutations of other projects under Demand Scenario 2.0; likewise for Project G to the right. Shown also in these graphs are the same standalone and decremental benefits as above, both being a form of incremental benefit. In between, Project A was of highest incremental value when added to Projects B and C. Project G was generally near its standalone value except when Projects C and H were already part of any sub-programme, in which cases Project G was of nil marginal benefit (for Demand Scenario 2.0). In other words, Projects C and H combined made Project G redundant for this level of demand. Note, this redundancy did not fully exist at higher levels of demand.

Figure 3.9 Incremental benefits of Projects A and G for Demand Scenario 2.0

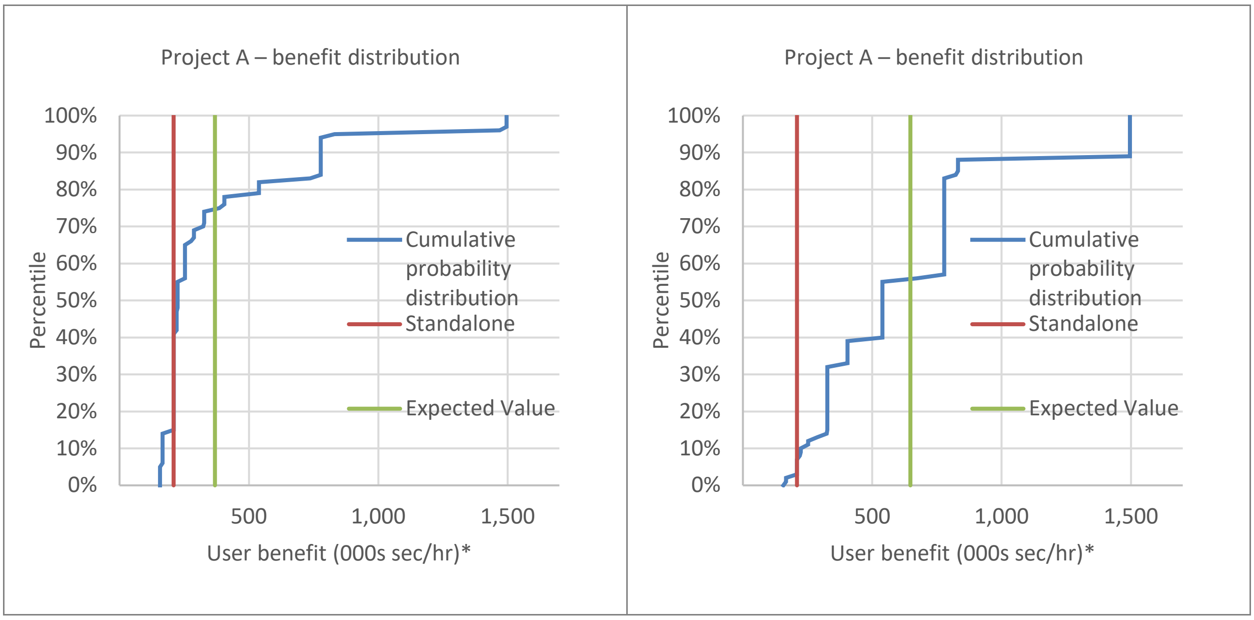


* 000s sec/hr = thousands of seconds of travel time savings per representative hour

Sketch Lesson #16. Projects can have expected benefits that exceed standalone benefits when other projects are uncertain.

On occasions, although the interdependent projects may not be certain to proceed, it may be that the probability is known as to each other project being delivered. In such a case, it is possible to calculate a distribution of incremental benefits for a project and also an expected benefit. Such probabilities are not known for the sketch network, but a couple of examples are offered to illustrate the calculation. Figure 3.10 shows the distribution of Project A benefits for two scenarios – when all other projects will proceed with a probability of 0.3 (left-hand graph) and where the probability of Project C is increased to 0.85 (right-hand graph). Whilst these probabilities are arbitrary, they do show (a) that it need not take a high probability of an interdependent project to generate value in a project that exceeded its standalone benefit, and (b) the expected value of Project A depends on the probabilities, as well as the project interdependencies.

Figure 3.10 Probability distribution of expected incremental benefit of Project A, Demand Scenario 2.0, assuming (left) probability of other projects is 0.3 and (right) as per previous but with now p(C) = 0.85



* 000s sec/hr = thousands of seconds of travel time savings per representative hour

Sketch Lesson #17. A project's expected benefits and the expected distribution of the benefits are very dependent on the probabilities assumed. This is an important evidence gap, and more research is needed on it.

It is unlikely that the probability of projects being actually undertaken is known at present, but there are likely to be patterns within the institutional framework. For example, it may be possible to show that historical projects included in a Land Transport Plan have proceeded *x*% of the time, while other projects at other stages of business case development and approval have had lower success rates. Just what these success rates are and how they might translate into a probability for future projects is a topic for research beyond this project.

Sketch Lesson #18. If undertaking project-level appraisal, decision-making processes need to be cognisant of several projects having a claim to 'the' interdependency benefits.

Figure 3.8 showed that the sum of standalone and decremental benefits will not sum to the total benefits of the programme when project interdependency exists. Figure 3.9 showed that there are also other measures of individual project benefits (ie, other increment benefits). These, too, will not sum to the total programme benefit. This creates a challenge when an analyst wants to apportion the value of the programme over the component projects, possibly to apportion funding across different transport authorities or simply for ease of presentation to decision-makers. Unfortunately, there is not one correct formula to apportion programme benefits across projects. The various incremental benefits can be used to address specific project decisions, but each is contingent on what other projects also make up the programme. This issue of attribution of total programme benefits will be taken up in Chapter 6.

Sketch Lesson #19. Projects proceeding on the basis of a probability-weighted expected benefit ***will*** *produce outcomes with low or negative NPVs sometimes.*

The corollary of the previous lessons is that there exist project outcomes that will be less than desirable. Just as there is a probability of a very high project benefit, the nature of risk is such that there will inevitably be outcomes with a low project benefit. A decision-maker using a probabilistic incremental benefit to justify a project needs to be able to also tolerate sub-optimal outcomes at times – this may not be the case when projects are very costly and not of a repeatable nature.

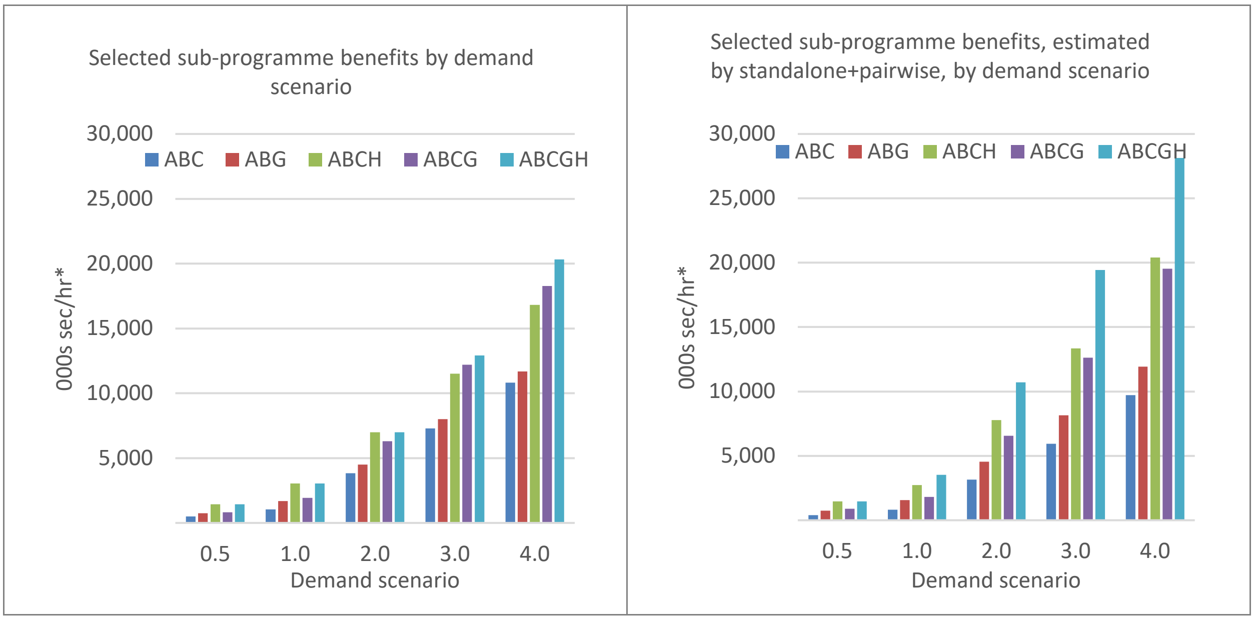
Sketch Lesson #20. Major investment errors can occur if negative interdependencies are ignored.

The actual investment undertaken would depend on the costs of each project and also involve alignment with other objectives of the programme. Ignoring the latter for now, we did assume project costs and showed the optimal programmes given a starting level of demand and a budget in Table 3.1. One conclusion reached was that Project G would likely have been undertaken too early. The potentially evolving benefit pattern that lies behind this judgement is shown in Figure 3.11. Here the benefits are at each demand level, shown on the left calculated from a full model run and on the right as a partial estimate based on standalone and pairwise benefits only (ie, using fewer model runs).

At low levels of demand, both benefit calculations show a sub-programme of ABG offered higher benefits than ABC. This relativity persists at all levels of demand. However, ABCH provided considerably higher benefits and, what's more, ABC was a component of all high-yielding programmes once higher demand levels were attained. Projects ABCG and ABCH provided roughly similar levels of benefits. At high levels of demand there was extra benefit from moving to a full programme of ABCGH, with this marginal benefit exaggerated if based on partial benefit estimates only. As stated, much will depend on project costs, but on this benefit analysis alone, there was more to be gained by phasing Project G after Project H (assuming growing demand and sufficient budget), and there is doubt that Project G would have been undertaken at all.

The fundamental issue with Project G is that it either added no positive interdependency benefits to the other projects or eroded the benefits of other projects. Ignoring the negative interdependency of Project G could have resulted in a major investment error.

Figure 3.11 User benefits for sub-programmes by demand scenario, with (left) benefits fully estimated and (right) benefits estimated from standalone and pairwise only



* 000s sec/hr = thousands of seconds of travel time savings per representative hour

3.6 Sketch planning models

Sketch Lesson #21. A sketch planning model could be useful as a pre-cursor to full traffic modelling.

One outcome of creating the sketch network is that it illustrated the usefulness of a simplified but fast model. This sketch network is a form of sketch planning model. De Dios Ortúzar and Willumsen (2011, p. 430) define sketch planning methods as a type of simplified transport demand model ‘more sophisticated than idealised models [eg, mental models] but much simpler than conventional models’. They say in practice their implementation ranges from ‘scaled down conventional aggregate modelling suites or programmes to ad hoc approaches developed from simple ideas’. They go on to say:

> *Sketch planning techniques seem to offer advantages in terms of simplicity, fast response and low data requirements. However, very often they rely too heavily on the transfer of relationships and parameters from one context to another. This detracts from the analysis unless it is performed only as an initial coarse sketch to select options for more detailed consideration.*

The use of such a model could therefore be very useful to narrow down options for inclusion in the more detailed interdependency analysis – by ruling out projects that have limited impacts on the project of interest and also to assist in combining projects. This is because they are quick to run and can hence be used to analyse a large number of options.

In our context, our sketch network was designed to consider principles around induced and re-routed travel demand in general, and as such it is highly simplified in that all behavioural responses such as destination and mode choice are encapsulated into a single demand curve, albeit it is quite elastic (as can be seen by the levels of induced traffic). For a real application in which sketch planning methods were to be used to narrow down the range of modelling options, it would be necessary to give a thorough consideration as to which behavioural responses were required to be modelled explicitly (eg, mode choice).

To repeat, the general point here is that each sketch model will be contextual. The model will be devised to consider the key interdependencies of issue. The model may be akin to our sketch model. Alternatively, it could be another transport model or a system dynamic model, or some other type of model. The type of model and the equations within the model will be chosen to provide insight into the interdependency of relevance at the time and to reduce the number of required runs with a fuller transport model. It complements rather than replaces the standard transport model.

For example, it may be that the interdependency of interest is multi-modal. There are several ways to develop a sketch model for this situation. It could be that the sketch network used here could be adapted to a multi-modal situation either through interfacing the SATURN model with external software such as DIAdem or just a spreadsheet model. Possibly this would entail ‘links’ on one route between nodes *X* and *Y* representing the road costs and parking costs of private vehicle travel and those on an alternative route representing the access, egress and in-vehicle time of public transport. Variations could include different cost factors for each component of travel, including a factor for crowding on public transport. It could be that if it was expected that user costs on the public transport network would be fixed (eg, no overcrowding), then the shadow matrix in the elastic assignment option in conjunction with a parameterised logit demand curve could have been used, though with this method it would not be possible to assess the interaction between different modal investment policies. If the interdependencies between different modal investment policies were to be assessed, then it would be necessary to explicitly model mode choice in the sketch planning model. It is not possible to generalise a simple sketch model here that would suit all multi-modal circumstances. However, it may be possible that a small group of sketch models could be developed to address key issues that are often encountered. This is possibly an extension of the current research project.

The value-add of any sketch model will vary by situation. It will depend on the extent to which the situation lends itself to a simple model and the extent that similar sketch models already exist. For now, it is simply noted that the sketch model set up here could reasonably be set up from scratch in less than one week.

3.7 Agglomeration, noise, carbon and safety benefits

An extension of the sketch modelling was also to test the interdependence sensitivity of other benefits typically additional to the primary benefits within a transport CBA. Agglomeration benefits for the 160 scenarios run within the sketch model exercise were highly correlated with travel time interdependency savings but the sign of the effect was not always the same, and generally agglomeration interdependency benefits were larger than the travel time interdependency benefits. Likewise, there was a correlation between each of the safety, noise and carbon interdependency benefits, derived directly from VKT, although the correlation was negative (due to more travel induced by less travel time) and weaker than above, plus the signs were not always consistent. In sum, we conclude from this analysis that if agglomeration, noise, carbon and safety benefits are relevant to the appraisal, then the interdependency analysis needs to explicitly consider these benefit categories also. Simply scaling time saving interdependency benefits up or down will potentially lead to biases.

3.8 Further observations

The following are further reflections from the creation and analysis of the sketch network – thoughts that naturally lead into the next chapter, where the challenge is to establish a method that requires fewer traffic model runs than the complete permutations of projects and demand scenarios.

3.8.1 Strategic decision-making versus project-level decision-making

An early decision is whether to undertake programme-level appraisal or project-level appraisal. With programme-level appraisal we reduce the uncertainty associated with project interdependencies, we can address path dependency, and we can use a decremental analysis on projects. Project-level appraisal has more problems with uncertainty and also leads to the situation that multiple schemes can make claims on the interdependency benefits.

3.8.2 Scenario analysis versus probability analysis

Scenario analysis is a standard approach at present to assist with consideration of uncertainty, whereby only a subset of project permutations that are considered significant are analysed. Robust probability analysis is not possible at the moment (as we do not have appropriate certainty regarding probabilities), but longer term it may be that the probabilities are obtainable.[11] A well-structured research project looking at historical local authority and national structure plans and comparing these to what actually gets constructed and when (and at what cost) will illuminate this; likewise, analysis of BCRs of projects that become accepted, or not. These are topics for further research.

3.8.3 Interdependency analysis of all projects in a programme versus interdependency analysis of key projects

If key projects can be identified prior to traffic modelling – for example, identification of Project C as an enabler project (see Table 2.2) – then the modelling task reduces to focusing efforts on analysis where

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[11] There are sophisticated traffic modelling packages that include probabilistic analysis, but this does not address the more fundamental problem that many probabilities are not known and/or are not appropriate for events that have deep uncertainty.

interdependency analysis is expected to affect a decision, and appears to be a promising avenue, albeit this covers only some cases.

3.8.4 Interdependency analysis focusing exclusively on project downsides

Another set of rules – a check for negative interdependencies – is required to give assurance when standalone benefits may be undermined by other projects, a risk when re-routeing is likely.

4 Methods to establish interdependency benefits

This chapter considers approaches and methods used to analyse the benefits of projects that are interdependent. Potentially there are two major reasons why decision-makers may wish to estimate interdependency benefits: first, to help shape a programme, including optimal project selection and phasing; and second, to measure the value contribution of one or more components of the programme, particularly if questions have been raised about these components. The focus of this chapter is primarily on the second decision, although similar methods would be followed to optimise a programme more fully.

The chapter ends with steps that can be taken in the analysis of a project that has benefits interdependent with other projects. These steps are tested and refined in the following chapters. A key part of the steps is the reporting of multiple BCRs, often three but potentially more, that show how the incremental benefit of a candidate project changes as less certain projects are taken into account.

Three caveats are important. First, these steps focus on the measurement of the monetised benefits within the CBA, which is only one part of the full business case analysis. Second, the steps presume that transport models exist for the programme under analysis. Third, the range of situations is wide and varied, so these steps are likely to require customisation at times.

The interdependency of transport projects can potentially be across both routes and modes. It is likely that the form of the transport model will differ with intermodal interactions from unimodal situations, but the methods presented here to identify and analyse transport project interdependencies remain the same.

The steps developed in this chapter follow from a recap of the key issues and practices.

4.1 Key influences on methods

4.1.1 Conditional nature of CBA

There are two features of a CBA that bear consideration when forming a method of analysis. The benefits calculated in *every* CBA are conditional – the future is simply not known. At one extreme, there may be a project that produces benefits that will be largely independent of what other projects emerge. In this situation, setting the reference case (ie, the counterfactual) as the current transport network and then calculating a standalone benefit would provide an accurate measure of the project's benefit. In fact, if the project were truly independent, then adding any other projects to the reference case to calculate an incremental benefit would produce the same number. At the other extreme, there may be a project that is interdependent with a group of other projects but it is known that all projects will be delivered. In this case, the accurate measure of the candidate project's benefit is the decremental benefit, which is found by setting the reference case at the current network plus all the other interdependent projects. In both these 'certain' situations the conditional nature of the benefit calculation is of little consequence. This is often the case with simple transport projects, especially where large benefits are delivered quickly. However, situations will arise where interdependent projects are planned to be delivered over many years and it is not certain as to whether all projects will be delivered in full and/or on time or budget or delivered at all. Here the conditional nature of benefit assessment is a reality that must be addressed – by analysts and decision-makers – when a candidate project is part of an interdependent and uncertain system and unfortunately there is no one 'black box' answer.

More generally the issue arises with any uncertain future event (eg, policy changes, land-use changes) that may affect the benefit of a project. Where the general interdependency is high, then models of general equilibrium may be required to appraise the benefits of a project. This remains a possibility with highly uncertain and interdependent transport projects, but the method outlined below is based around the partial equilibrium approach of a CBA.

4.1.2 Potential behavioural and institutional bias

Further to above, the second feature of a CBA is that the benefits of any project will turn out at times to be either higher or lower than forecast when high levels of uncertainty exist. This is where a human trait, and the institutional framework as noted earlier, interacts with project appraisal. A project typically comes with a proposer. It is human nature for that person or team to attach themselves emotionally to the proposed project, seek reasons to support its case, and to be confident that the project is merited. This tendency suggests appraisals will tend to find benefits not initially apparent but also a tendency to *not* find uncertainties that would reduce an otherwise apparently beneficial project. In terms of the sketch network described in Chapter 3, in considering Project A there was potentially a need to show the competing effects of Projects G and H, but this might only have been revealed by following a methodical approach, especially if Projects G and H sit outside the candidate programme and/or are the responsibility of another agency. It is important to guard against systematic bias such as, for example, considering or searching for complementary schemes/initiatives as ‘relevant’ but discarding (or not searching for) competing schemes/initiatives as ‘irrelevant’ or ‘outside scope’.

4.1.3 Consistency with Better Business Case methodology

Rightly, the response to these issues, and others, has been to take a broader approach to CBA, with emphasis also placed on what happens before the number-crunching stage of a CBA and what happens afterwards. The Better Business Case methodology adopted by the New Zealand Treasury is such a response. The intention below is not to recreate the Better Business Case method but to point out where more emphasis might be required when appraising interdependent projects, keeping in mind that the mix of projects under consideration may not sit within a programme or that projects outside a programme may also be of importance.

4.1.4 Transport model runs can be costly

Ideally, if benefit interdependency between projects is suspected, then a full set of project permutations could be modelled to establish the nature and magnitude of any interdependency. However, the number of model runs required will typically double with each additional interdependent project, so often some form of run pruning process will be required to reduce the cost of – and time for – analysis.

4.2 Experiences with analysis

4.2.1 A range of conditional incremental benefits

Several methods exist in theory and amongst global practitioners as to how to measure the benefit to be gained from the completion of a project. Methods vary depending on information and data availability and the institutional framework of project investment decisions. Broadly, the methods can be categorised into four approaches.

1. **The standalone appraisal (Incremental Approach 1).** The most common form of benefit appraisal is to consider the candidate project as a standalone project, in which case it is preferable to be able to prove, or at least convincingly argue, that the project is indeed independent.
2. **The decremental programme/route-level appraisal (Incremental Approach 2).** A programme approach is taken by Germany and some Scandinavian countries using 5- or 10-year plans and by the Scottish Government in its strategic review at the route/strategy-level appraisal. Here the marginal value

of any project is based on the value of the programme and a decremental test of the project's contribution to that programme. This requires a defined programme that (a) has full commitment and (b) includes all projects that are interdependent. Variations of this approach are (a) to include in any benefit analysis the projects outside of the programme that are judged to be interdependent with projects within the programme, and/or (b) to assume that all projects have full commitment even if this is not strictly the case.

3. **The multiple core appraisal (Incremental Approach 3).** An approach that bridges the above two approaches is to also focus on the effect of uncommitted interdependent projects. The starting point here is that running all potential project permutations is not possible. Instead, the project is assessed as an incremental project against a set of potential future network configurations, giving rise to several alternative BCRs. The likelihood of these future configurations (and BCRs) occurring are then described qualitatively for decision-makers. This is being tried as a UK Department for Transport pilot method. It establishes three conditional incremental benefit estimates by considering the projects of interest against three DoMin scenarios: with all committed projects included (the standard DoMin); with the 'highly probable' projects added as well; and with all projects under active consideration. This leads to three incremental benefit tests and three BCRs. The likelihood of each scenario occurring needs to be described qualitatively.
4. **The probabilistic project-level appraisal (Incremental Approach 4).** This textbook approach is to assign probabilities to each non-candidate project, ranging from near 0 (very unlikely to proceed) to 1 (certain to proceed) and then apply these probabilities to the incremental benefit for each sub-programme permutation for the candidate project. The expected economic benefit of the project can be calculated, as can the probability distribution of economic benefits. Whilst conceptually attractive, this approach relies on having probabilities available to assess the likelihood that each other project will proceed. Potentially these probabilities could be informed by a history of previous proposed projects and how far they were able to pass through the approval process. It also requires a full set of model permutations to be modelled, which for medium to large programmes will likely be infeasible. We are not aware of any applications of this approach in transport project appraisal.

In all cases, there is a transparency advantage to presenting the standalone benefit and BCR along with whatever other measures are chosen. This is not always the practice in the above examples.

4.2.2 Established steps within analysis

Whilst the different analytical approaches exist, there is consensus about some components of the methods that lead to a measurement of a project's benefit. These are discussed for the 'Before', 'During' and 'After' phases of the CBA.

What do we know about the 'Before CBA/modelling' phase?

- There is a need to tie in with strategy. This is a common approach across many forms of investment, both to put a strategy into action and to create a higher probability around interdependent projects proceeding that are aligned with strategy. In transport, the strategies of interest include those in the Government Policy Statement (GPS) on Land Transport and the local strategies around land use and transport.
- A process is required that takes a lateral and critical approach to optioneering. One part of the Better Business Case method of emphasis here is the identification of interdependencies, including across modes.
- A filtering process is required to reduce a wide choice of project options – the long list – down to a few for closer analysis. Show-stoppers need to be identified early. Project interdependency is one factor to be taken into account when forming and consolidating projects options.

- It is important to consider long-term objectives and issues around project irreversibility. Undertaking projects that offer value in the short term may not be consistent with value creation in the long term. Again, interdependency can be relevant here.
- The level of analysis required of the short-listed options should be fit for purpose. Forethought about the sensitivity of any decision to be made can identify which interdependencies require closer examination, including which projects are at risk of crossing an investment threshold.

What do we know about the 'During CBA/modelling' phase?

- Interdependent benefits may be the reason for an intense level of analysis, but more generally project interdependency is often a subset of the wider issue of uncertainty, given that projects within a programme usually do not have full funding commitment.
- There will be times, such as when the cost of projects is large and/or very risky, that a large number of model runs will be justifiable. More often, though, model run pruning is required.

What do we know about the 'After CBA/modelling' phase?

- The conditional nature of the benefit assessment does require emphasis when risk and uncertainty imply that outcomes beyond tolerable bounds will occur more often than, say, 1 in 20 times (another threshold to consider in the Before phase).
- Decision-makers are likely to want to know of – and avoid – projects that have a high chance of being low value (ie, not the same as being the highest expected value), a risk that can be high when competing projects exist.
- It is difficult to convey the effects of risk and uncertainty – methods such as an uncertainty log are available but graphical presentations are likely to be valued.

4.2.3 Techniques to prune the number of model runs and present results

The research team has collated the following table of the advantages and disadvantages of techniques used at present, or potentially available, to reduce the number of runs of a transport model when establishing project interdependency benefits, collated in the 'Before' and 'During' sections of the table. Similarly, the pros and cons of techniques to present the results of an interdependency analysis are shown in the 'After' section of the table.

Table 4.1 Pros and cons of method components to streamline appraisal when projects are interdependent

Before	Pros	Cons
1. Checklist (eg: Is the project expected to be interdependent with other projects? What project decisions depend on interdependency detail? Is project core or peripheral to strategy or programme? Can projects be condensed?)	• Forces early consideration of project interdependency • Forces consideration of required scale of analysis	• Risk that questions get treated as 'quick form-filling exercise'
2. Dependency matrix (including construction, benefits, funding interdependencies, both unimodal and intermodal)	• Forces early consideration of project interdependency, with more detail than above • Communicates to others the *a priori* expert judgement	• Requires reduction of projects to tractable level, say less than 10 • Relies on pairwise comparisons

Before	Pros	Cons
3. Higher-level strategic modelling (eg, sketch planning, models, system dynamic models, gross value added models)	• Provides insights into nature of interdependencies, which in turn can lead to a reduction in traffic modelling later required	• Cost of modelling • May not capture transport interdependencies accurately enough, and thus leads to erroneous traffic modelling mix chosen

During	Pros	Cons
4. Combine projects	• Reduces number of project permutations and hence model runs	• Relies on expert judgement • Limited when interdependencies are many and complex • Limited by number of projects that are uncertain • Decision-makers may require lower-level project CBA for funding
5. Collapse programme to one ‘project’ (ie, limiting case of above)	• Puts focus on outcome of the mix of projects rather than any one project	• As above
6. Stage analysis (eg, make a few initial runs to enable learning)	• Early runs could be standalone, decremental and/or pairwise to give confirmation of interdependency • Enables fewer (than all) subsequent runs, which can then focus on the interdependencies of significance	• May be just as time consuming as batching all model runs, especially if each run phase leads to more questions
7. Randomly include some higher-order dependencies in first model runs (a variation of above)	• Potentially reduces likelihood for second-stage modelling	• Not apparent that this would capture key interdependencies with confidence
8. Assume higher-order (beyond pairwise) dependencies are zero	• Reduces model runs	• Risks missing significant interdependencies, especially those of competing projects
9. Exclude or run modelling of uncertain projects in second stage	• Enables incremental benefits to be calculated on known projects • Makes transparent that further benefits (+ve or –ve) are uncertain	• Model run reduction only possible if uncertain projects grouped as one ‘project’

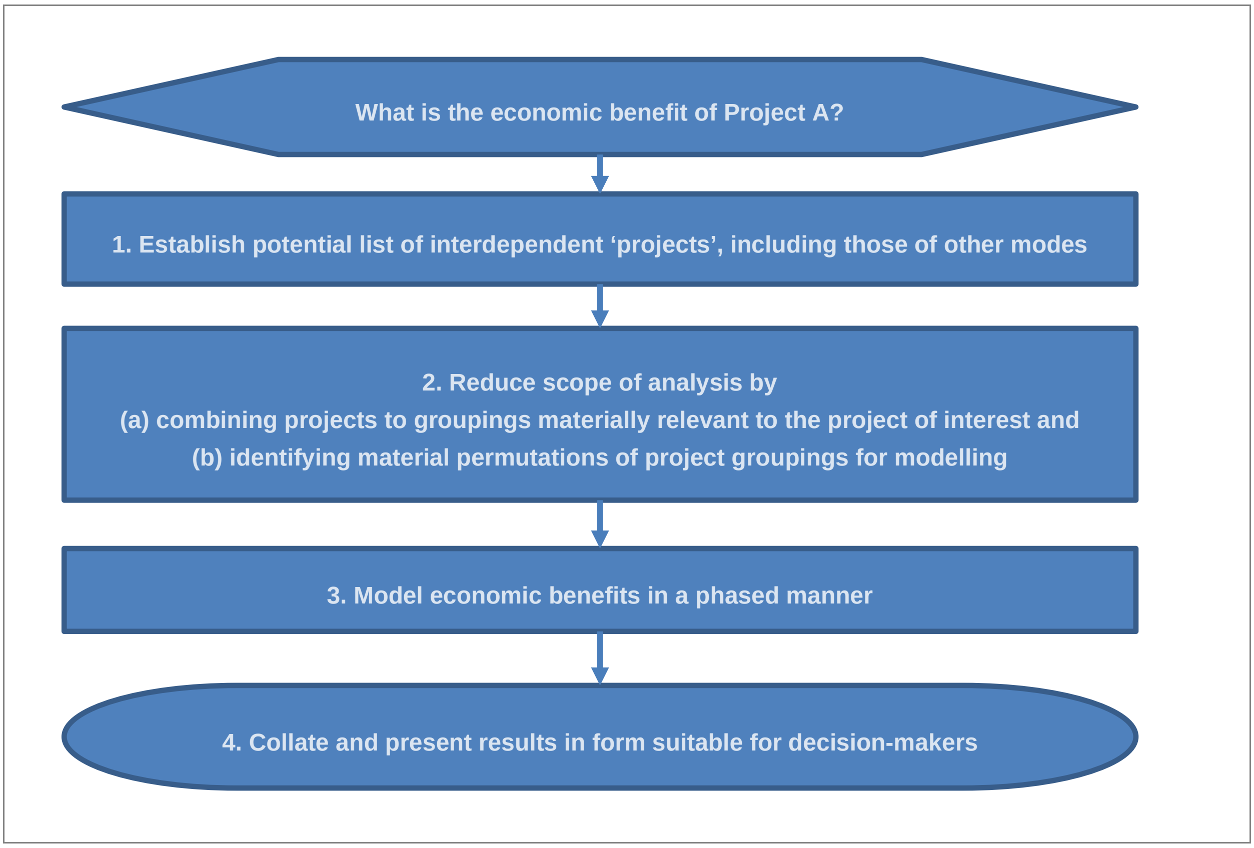
After	Pros	Cons
10. Graph range of benefits for key projects	• Quickly shows range of benefit outcomes possible	• Includes outcomes that may be unlikely
11. Combine above with probability judgements and show as distribution curve	• Quickly shows most likely outcomes and the likelihood of intolerable outcomes	• Probabilities are usually unknown so can provide misleading information and a false sense of certainty about thresholds being breached (or not breached)

After	Pros	Cons
12. Show both standalone and expected BCRs (against thresholds for each)	• Transparent representation of information, consistent with 2-step BCR thresholds (eg, standalone > X and expected > X+Y) or addresses using the expected incremental pairwise value to justify a costly project with a standalone BCR significantly below 1	• Probabilities to derive expected benefits not known • Especially a problem when expected value below standalone • Still does not address possibility that negative interdependency exists with excluded project – this issue is difficult to specify as a rule and suited to a checklist approach
13. Provide narrative describing the range of likely outcomes and their uncertainties (as per uncertainty in general)	• Transparent representation of decision-maker's choice	• Can be challenging to communicate complicated situations

4.3 Method to analyse the economic benefit of a project with interdependency benefits

Our proposed method, subject to refinement, for assessing the economic benefit of a project, say Project A, when it is interdependent with other transport projects, including projects applied to different modes, is outlined in Figure 4.1 and described in the sections below. It comprises four steps, starting with establishing the list of potential interdependent projects through to the collation and presentation of results to the decision-maker. Key aspects are the treatment of uncertainty and the reduction in the number of interdependent projects and project permutations to model. It is expected that this level of analysis would only be taken when the cost of Project A is high and/or the standalone BCR has been already measured to be, or is expected to be, relatively low. It is also anticipated that there may be some iteration and re-ordering of tasks, but there will remain a need for each step.

Figure 4.1 Outline of method for assessing the economic benefit of a project with interdependencies



A key philosophy of the method is to use information available both before and during the modelling to produce a fit-for-purpose analysis. This requires the calculation of various BCRs during stages. The method assumes that the components of these BCRs are well defined and multiple BCRs will be acceptable to decision-makers. In practice, there will be required institutional agreement as to (a) what components to include in a standalone BCR (eg, transport only? Or WEBs also?) and (b) how current presentation and decision-making processes would change to allow for multiple BCRs. These matters are taken up in Chapter 6, following testing and refinement of the method presented below.

4.3.1 Step 1. Establish potential list of interdependent 'projects'

This step will generate a list of projects and/or schemes that are interrelated with the projects of interest, although the actual number of projects identified will vary widely. For purely illustrative purposes, an example might be a list of 25 projects and/or schemes revealed for further consideration in Step 2.

Essentially, this step requires accepting the projects within the programme (if a programme exists) as potential projects of interest and exploring beyond the programme for other transport projects that may be interdependent with Project A (or with B, C etc as well if the benefit of more than one project is analysed).

A likely starting point is the set of projects in a defined programme. However, this can often involve consideration of options below the project level, such as for schemes or links etc. Importantly, it requires consideration of potential projects that sit outside the programme expected to increase or decrease the benefits of Project A.

Alternatively, the starting point is the set of projects of current interest to the decision-makers, even if they each sit in different programmes or not in any programmes.

Interdependent projects are those that are likely to change the demand for and/or the cost of using the candidate project (Project A). Qualitative and quantitative techniques based on shared markets (origins/destinations served, journey purposes served, etc) and geographic proximity can be used to search for interdependent projects, including those projects applying to different transport modes.

The following techniques may be used to identify projects or sub-projects of relevance (not all need be used).

- Use a checklist to consider whether projects not already within the set are interdependent with projects within the initial set – looking for projects that are likely to share travellers between a common origin and destination, including by different modes (a suggested checklist is provided in Appendix E).
- Use select link analysis to analyse the origins and destinations of the route to be upgraded and users of other potential projects (eg, travelling between a residential suburb and a large work centre).
- Likewise, measure travellers that could potentially interact but not necessarily use the section pertaining to each project (eg, travelling between a residential suburb and another large work centre that crosses the route above).
- Seek expert opinion amongst the project team.
- Canvass local practitioners as to their opinions.
- Use the interdependency table that should (may) be within the strategic case for the projects of interest.

The outcome from this analysis will be a potentially large list of projects, plus details of transport projects under active consideration and the level of their analytical development, if necessary.

4.3.2 Step 2. Reduce scope of analysis

More than likely the outcome from Step 1 will be a list of projects and a list of project permutations too large to subject to a detailed appraisal analysis, some or all of which might be informed by modelling. There is therefore a need to reduce the scope of the analysis to those projects and model runs that are materially relevant.

However, first, the question needs to be asked whether further analysis is warranted. If the standalone BCR of the project(s) of interest is(are) already high *and* is(are) not expected to face a competing project (eg, an alternative project to build a parallel route or provide alternative mode choice), then it is likely that taking the steps below will not change the decision to be made and hence additional modelling may be of little value. It may be that the standalone benefit is already known or reasonably estimated; otherwise, it can be modelled first and then the decision is made whether to proceed further.

Ideally any number of projects could be analysed for interdependency benefits. Likely the number of ‘projects’ to proceed to transport modelling of interdependency benefits will be less than 10 (more likely 5 or less), simply due to the time and cost of modelling many project permutations. Step 2a aims to do this.

Even then the number of permutations to model is still large and further analysis will be required to reduce the number of project permutations that require modelling. This is the objective of Step 2b.

To continue the illustrative example above, it may be that the combined step reduces the list of projects to take to Step 3 from 25 to 5, which has 32 permutations of projects and hence potentially requires 32 model runs for each year of analysis, and then the list of runs is further reduced from 32 to 16 or fewer. Recall these numbers are only used to illustrate the potential change in scale of each step – in reality, the list of projects and the descaling possible will vary considerably.

The step to reduce the number of projects to analyse is composed of a set of interrelated tasks and techniques to home in on the project interdependencies that are significant, combine projects/schemes that are similar, and remove or combine projects that do not have a large effect on project interdependency and/or the investment decision to be made.

4.3.2.1 Step 2a. Combining projects to groupings materially relevant to the project of interest

Some projects within the programme (if a programme formally exists) might provide benefits that are independent of Project A, or any interdependency might be small. The information on interdependency from above can be used to either remove projects with low interdependency from further modelling or group them as one ‘project’.

It is also likely that some projects will impact on the candidate project in similar ways and can be combined for modelling of interdependency purposes. For example, factitious Projects I and J may be similar road widening to adjacent sections of a route and both share a similar interdependency with the other projects – therefore, group I and J as one project.

If using the multiple core approach to measure incremental benefits, then projects will also require grouping into those that are certain, those that are probable, and those that are uncertain.

Techniques available to identify and/or confirm project interdependency:

- use of techniques from Step 1
- use of a high-level sketch planning model to assess core network interdependencies.

4.3.2.2 Step 2b. Identifying material permutations of project groupings for modelling

The intention in this step is to identify those project permutations that are expected to deliver material interdependency benefits – and those that are not. This second set of model runs can then be excluded, subject to confirmation tests in Step 3.

There may also be project permutations (ie, sub-programmes) that simply cannot be built or operated within the expected budget or may be inconsistent with the strategic aims of the project. These model runs can also be excluded.

For the projects identified as most likely to deliver interdependency benefits, the aim is to ensure that the model runs to measure these effects are undertaken. One particular matter of interest is to identify those projects that are expected to be an enabler project (ie, other projects require this project to, say, remove a bottleneck to improve flows across other project locations). The second major type of interdependency of interest is a competing project (ie, will at times take demand away from one or more of the other projects) and as a consequence would reduce the potential benefits of the candidate project.

Extra care is needed with Step 2a as (a) interdependency can be difficult to predict and (b) project budget caps can in time be raised.

Techniques available to prune model runs include:

- use of a sketch model to analyse key interdependencies in a less detailed but faster model
- seeking expert opinion and/or considering precedents elsewhere and prior modelling etc
- simple application of cost constraint. It might be possible, for example, within a cost budget to only build 3 or 4 projects out of a potential 10 projects. Project permutations of more than 4 projects need not therefore be considered. Note, this may require change in the Waka Kotahi analysis process, where currently costs are to be considered late in the CBA process.

4.3.3 Step 3. Model economic benefits in a phased manner

The intention in this step is to undertake the required model runs to measure project interdependency benefits but do so in a manner that tests and adapts the need for further model runs in the process. The modelling may be unimodal or multi-modal, as is appropriate for the situation. The number of model runs will depend on which incremental benefit approach is to be used.

4.3.3.1 Standalone, decremental and multiple core incremental approaches

For the first three approaches in section 4.2.1, the following phasing is recommended to assess the value-add of Project A. The first step is the standard standalone test where, to be transparent, the test is labelled as M versus MA to represent the DoMin scenario, comprising the committed project group M and the (unlabelled) current network, tested against the DoMin plus Project A. If modelling is to proceed beyond the standalone test, then further grouping of projects will be required. First, all projects outside the programme likely to be interdependent with Project A can be grouped, referred to as X in Table 4.2 below. A test as to whether the level of interdependence is material will determine whether the programme should be expanded (possibly only for interdependency analysis). The next combination required is for projects within the programme, possibly now expanded, to be sorted into two (or more if required) groups: those projects without full commitment but that are highly probable to proceed (P), and the remaining projects, which by default are referred to as uncertain (U).

Table 4.2 **Model phasing when undertaking standalone, decremental and multiple core approaches**

Model run	Question posed	Comment
M (ie, DoMin), MA (2 runs)	Is standalone BCR for Project A sufficient? (In which case further testing is only required if competing projects are likely)	If not, *or* if competing projects are likely, then decremental test required. But first, is the current programme sufficiently defined (in terms of interdependency)?
MAPU, MAPUX (2 runs)	Should the programme be expanded (in this analysis) to include external transport projects?	If the programme is to be expanded, X needs to be added to M, P and U. Test requires prior judgement of what projects to include within X.
MPU, MAPU (2 runs or 1 if X was excluded above)	Is decremental BCR of Project A sufficient?	If NO, then STOP unless low value is believed to derive from a competing project. If YES (but standalone low), then test whether value will be derived if other projects are not delivered. Note, P and U may differ from previous if the programme is now amended to include external interdependent projects.
MP, MAP (2 runs)	Is incremental sufficient if only committed and probable projects are delivered?	If YES, then STOP. If NO (and decremental is higher), then enabling project(s) sits within U.
Potential total runs = 8		

This phasing will determine and deliver the appropriate test of whether Project A provides sufficient benefit to meet a BCR threshold. This modelling will not show the interdependency between two individual projects, but it will indicate where the major interdependencies occur – that is, it will show whether a major enabling project for Project A sits within the probable projects or the uncertain projects or across a wide set of projects. This may be sufficient information for the decision at hand. If more detail about specific interdependency is required, which is likely to be the case when a major competing project exists, then further modelling can be done on permutations of Project A with selected individual projects.

4.3.3.2 Probabilistic project-level appraisal (Incremental Approach 4)

The probabilistic approach, including the accompanying modelling, is likely to be preferred when there are a smaller number of projects and/or when it is important to isolate key project interdependencies. The modelling that would likely proceed for, say, four projects (A, B, C and X) is shown in Table 4.3, again from the perspective of 'What is the benefit of Project A?' The requirement of the probabilistic approach is to measure the benefit of all project permutations – in this example 16 – while the aim of phasing the modelling is to exclude further model runs where the interdependency benefit of the permutation can be inferred to be zero or low. Again, the set of committed projects (M) is shown explicitly in the tables.

Table 4.3 Model phasing when undertaking the probabilistic approach

Model run	Question posed	Comment
M (ie, DoMin), MA (2 runs)	Is standalone BCR sufficient? (In which case further testing may only be required if competing projects likely)	If not, *or* if competing projects, then continue. But first, is the current programme sufficiently defined (in terms of interdependency)?
MABC, MABCX (2 runs)	Should the programme be expanded (in this analysis) to include external transport projects?	If the programme is to be expanded, X is retained in further modelling along with A, B and C. Test requires prior judgement of what projects to include as X.
M, MA from above MB, MC, MX as standalones Total programme from above (MABC if X was excluded, or else MABCX) (3 runs if X retained)	What is the extent of interdependency? (Difference between ABCX and A+B+C+X = interdependency benefit)	Requires materiality threshold (eg, programme interdependency benefit > 20% of sum of standalones), although this test may not be appropriate if programme includes a competing project.
Say B is most likely the enabling project MA, MB from above MAB (1 run)	What is the pairwise interdependency that most likely complements A?	If residual interdependency is still high, then repeat for next most likely interdependency (could be pairwise or triple).
Say ABC is next most likely enabling project MAB, MC from above MABC (1 run)	What is next interdependency that most likely complements A?	Note, similar testing required for competing projects are expected within programme.
Potential total runs = possibly 8 or less but up to 16 (for 4 projects)		

The point of the above phasing is to undertake sufficient model runs to estimate the significant interdependency benefits and to otherwise infer a zero interdependency benefit for the project permutations not modelled. Extra care is required (ie, more modelling or other validation of prior judgements) when competing projects are involved.

The various incremental benefits can then be calculated and the project probabilities applied to derive an expected incremental benefit. Alternatively or additionally, the now estimated complete set of project permutations can be used to derive optimal project phasing given constraints such as construction timing and programme funding.

Depending on the expected sensitivity to demand and congestion, the modelling for any of the above approaches may need to be repeated for other demand scenarios.

4.3.4 Step 4. Collate and present results

The above steps will often produce more than one incremental benefit estimate and hence more than one BCR. It is not possible to exactly define how to present the results of an analysis that would apply in all circumstances, but the key presentation requirements are likely to consist of some of the following:

1. a table and/or graph with the various key BCRs
2. a table and/or graph with an estimate, or in some cases a judgement, of the, say, 15th percentile for each BCR
3. a brief description of the conditions required to produce each BCR tabled
4. a narrative describing the major uncertainties around the BCR.

Table 4.4 is provided as an example (first 4 columns only) of a summary that includes a brief narrative, with the last column providing observations about the measurement. In this case, it is assumed that all the incremental benefit approaches above have been undertaken – more likely only the standalone and one other approach would have been applied.

Table 4.4 Presentation of interdependency results for Project A

BCR	Description	BCR (say)	Comment about result (illustrative only)	Notes applicable to this research study only
BCR_{stand}	Standalone BCR (ie, assumes all committed projects completed and any uncommitted projects are either not completed or are independent of Project A)	2.5	Maybe… *This BCR is of high chance of being surpassed as the programme has strong positive interdependency, plus benefits are only modestly sensitive to events more generally.* or in other circumstances… *This BCR is unreliable because competing projects are likely to emerge.*	Expected to be shown for all appraisals. Likely to be realised only if strong interdependencies do not exist.
BCR_{likely}	BCR if it is highly likely that projects will be delivered (ie, assumes all committed and highly probable projects are completed and any remaining uncommitted projects are either not completed or are independent of Project A)	2.7	Maybe… *This result implies that a small additional benefit (as in decremental) could be delivered if the remaining uncommitted projects were to be delivered, although the exact interdependency relationship between any two projects has not been measured. It is unknown which remaining project(s) provides the interdependency benefit.* or in other circumstances… *This BCR is unreliable because there exist strong interdependencies with projects that have not yet been approved or subjected to the required business case analysis.*	Part of multiple BCR approach. As above but (a) may depend heavily on delivery of one or more uncommitted projects that cannot yet be given a high probability of completion and (b) may require adjustment to the reflect the probability of 'highly likely' project completion.

BCR	Description	BCR (say)	Comment about result (illustrative only)	Notes applicable to this research study only
BCR_{decrem}	Decremental BCR (ie, assumes all other programme projects and those outside of the programme that were considered part of the programme for benefit analysis purposes are completed)	3.0	Maybe… *This provides a reasonable expectation as there is a high probability that the full programme and accompanying interdependent projects will be delivered. Note the specific interdependency been any two projects has not been explicitly measured but is judged to be primarily between Projects A and D (say).* or in other circumstances… *This BCR is unreliable because there is no strong current commitment to the programme.*	Useful as potential benefit but may depend heavily on delivery of one or more uncompleted projects.
BCR_{expect}	Expected BCR (ie, assumes all committed projects are completed, the probability of uncommitted projects has been correctly identified and the delivery of projects occurs independently)	2.9	Maybe… *This result implies that the full programme benefits associated with Project A are expected to centre on this value but may be higher or lower should part of the programme not be delivered. The key interdependency benefit depends on delivery of project D (say).* or in other circumstances… *This BCR is unreliable because there exist strong interdependencies with projects that have not yet been approved or subjected to the required business case analysis (and hence have been given a low probability of delivery).*	The probabilistic approach. Expected to be similar to BCR_{likely} when there are few and/or independent projects that are not already committed or highly probable. Potentially will differ if high probability given to one or more remaining projects, although it does require a means to determine these probabilities.

More generally, other techniques to present the uncertainty that surround the results include:

- graphs similar to those in Chapter 3 and below
- a longer narrative on the probabilities around uncommitted projects, either included or not, in the modelling
- an explicit narrative on the risks around interdependency with competing projects, including potentially those applying to different modes
- real option values if appropriate.

4.3.4.1 Suggested graphical formats

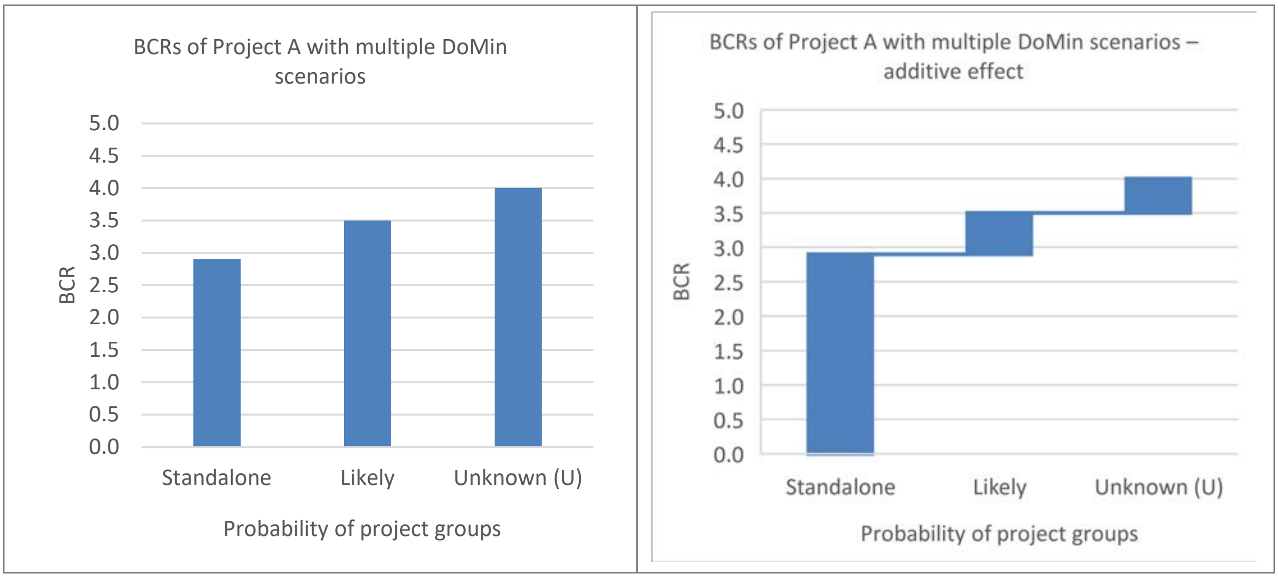
Step 4 is the presentation of the results. The key aim of the recommended method is to answer four questions:

- Is Project A expected to add value to the current and committed transport network (ie, the current standard question)?
- How will this value change if transport projects planned for in the near term, but without funding commitment, are completed?
- Will value be maintained if competing projects being considered, say within the current long-term plans, are undertaken?
- Will the value of Project A be sufficient if all projects being considered within current long-term plans are undertaken?

This amounts to creating the standard DoMin, plus several alternative DoMin scenarios (consistent with scenario testing of the MBCM; Waka Kotahi, 2020c, p. 25) and a probabilistic BCR if that is possible.

We propose adopting a standard way of presenting the BCRs that enables these questions to be answered. Several examples are illustrated below.

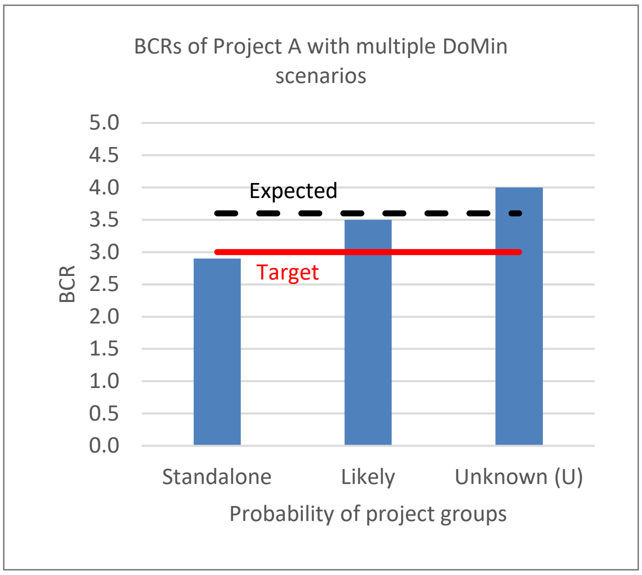
Figure 4.2 Illustrative multiple BCRs for key transport project scenarios



The graphs in Figure 4.2 show three BCRs, created by adding Project A to three alternative DoMin scenarios. Both graphs represent the BCR for a candidate Project A against a growing list of projects, with the probability of the delivery of these projects decreasing as we move from left to right between each scenario. The left column in each graph is the standard 'standalone BCR'. The second column represents the BCR if a 'very likely' group of projects that are being planned are completed, with the left-hand graph showing the level of the BCR and the right-hand graph showing the difference as we move from each BCR to the next. Likewise, the third column in each graph shows the BCR for Project A when taking into account all projects that are planned but have an unknown probability of completion – the left-hand graph again showing the BCR level and the right-hand graph showing the change shown.

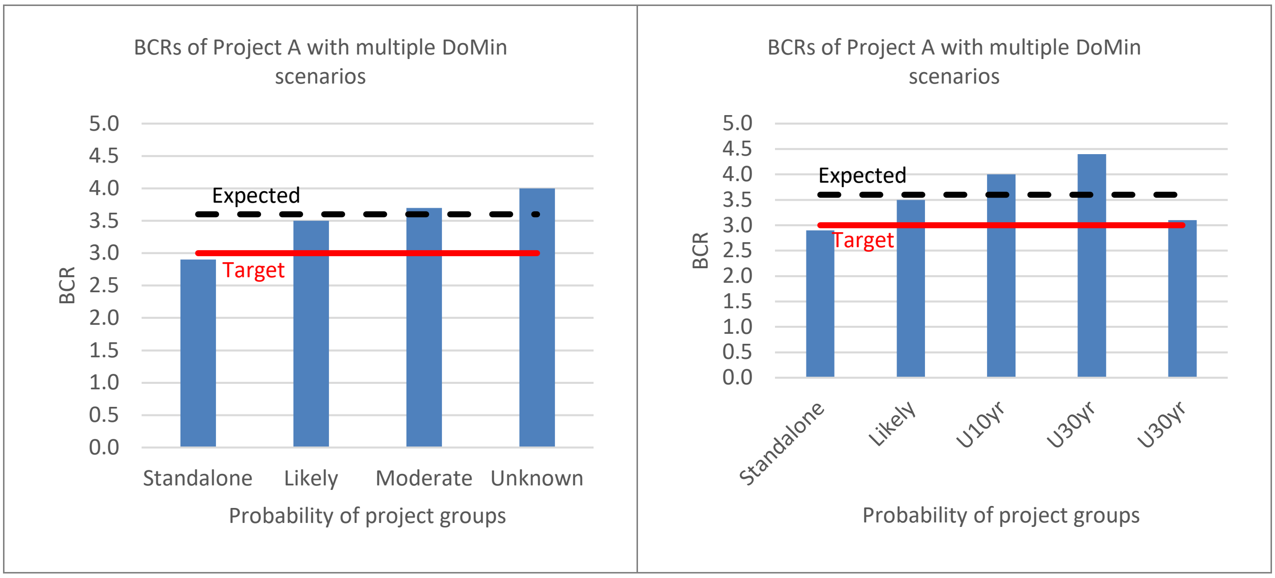
Variations of these basic concepts are considered below. If it were possible to derive a probabilistic BCR and if one or more target BCRs existed, then an expected BCR and a target BCR could be added to the above graph, as in Figure 4.3. This format provides for quick interpretation but risks creating confusion if probabilities and targets do not actually exist.

Figure 4.3 Multiple BCRs with expected BCR and target BCR also shown



It is also possible to further sub-divide and/or extend the scenarios. The left-hand graph in Figure 4.4 shows a BCR when a group of projects judged to be of 'Moderate Likelihood' are also analysed as a DoMin scenario. The right-hand graph is an example where uncommitted projects within the 10–20-year and 20–30-year planning horizon are added as further DoMin scenarios ('U 10yr' is projects within a 10-year horizon of long-term plans that at present lack full commitment and/or funding, 'U 20yr' is the same within 10–20 years, and 'U 30yr' within 20–30 years). Again, while these formats increase the information content of the graphs, both formats risk creating confusion – the left-hand graph if it was not possible to reasonably assign moderate probabilities, and the right-hand graph if the uncertainty about these later projects being completed was very high.

Figure 4.4 Multiple BCRs, with further subdivision (left) or extended time horizon (right)

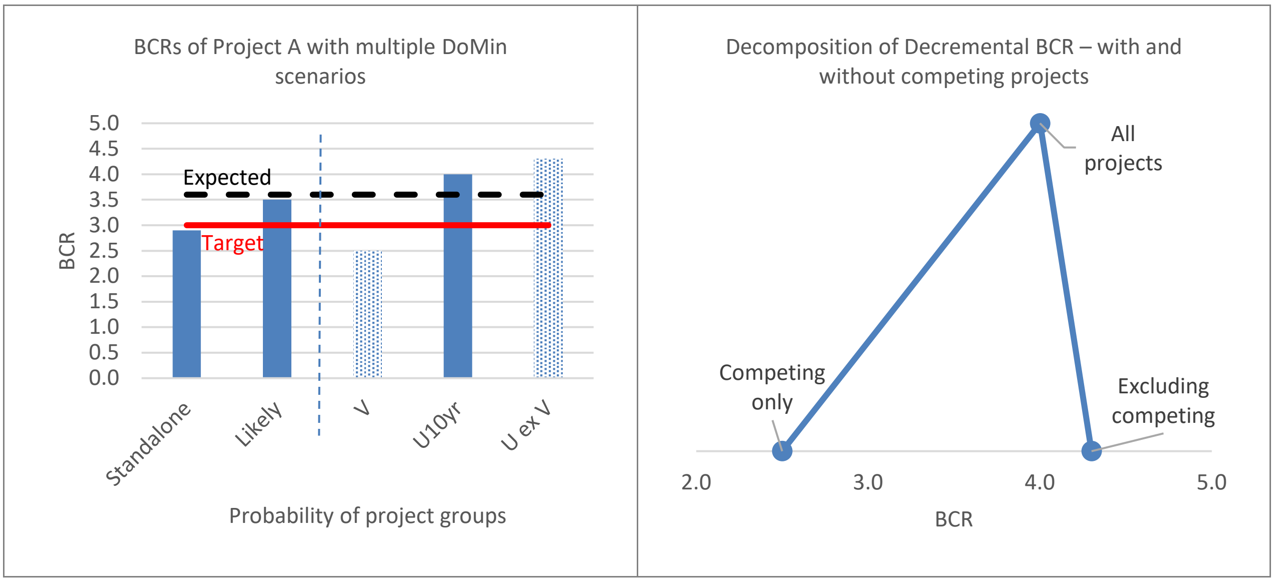


Another variation that leads more naturally into a wider presentation of uncertainty is to show the Standalone and Likely BCRs plus a range of scenarios for the other uncommitted projects. In Figure 4.5, the left-hand graph shows the Unknown group (from 10-year plans) split into three DoMin scenarios:

- the project(s) causing the competition within the Unknown set (labelled ‘V’)
- the Unknown scenario as previous
- the Unknown set of projects without the ‘V’ projects (labelled ‘U ex V’).

The right-hand graph shows another way to depict these last three BCRs.

Figure 4.5 Multiple BCRs, with low and high scenario also shown (left) or low-high scenarios shown as triangle (right)



Each format has advantages that will be considered further in the following chapters. The key point is to select a standard format so as to increase immediate understanding by decision-makers. The bar graphs are well known and make comparison simple with a target BCR, where one exists, but adding multiple targets may make the graph less easily understood. The waterfall graph (right in Figure 4.2) readily shows the interdependency effect on BCRs as other less-probable projects are brought into the DoMin. The triangle graph tends to visually reinforce the gap between the effect of including or excluding the competing projects.

5 Case study

5.1 Introduction to case study

The method proposed is now tested in a case study. The programme selected is the Major Cycle Routes (MCR) programme in Christchurch, chosen because it includes multiple interdependencies and because transport models existed that were readily accessible. While the results of the case study hold plenty of interest, the key purpose of the case study is to test and refine ways to analyse and present interdependencies, and hence this chapter focuses on method rather than actual results. In fact, the results from the case study modelling proved to show only moderate net effects from project interdependency, but the result belies the extent of interdependency that does exist within the cycleway and road networks – many offset when combined – and does not diminish the presentation of the analysis method. The learnings from the case study – and the previous research – will be discussed in the following chapter.

5.2 Description of case study and models

Christchurch is a mostly flat city with a population of just under 0.5 million people at the 2018 census. The central business district (CBD) was extensively damaged in the 2010–2011 earthquakes but had been rebuilt by 2018 to have a workforce of around 26,000, including at shops, cafes, hotels, offices, schools and a large hospital. A university sits near the CBD. As at 2018, cycle mode share was around 2.5%.

The MCR programme was started in 2014 and is planned to consist of 13 cycleways, plus a network of cycleways within the CBD and another extending along the south coastline. A key motivation for the programme was to provide safer cycleways, particularly for the local adult population believed to be open to cycling but choosing not to cycle at present because of concerns for their safety – this proportion is estimated to be up to 30%.

The cycleway programme sits within the responsibility of Christchurch City Council, but co-funding has come, and is expected to come, from other parties, including Waka Kotahi. Waka Kotahi, and Christchurch City Council and Waka Kotahi jointly, also have major transport projects being undertaken or committed within the city, some linked with the MCR.

There also exist plans (within 10-year planning reports) for other cycle projects, other road projects and public transport projects that have not yet started that do *not* have funding commitment.

Earlier modelling for the MCR had been done by integrating three models: the strategic Christchurch Transport Model; the Christchurch Assignment and Simulation Traffic model; and a purpose-built 4-stage Christchurch Strategic Cycle Model. Being sophisticated models, running the combined cycle and traffic models is very time-consuming, both in terms of computer processing time and modeller input. The latter two models were used for modelling in this case study to consider the key intermodal effects of the cycle projects.

Key features of the combined models are listed below.

- Trips are modelled between some 1,400 zones.
- Cycling potential is modelled by considering four trip purposes: home-based work trips (ie, trip base is home), home-based education trips, other home-based trips and non-home-based trips.
- Trip projections are based off land-use forecasts for 2021 and 2041.
- The cycle mode share of trips between each zone pair is derived using an incremental choice equation that results in higher cycle share when cycle paths/lanes are improved (in a perceived sense) and/or when road travel costs increase, including due to congestion.

- The benefits reported are those due to less traffic congestion (decongestion) resulting from those people shifting from cars to cycling, and those due to people cycling (safety, health, environment, and user preference).
- A present value for benefits was estimated over 40 years by extrapolating model results between (and before) 2021 and 2041, with benefits capped beyond at 2041 levels, and with future values discounted at 6% per annum.[12]

For practical purposes a 'time zero' had to be chosen. This was set at 2018, primarily because at that stage there were major parts of the MCR that did not have funding commitment but were planned to be phased in, both in the next 2–3 years and some within the next 10 years. This mix of funding uncertainty and phasing provided the conditions suited to the interdependency analysis of this case study. The DoMin network for modelling was the existing 2018 network plus those projects that had funding commitment (more on this below).

5.3 Method to test

The method developed in earlier chapters and to be illustrated, tested and refined in this case study consists of four steps:

1. Establish the set of projects of relevance to the project to be analysed.
2. Group projects and identify likely key interdependencies.
3. Conduct phase modelling to incrementally address issues.
4. Present results.

First, to standardise the nomenclature for this research report, the work yet to be completed on the 13 cycleway routes will be referred to here as 13 'projects'. Each of these projects may consist of 'sub-projects' that are likely to be referred to elsewhere as projects in their own right. The 13 projects make up the programme.

For this case study, the NorWest Arc cycleway was specified as the project to analyse, dubbed Project A. It was a route with a potentially large origin (or production) catchment that was also shared with other cycleways, it was close to major destinations such as the CBD and University of Canterbury, and it did not have (fully) committed funding in 2018. In other words, it was a major cycleway that was likely to have significant interdependency and at that stage would require funding soon, but such funding was not certain in 2018.

The NorWest Arc route, as with other major cycle routes, had been split into several sub-sections, meaning Project A was effectively a grouping of five sub-projects. Grouping these sub-sections together as one project was appropriate to address the question posed here of 'What is the benefit of the NorWest Arc?' but such grouping would have not been appropriate if the question of interest was about a specific sub-section of the route. The grouping of A does not preclude modelling also of the sub-sections of A, although this was not undertaken in this case study. More generally, the selection of just what constitutes the candidate project to be analysed will depend on the context and will likely require some judgement.

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[12] Waka Kotahi has since changed to a 4% per annum real discount rate. Their standard analysis period remains at 40 years. However, an increase of the analysis period to 60 years is now permitted to ensure that the whole-of-life costs and benefits of long-lived infrastructure activities are captured. The approach here, however, was to use the 'as at 2018' method.

5.3.1 Step 1. Establish potential list of interdependent ‘projects’

Table 5.1 summarises the techniques suggested in Chapter 4 that were used within this case study to identify those projects considered to be potentially interdependent with Project A.

Table 5.1 Use in case study of suggested techniques for potential list of projects

Technique suggested	Use and comment
Use a checklist.	Yes – a list of cycle, road and public transport projects planned was made available from Christchurch City Council and checked as to potential interdependency with Project A.
Use select link analysis.	Yes – select link graphs were available from previous businesses cases.
Measure travellers that could potentially interact.	Yes – a sketch model was created that focused on the production catchment and a high-level assumption about the joint use of cycleways.
Seek expert opinion amongst the project team.	Yes – the team included persons who work with the Christchurch transport projects.
Canvass local practitioners as to their opinions.	Reliance was placed here on previous feedback from local stakeholders.
Use the interdependency table from the strategic case.	The 2014 strategic case viewed did not include an interdependency table.

Potentially there are many transport projects[13] that could interact with Project A. The research project team and steering group includes persons who had been – and still are – working on the MCR programme, so a large portion of canvassing stakeholders about potential interdependency was undertaken internally but nonetheless did still require discussions with Christchurch City Council staff, searches of Christchurch City Council and Waka Kotahi planning reports and, of course, some cycling. A set of transport projects, discussed below, were judged to be potentially interdependent with Project A, including all projects (and sub-projects) within the MCR programme and several external projects.

5.3.2 Step 2a. Combine projects to groupings materially relevant to the project of interest

Before proceeding to grouping projects, it should be noted that, as is standard with Waka Kotahi projects, projects with funding commitment but not yet started are grouped together and added to the existing 2018 network to establish the DoMin scenario. These committed projects are referred to as Group M.

Table 5.2 summarises which techniques suggested in Chapter 4 were used within the case study.

Table 5.2 Use in case study of suggested techniques for grouping of projects

Technique suggested	Use and comment
Use of techniques from Step 1	Yes, in that local knowledge of the MCR was used to select the grouping method
Sketch model	Not used for grouping

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[13] The method is designed to consider the interdependency of transport projects only.

The interdependence expected in this situation largely took on two forms:

- there were cycling projects that could add more demand to the rest of the cycling project
- there were road and cycling projects that could compete for travel demand between specific origin and destination pairs, either by providing alternative routes for the same trip or by potentially slowing travel times at intersections.

Two matters quickly became apparent at this stage of the case study.

First, the number of project groups had to be relatively few to undertake the modelling of all permutations of the groups. The compromise taken here was to select four cycling project groups for full modelling and a fifth group of road projects for partial testing, with this partial testing precautionary but with the willingness to model further if higher-than-expected interdependency between the road and cycling projects was revealed. A judgement was made that the cycle projects and planned public transport projects would not show large interdependence, although this was not tested.

Second, this leaves the definition of the full set of projects only loosely defined and hence can lead to multiple ‘decremental’ benefits if we were to change which projects constituted the full set projects. More generally, this is likely to be a common occurrence as there will often be other projects that could be brought into the mix of potentially interdependent projects, leading to a series of redefined decremental tests. Note, only the last test would strictly be the decremental test, but in the process of iteratively finding such a test, confusion is likely to be created by the multiple use of this term. In the interests of avoiding confusion, we will only refer to a decremental test in the final presentation of results in this chapter (based on the group of projects determined to be of key relevance by then).

The groupings that were judged most appropriate were:

1. projects planned to be undertaken near-term
2. projects planned beyond the next 3 years (and in this case within the 10-year horizon of local plans)
3. external projects that might compete with Project A.

These groupings reflected different levels of funding/planning commitments and therefore different likelihoods of occurring. This also fit neatly with the multiple core approach discussed in Chapter 4. However, this matching to the institutional set-up – in terms of funding commitments, local council plans, and modal investments – may not always be the only or most appropriate grouping method.

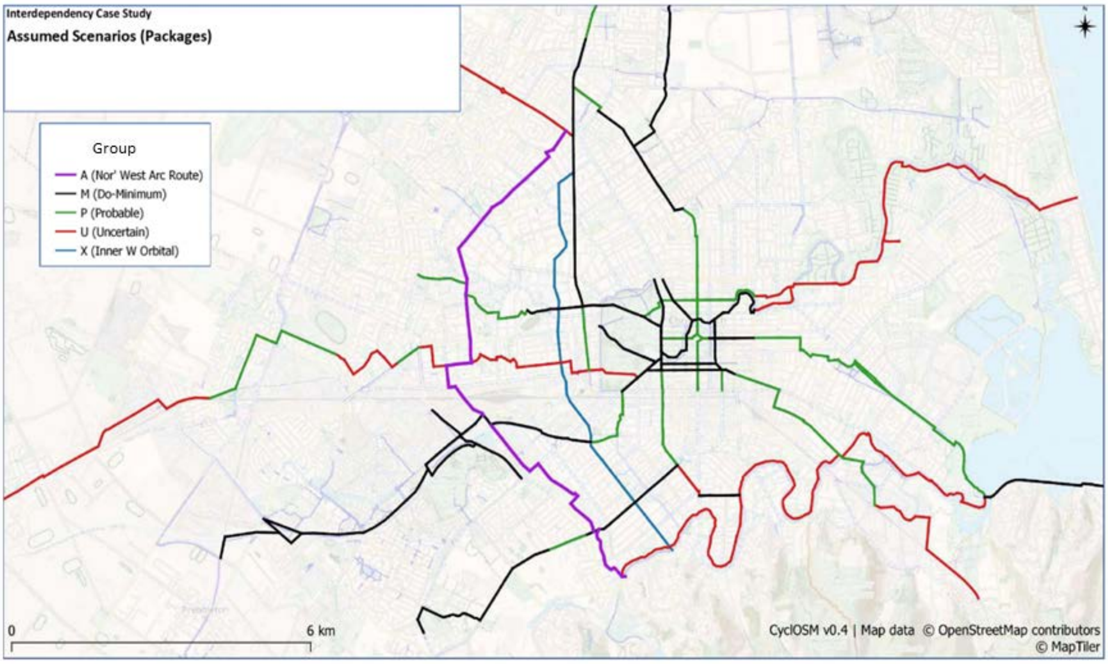
For this case study, this required splitting off sub-projects (or sections) within a cycle route, as routes included a mix of sections: some had been built or had funding commitment; some were judged likely to be built within 3 years even though funding commitment did not exist; and other sections were planned but funding commitment was simply unknown. Note, this wording is important in that projects planned to start beyond the next 3 years were not judged to be probable or improbable; rather, the probability of any project or sub-project completion was unknown.

The rule used to group projects was ‘MCR sub-project is in Group P if it sat within the first 3 years of Christchurch City Council’s 10-year plan (as at 2018) or had contractual commitment’, while all other MCR sub-projects within the 10-year plan were put into Group U. Note, this grouping sets up the initial scenarios for modelling but does not preclude modelling below the group level.

Projects outside the MCR programme that were planned but did not have funding commitment were split into two further groups: the uncommitted road projects within the 10-year plans that were potentially interdependent with the MCR (termed Group R), and other uncommitted local cycle projects within the 10-year plans that were potentially interdependent with Project A (termed Group X). As it was, all planned but not started road projects were included in Group R as the number of projects were few. Also, only one set of local cycle projects that were parallel and near Project A were judged to be materially interdependent.

The set of sub-projects within the cycleway groups is shown in Figure 5.1. The road projects were spread across the city and not concentrated near any one MCR.

Figure 5.1 The sorting of sub-projects into five groups



Note: The black lines show earlier sub-projects within each route that had been completed as at 2018.

5.3.3 Step 2b. Identify material permutations of project groupings for modelling

Table 5.3 summarises which techniques suggested in Chapter 4 were used within the case study.

Table 5.3 Use in case study of suggested techniques for judgement of interdependencies

Technique suggested	Use and comment
Sketch model	Yes – with sketch model later refined as results became available
Seek expert opinion, precedents elsewhere, prior modelling etc	Yes – primarily based on local knowledge and earlier business cases
Simple application of cost constraint	No – although the MCR funding is not fully committed, there was no explicit budget cap that would immediately exclude any planned project

Previous modelling gave insight into interdependencies, plus a sketch cycle model was created to consider the catchment effect of each sub-project. The expectations formed were that competing effects for A were mostly likely to be found within X, a proposed project for a nearby parallel local cycleway, and general competition could come from planned road projects. Otherwise, there was expected to be a dominant network effect associated with new cycle sections.

5.3.4 Step 3. Model economic benefits in a phased manner

A modelling schedule for scenarios was established, similar to that in Table 4.2, even though the intention in the research project was to undertake as near a full set of model scenarios as possible. Devising a schedule of scenarios to be modelled did allow the team to test phasing options in a ‘real-time’ sense but it also proved necessary to keep the scale of modelling within the time and budget constraints of the research project. Alternative phasing is discussed following the presentation of the results below.

5.3.5 Step 4. Collate and present results

The table and graphical formats of Chapter 4 were adopted and refined.

To recap the planned steps, there are project groupings M, P, U, X and R plus the focal Project A.

1. Projects in Group M were added to the 2018 network base to form the DoMin scenario.
2. We want to estimate multiple BCRs for the NorWest Arc cycle route, our ‘Project A’.
3. We judge positive interdependency to exist with several ‘Very likely MCR projects’ (P) and several ‘Unknown Probability MCR projects’ (U).
4. Negative interdependency is likely to come from one ‘Unknown probability non-MCR cycle project’ (X) that, if built, would be parallel to and near A.
5. We judge only limited interdependency is likely to occur with the ‘Unknown probability road projects’ (R), but wish to confirm that judgement.
6. We have grouped projects and sub-projects as Groups P, U, X and R and will proceed to model required permutations of these groups to derive (2) – rather than model the interdependency with each project separately (which would take many runs).
7. If further detail is required to determine the impact of individual project or sub-projects, then further model runs will be undertaken.

In this case study we will model as near as possible a complete set of scenarios – that is, beyond what is evident as sufficient during model phasing – to provide confirmation (or not) that benefits could indeed be reasonably approximated with a reduced number of model runs.

The results of the full modelling set are produced first to show what would be the correctly estimated benefits. Then the methods used to reduce the number of model runs are examined to determine whether they indeed provided reasonable approximations.

5.4 Results from full modelling

The combination of cycle and traffic models was run for 18 combinations of project groups, referred to as scenarios, which is much more than may be undertaken within a typical business case.[14] The 18 scenarios comprised all permutations of the 4 cycle project groups (ie, 16 scenarios) plus an extra 2 scenarios to test for interdependency between the road projects and the cycleway projects. The actual number of model runs was much greater because results were derived for 2 years, 4 trip purposes, 3 times of day etc to give a total of 60 assignments per scenario. The results are presented below for the full set of runs with benefits reported in present value terms and BCRs. For illustrative purposes, a target BCR is presented in some graphs as a reference point, although no explicit BCR target exists for Waka Kotahi and Christchurch City Council projects. The ‘target’ shown is a BCR of 3, which is the threshold for a ‘medium’ value classification by Waka Kotahi. The Waka Kotahi threshold for low is a BCR of 1 and for high is 6.[15]

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[14] Many model runs are common in business cases, but it would be unusual to model 18 options.

[15] There are BCR thresholds for mutually exclusive projects that have not been applied here.

5.4.1 Full results for Project A

Even though a full set of scenarios was preferred in this research, it quickly became apparent that not all permutations of the five grouped projects would be possible within budget and time. Hence the first test undertaken was to test whether the inclusion of planned road projects (ie, beyond those already committed and hence included in the DoMin scenario) either increased or diminished the benefit of the cycle projects. This test is achieved by incremental tests of R with selected other projects, as set out in Table 5.4 (these types of tests are repeated below but are subsequently shown as graphs). These two incremental tests showed that the road projects (R) would reduce the benefits of already committed cycle projects by $22.1 million and reduce the benefits of all cycle projects, either committed or planned, by $27.2 million (largely due to fewer people cycling when more road options are available). Note, these tests do not measure the benefits of the road projects in total but merely the effect that the road projects are expected to have on the extended cycle programme. While the results show that the planned road projects are expected to reduce the benefits of cycling projects, the magnitude of the interdependence between R and the remaining extended cycle programme (APUX) is small ($5 million) – less than 1% of total cycleway benefits – and was considered immaterial to any decision, so no further modelling was undertaken with the road projects included.[16]

Table 5.4 Present value of MCR-related benefits ($m) of planned road projects (Group R)

Other projects	Scenarios	Without R	With R	Incremental of R
M	1, 4	$0.0	−$22.1	−$22.1
MAPUX	5, 3	$959.6	$932.4	−$27.2
Difference (ie, effect of road projects on APUX)				−$5.1

The primary objective is construed as measuring the benefit of A – this is the next step. The various incremental measures of the benefit of A show a range of $145 million to $164 million, the former being the standalone benefit.

The results are presented in Figure 5.2. There are two methodological matters to note. First, the two graphs are variations of Figure 4.2 – the first two columns are equivalent to the ‘standalone’ and ‘likely’ columns discussed in Chapter 4 but now there are two ‘Unknown’ benefit measures, one for A within the MCR programme and the second for A within the extended programme. This arises because we wished to explicitly test for influences beyond the MCR programme. Alternative approaches would be to either ignore the external cycle project or include X within the U group, both effectively reverting to the 3-BCR approach. Each alternative is reasonable in this case study as the interdependency between groups was relatively small, but it was of interest later in the case study to consider some ‘what-if’ scenarios for X, hence the 4-BCR approach taken here. This also serves to show that a multiple BCR approach need not be restricted to three BCRs, but this potentially does risk confusing the decision-maker. The second methodological issue to note is showing the BCR effect in the left-hand graph and the additive BCR effect as less certain projects are brought into account in the right-hand graph. One advantage of the second graph is that the magnitude of the incremental benefits to Project A of additional projects is very apparent (even though these are relatively modest in this case). This is of interest in its own right, but also of wider interest, because these

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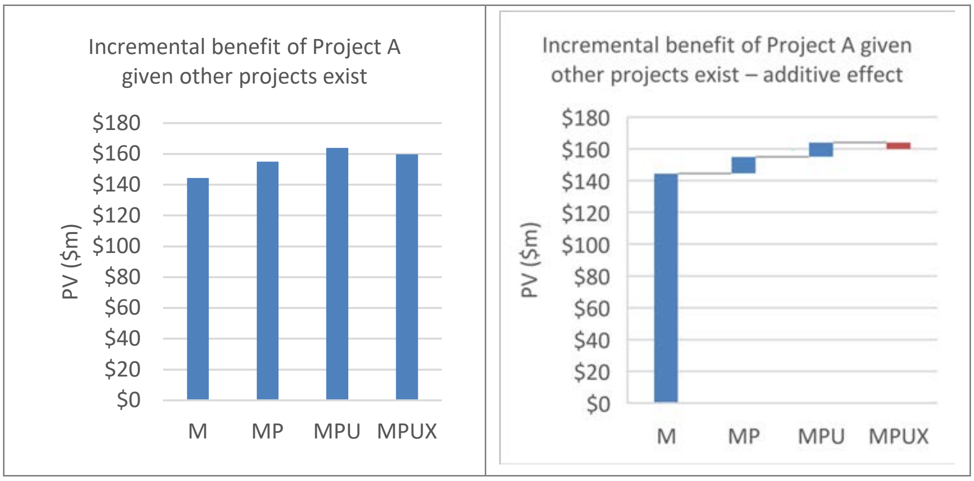
[16] Alternatively, all further runs could have included R within the DoMin, which is likely to provide a similar outcome, but this approach would have been more conservative if the effects of R were judged to fall largely on Project A.

interdependency benefits, presented here as an incremental ‘benefit to A’, will also show as interdependency benefits for other projects should their incremental benefits be calculated.

Figure 5.2 Present value (PV) of benefits ($m) for Project A – by level and change



The interdependence shown with other projects is that A is more beneficial if projects in Groups P and U exist (a complementary effect) but less if X is present (a competing effect). The two largest benefits require projects in Group U to exist, an event that was not certain in 2018 given that funding for these projects had not been committed.

The magnitude of the benefit interdependence was relatively modest (being up to 14% of the standalone benefit), but this figure belies the extent of interdependence in the network. Within these *net* effects, and hence not shown, there was a mix of decongestion and cyclist effects that were complementary (eg, adding to total network demand) or competing (eg, nearby parallel sections) between component projects, plus there were the partially offsetting effects of any extra cycleway diminishing the production catchment for nearby cycleways (eg, the first of two new cycleways will typically show the largest catchment effect when the catchments overlap) but increasing the number of cyclists due to the network effect (eg, the second cycleway still potentially increases demand for all cycleways beyond the initial local catchment effect).

The benefits shown above translate directly in the respective BCRs that were discussed in Chapter 4 and are now reported below in Table 5.5 and shown in Figure 5.3. The figure again shows two graphs: one in level terms and one including differences. In both graphs, the standalone BCR is shown by the first column, a ‘Very likely’ BCR as second, and two less-certain incremental BCRs last. The last two emerge in this case as it was judged important to extend the MCR programme to include a potentially competing local cycle project. As it was, the competing effect was small. The four columns make up the multiple core approach. A fourth method was discussed in Chapter 4 – the probabilistic approach – but it proved futile to place a probability on the various scenarios in this case study, so this method was not pursued.

Note that for the purposes of this research report, the capital expenditure (capex) costs estimated for each project have been assumed to be spread over the first three years and have been discounted accordingly in the present value calculation. There were several missing capital costs estimated and the relatively small operating costs of potentially less than 5% of the present value of costs have been ignored (unlike the business case actually submitted for the programme and projects in practice). These shortcuts within a research project are not part of the recommended practice.

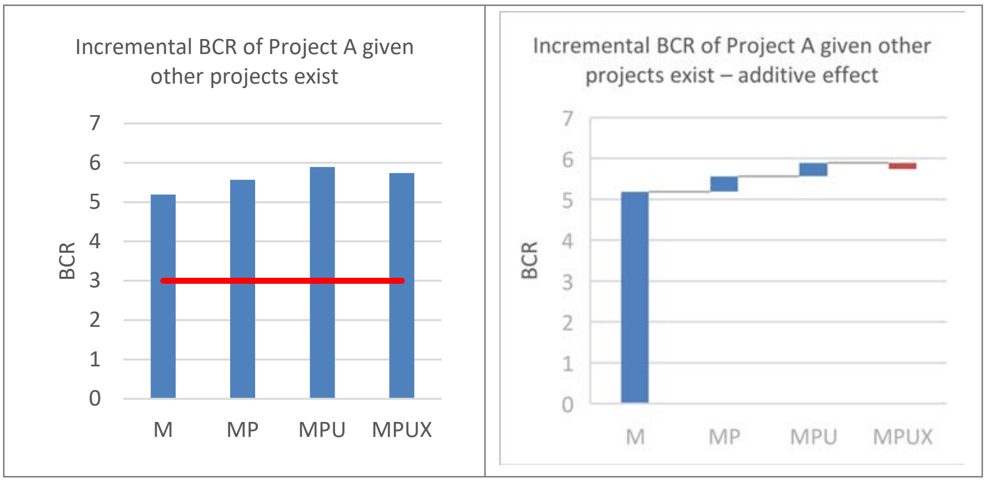
Table 5.5 Benefit of Project A to report

BCR*	Description	BCR	Comment about result
1. BCR_{stand}	Standalone BCR	5.2	Ignores network benefits of complete MCR
2. BCR_{likely}	BCR if highly likely projects delivered	5.6	A BCR expected to be exceeded once other parts of MCR are completed (which is highly likely)
3. BCR_{decrem}	Decremental BCR (extended programme)	5.7	While potentially possible, this outcome requires full MCR to be completed – this is likely but not assured, especially given lower BCRs of later projects
4. BCR_{expect}	Expected BCR	N/A	Not calculated as probability of planned projects is unknown

* The cost used is approximate only, as relatively small operating costs are excluded.

The BCRs for each project group are shown in Figure 5.3, together with a red line that represents a BCR of 3, being the (current) *incremental* threshold adopted by Waka Kotahi between medium and high efficiency. Such a target is not fixed but used here to provide perspective.

Figure 5.3 Multiple BCRs for Project A based on complete modelling runs



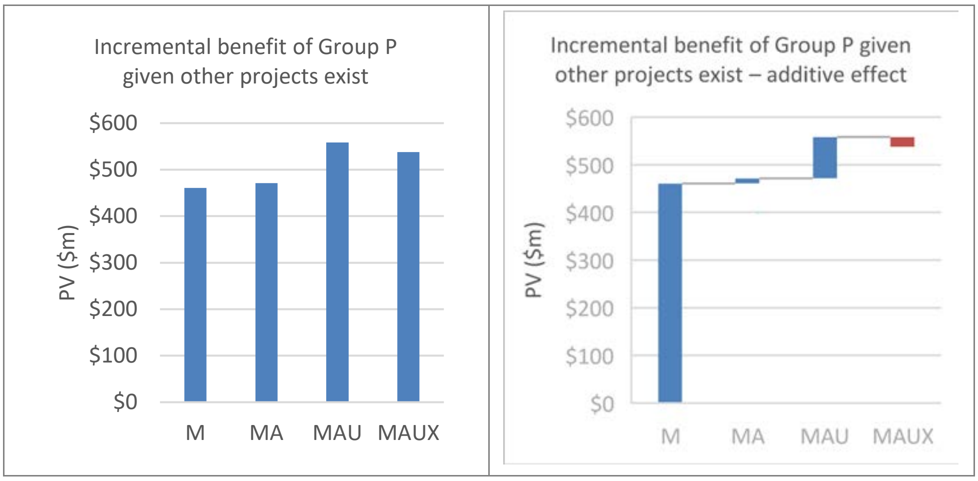
In this case, the difference in the BCRs is not material enough to alter any decision about Project A. In fact, the standalone BCR is so high that unless strong competing projects were suspected – they were not – then it is unlikely that further analysis would have proceeded. Such a readily apparent result will not always emerge. In the interest of research, further analysis was undertaken, and the results are presented here. The next likely BCR will be if the Group P set of projects are completed. This has been termed here the ‘Very likely’ BCR. It is expected that with strong institutional rules around the selection of Group P projects that the ‘Very likely’ BCR is given high (unspecified) weight in any investment decision. If it happens that the decremental BCR is markedly different than the others, then further analysis of the value and probability of completion of projects in Group U and/or Group X would be required. An example of this is provided below, following the presentation of results for other project groups and a discussion of programme optimisation.

5.4.2 Full results for other project groups

Similar results to above are also shown below for the other project groupings.

The incremental benefits for projects in Group P – those MCR projects judged very likely to proceed – ranged from $461 million to $558 million (Figure 5.4), with again the lowest measure being the standalone benefit; the highest being without X and the range being modest (21% of standalone).

Figure 5.4 Present value of benefits ($m) for Group P – by level and change



The benefits of U range from $225 million to $323 million (Figure 5.5), depending on what other projects are present, and for X from $17 million to $34 million (Figure 5.6). Projects in Group U had a strong complementary effect with projects in Group P due to the sections within the P and U groups providing links that better match demand between specific origins and destinations. The interdependency of Group X came largely from decongestion effects that, due to the low magnitude, were retested with a tighter model convergence objective but were not otherwise explored in any detail.

Figure 5.5 Present value of benefits ($m) for Group U – by level and change

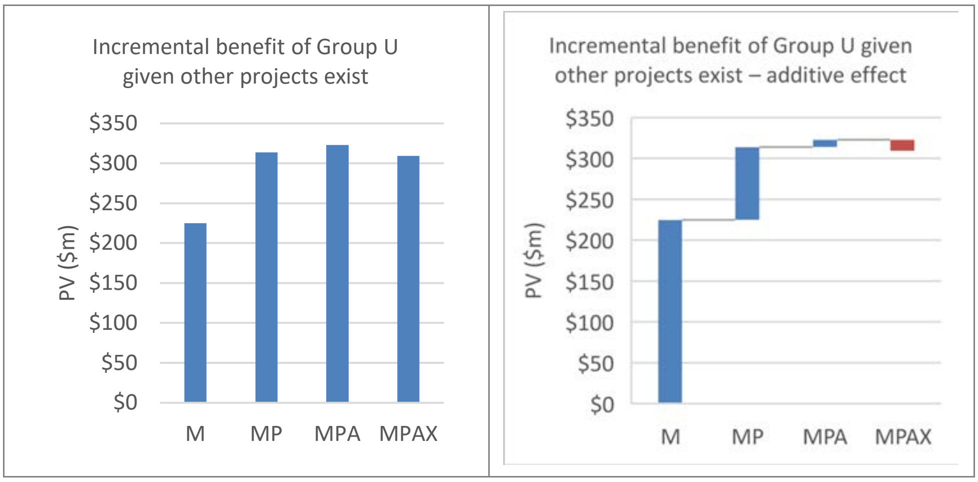
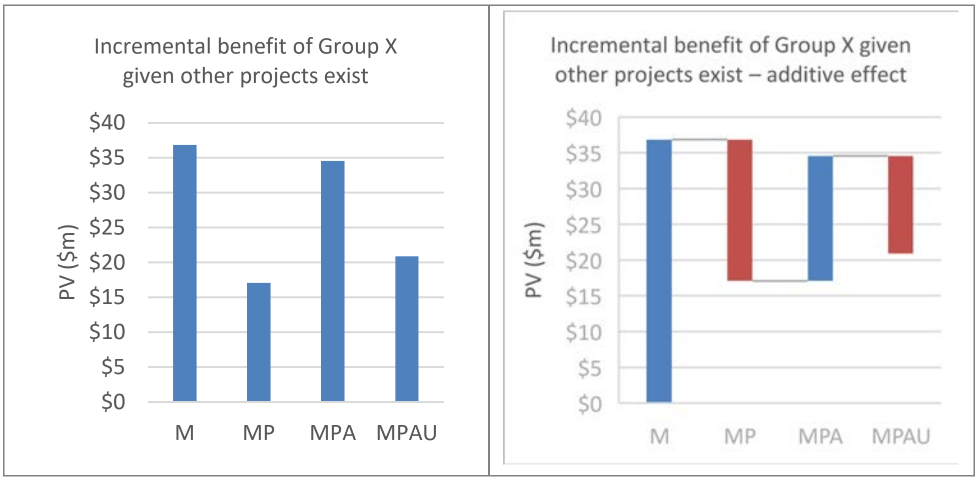
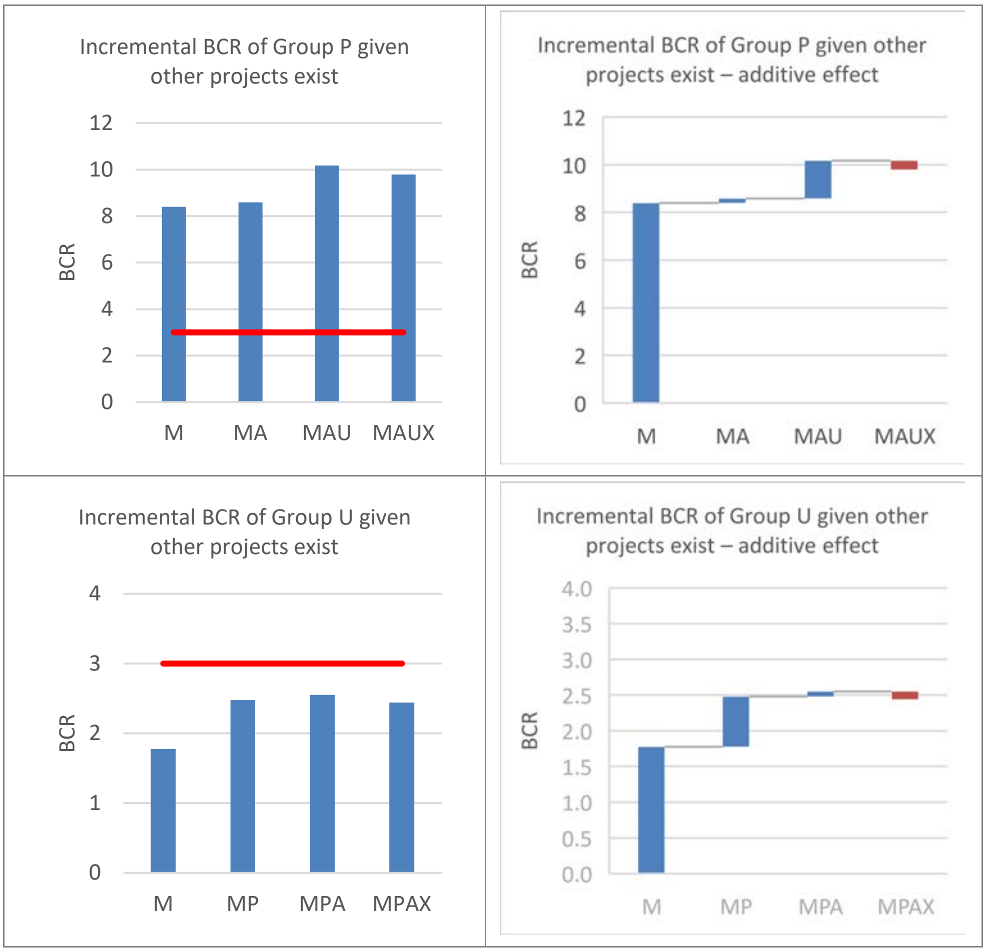


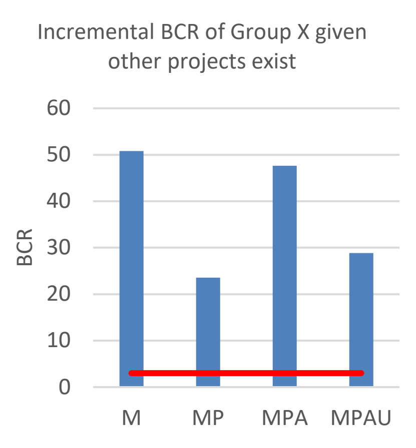
Figure 5.6 Present value of benefits ($m) for Group X – by level and change

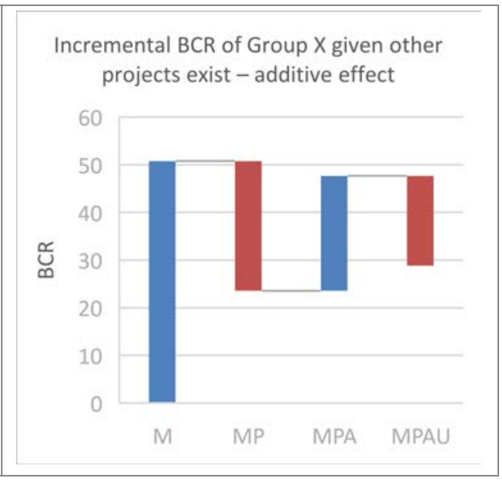


The accompanying BCRs for the above analyses are shown in Figure 5.7 below. The BCR for Groups P and X are high regardless of what happens with the other projects. The BCR for U improves with the other projects but it is generally at a much lower level.

Figure 5.7 Multiple BCRs for Groups P, U and X based on complete modelling runs







5.4.3 Project attribution

The results for the extended programme often raise the issue of benefit attribution of projects. Table 5.6 shows that the sum of the standalone benefits does not equal the benefit of the combined projects – the difference is the interdependency benefits. The table also shows that the sum of the decremental benefits does not equal the benefit of the combined projects – now the sum of the parts is above the total and the difference is due to 'double counting' of some interdependency benefits. This situation persists with interdependent projects and requires use of benefit measures for their appropriate purpose: the benefit of the combined projects is the collective benefit of the projects and is used to test the value-add of the programme, while each decremental benefit provides a measure of the marginal benefit of a project (a group of projects in this case) and is used to test whether the project adds sufficient value to the programme. We will return to this point in Chapter 6.

Table 5.6 Benefits of each project group and the benefit of the combined group

Project group	Standalone benefits ($m)	Decremental benefits ($m)
P	$461	$538
A	$144	$160
U	$225	$309
X	$37	$21
Sum of above	$867	$1,027
Combined	$960	$960

5.4.4 Programme optimisation

The modelling undertaken also provides BCRs for other project combinations within an extended MCR programme. Again, the effect of the external local cycle projects (Group X) was shown to be relatively modest, but it has been retained in the following analysis simply to reinforce the point that the 'programme' to analyse is not necessarily just the administrative programme.

The optimal project mix is typically subject to a budget constraint, which has two implications: first, a fixed budget will clearly constrain the mix of projects that can be delivered; second, this is typically managed within a wider institutional process by imposing a minimum incremental BCR threshold in recognition of wider opportunities that likely exist outside the programme of interest.

The optimal programme mix for various budget and BCR constraints are tabled below. Project A and Group X deliver the highest NPV at a low budget, although only X survives the high incremental BCR threshold.[17] The project mix A, P and X are otherwise optimal unless the incremental threshold for U was 2 or less.

Table 5.7 Optimal mix of projects[18] for various budget and incremental BCR constraints

Efficiency scale as per Waka Kotahi	BCR > 1 (Low)	BCR > 3 (Med)	BCR > 6 (High)
Capex < $50 million	AX	AX	X
Capex < $100 million	APX	APX	APX
Capex < $250 million	APUX	APX	APX

A closer look at U shows:

- The benefits of U are higher when the P set of projects are present or, conversely, the existence of U makes P more valuable – by around $70 million, should Project A and Group X also exist.
- The current BCR of U is 2.4 and a closer examination of the results shows that the expected benefit would increase if the project were to be delayed, although not sufficiently to push the incremental BCR over 3 at any time in the next 10 years (and that is assuming costs remain as per 2018 estimates).
- The sketch model points at sub-projects within U that appear to create a relatively low production catchment, at a relatively high cost, and also lack other network enhancement attributes.

These issues can be brought together within a real options framework. The construction of P and the deferral of U creates an option to expand. The value of this real option cannot be measured exactly, but factors that would determine this value can be examined. On the benefit side, the $70 million extra benefit will only be delivered if (a) uptake of the rest of the MCR is relatively strong (hence encouraging continuation of the programme) and (b) the projects can be refined to improve the BCR of U (or U is believed acceptable on other grounds such as increased leisure cycling, which is not taken into account in this benefit estimate). The combined probability of these two events is unknown, but it seems reasonable to assume it will be below 50%, making the expected value of the extra benefit less than $35 million, or less than 0.6 of the costs of P, in present value terms. This value would be reduced by (small) road congestion costs in the meantime. On the cost side, it is likely that some cost escalation was expected in 2018 if U were delayed and hence the expected option value (extra benefits less extra costs) created by the construction of P would have been well below 0.6 in terms of the BCR for P.

In sum:

- Project group P is likely to produce a BCR of 8.0–8.6, depending on the existence of Project A and Group X, plus it potentially creates an option value that could push the BCR to near 9.0 on an expectation that a delayed and refined version of U could proceed.
- Project group U is unlikely to meet a BCR threshold of 3 (considered to be where medium value is attained), but sketch modelling suggests refining of projects and timing could raise the BCR, although this requires costs to remain relatively stable and the speculative nature of this refinement points to the importance of the wider Better Business Case framework in helping decide about U.

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[17] Thresholds may differ between organisations and over time.

[18] In all situations it is assumed that the committed projects (M) are part of the optimal mix.

- Project A is expected to produce a BCR above 5.2, very likely above 5.6, and while there may be further benefits if projects within U are completed, the additional benefit is immaterial to an investment decision about A.

This, then, completes the analysis made possible by having a full set of scenarios modelled. It is possible to break down the results further, but that largely lies beyond the scope of this project. Investigation of how the components of the benefits differed, especially decongestion effects, was undertaken, but the results did not materially alter the outcomes and implications for decision-makers discussed above, so they are not reported here. The joint cycle and road models were not used to consider individual projects or sub-sections within each group, although this was possible, and had been done previously, but instead sub-section analysis here was confined to the sketch model. The case study has enabled the recommended method to be tested, including around the phasing of model runs to be discussed below, but no conclusions have been drawn as to where the case study sits in the spectrum of cases likely to be encountered.

We now turn to the methodological question as to whether less modelling would have sufficed.

5.5 Results from reduced scenario modelling

The above results derive from running 18 scenarios for 2 demand periods through the two models, one for cycling and one for road traffic, which is an excessive amount of modelling for this programme and will often not be necessary. However, having derived the full results, we can now examine whether a similar conclusion could be reached with less modelling – and more generally produce reasonable results when project interdependency is even larger.

Recall the context for this question is that other steps have already been taken to reduce the number of project permutations and hence the potential number of scenarios to model, but with 4–5 project groupings this still leaves a large 16–32 potential scenarios, potentially beyond the resources of many if not most business cases. Hence, steps to phase modelling in a way that will reduce the need for the modelling of all scenarios may need to be taken – and are recommended by our research.

Two approaches have been discussed in the previous chapters: the *pairwise rule*, which assumes the higher-order interactions are likely to be low, and the *selective approach*, which can be used to identify the projects ultimately of importance, assuming all other projects are completed.

A summary of our findings follows below, while more detail on the modelling is provided in Appendix F.

5.5.1 The pairwise rule

The pairwise rule is to assume all 3-way and higher-order interdependencies are zero and instead estimate the scenarios that involve three or more projects from the benefits of singles and pairs of the constituent parts.

Applying this rule does not change the results for the standalone and ‘Likely’ BCR tests presented above. Referring back to the columns of Figure 5.4, the standalone BCR for A can be produced with two scenarios: M and MA in this case study. The ‘Likely’ BCR can also be produced with two further scenarios: MP and MPA. Neither rely on approximation.

The decremental test is more complicated in this case study and likely will be in other studies. Starting with the simplest situation, to estimate the equivalent of a decremental test within the MCR programme would require modelling three more scenarios (MU, MAP, MPU), which are then used to derive an approximation of the MCR programme benefit (MPUA) and hence also the decremental test of A. If instead the extended programme (MAPUX) was considered as the full set of interdependent projects then the three scenarios above would need to be supplemented by four more (MX, MAX, MPX, MUX) – that’s a total of 11 scenarios now (the initial four plus the seven extra). It was anticipated that the road projects (R) would also create benefit interdependencies, making the potential full set of interdependent projects even larger (MAPUXR), which would require the modelling of another five scenarios (MR, MAR, MPR, MUR, MXR) when applying the pairwise rule – that's now 16 scenarios. This is an onerous and unnecessary amount of modelling for one project.

The problem here is the uncertainty about which projects constitute the 'full set of interdependent projects'. The many scenarios could have been avoided by using other methods to establish the full set but will sometimes be preferable to test such pre-conceptions with the iterative approach used in this research study. A more direct approach can address this issue, as discussed in the next section, but this is a warning when building benefit measures from individual and paired projects that many scenarios may still require modelling.

The large scenario disadvantage for the pairwise rule reduces as more projects are treated as a candidate project. For example, the results for the 7–16 scenarios above can also be used to provide multiple BCRs for P, U and X. At the upper case, this is a slight reduction on the 18-scenario fuller approach discussed previously.

For this case study the results from using a pairwise estimation method were similar to those of the fuller approach. The standalone and 'likely' BCRs were as previously produced, as to be expected, while the 'Extended Programme Decremental' benefit for A, for example, was marginally higher at 5.8 if using the pairwise rule than the actual 5.7.

This result should be treated with caution as such a close approximation is unlikely to be repeatable when larger interdependency exists – as will be shown below after discussion of an alternative method for model phasing.

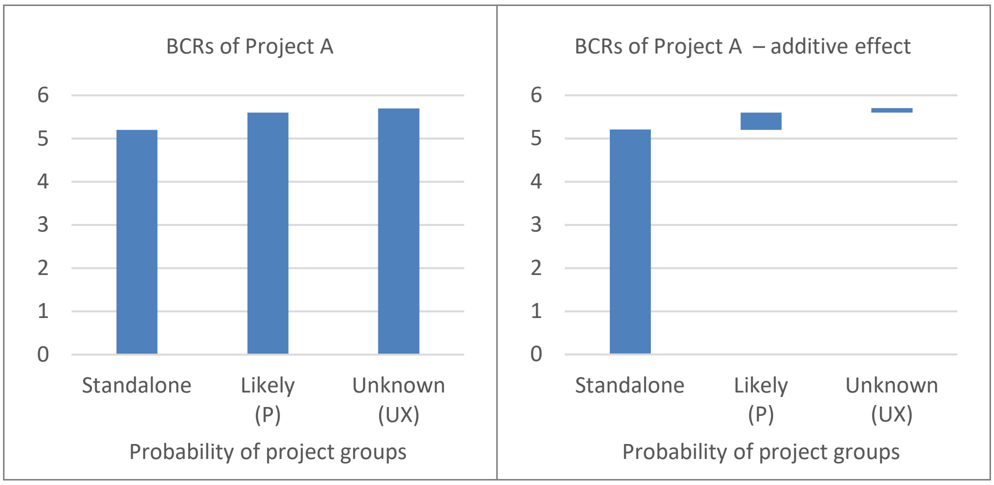
5.5.2 Judgements and selective testing

An alternative approach to applying a pairwise rule is to selectively test for interdependency only where it is expected, with expectations based on an initial decremental test, project knowledge and possibly sketch modelling.

Rather than building up a combined benefit using single and pairwise scenarios to calculate the BCRs for Project A, as above, a more practical process would be to calculate the decremental directly. In this case study, this would have been a 4-scenario test of R (M, MR, MAPUX, MAPUXR) and then, assuming the interdependency of R was found to be relatively small, either the cycle programme (MAPU) or the extended cycle programme (MAPUX) would have been used in a decremental test for A. The total number of scenarios modelled would have been eight for the extended cycleway programme (ie, M, MR, MAPUX, MAPUXR, MA, MP, MPA, MPUX), and this would have produced the same results for Project A as shown in Table 5.5.

However, these eight scenarios only provide partial benefit estimates for the other cycle projects, and context will determine how many more scenarios to model. It will depend on what interdependency is revealed and whether it is of more importance to focus on projects and sections within one or more particular groups or whether the entire programme was of equal importance. The limit for the number of scenarios will be the same as with the full analysis, but the opportunity exists to provide the required information with fewer scenarios. In this case study, the 3-BCR results for Project A (Figure 5.8) could have been attained with eight scenarios, and a robust summary of all projects was available with 12 scenarios. To repeat, the number of runs required will vary by situation. As will be shown next, the benefit estimates also remain accurate under a situation of more extreme interdependency.

Figure 5.8 Multiple BCRs for Project A calculated from eight selected scenarios



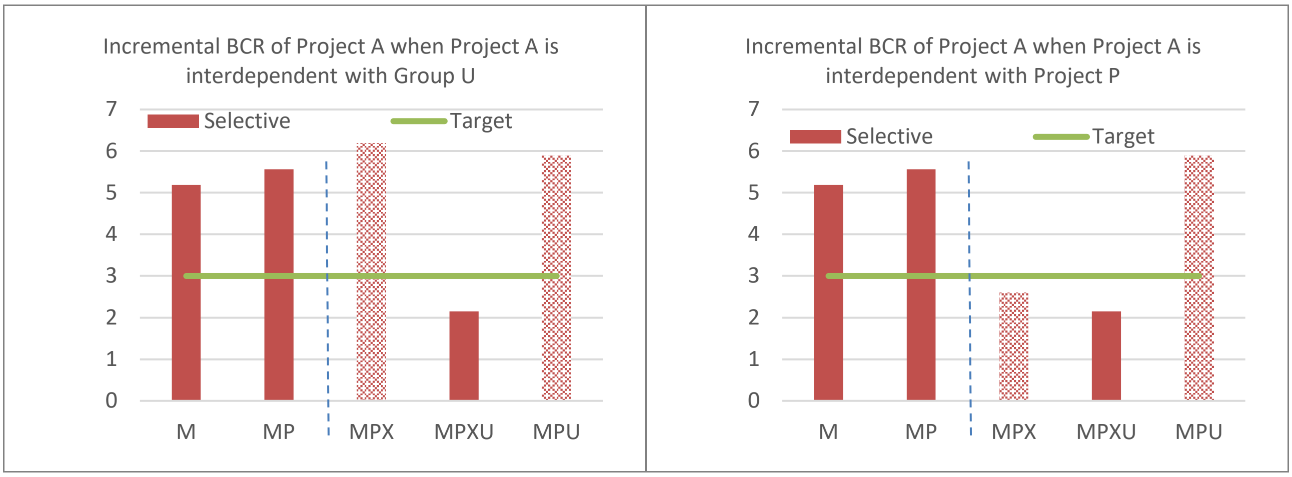
5.6 Testing the method with hypothetical results

The relatively low net interdependency shown between project groups did not allow for a robust test of the recommended method of analysis. In particular, the low magnitude of competing effects did not lead to situations where decision-makers have to weigh up different outcomes for different project mixes. To illustrate the effect of strongly competing projects, the model results reported above were adjusted to show a costlier X that strongly competed with A, but only in the presence of other projects: first, assuming the A–X competition occurred in the presence of U; and second, assuming the A–X competition was only in the presence of P. The possible narrative to match these situations would be that X and A are nearby parallel cycle routes, that both A and X attract cyclists when they co-exist but when, say, demand increases due to an additional feeder route U, a large part of the demand on A shifts to X (maybe it's a new coffee shop on X that can survive when the demand created by U exists). In the second situation, the role of the feeder route would be P rather than U. Note, this situation is contrived and used for illustration of the method – it is not a situation that is expected, nor being advocated. It does, though, highlight key issues. The competing effect is created by cyclists re-routeing due to either P or U and, as we found previously in the sketch network, the pairwise rule does not hold with re-routeing. Thus, an alternative 'selective approach', as above, may be required.

The results of the hypothetical modelling were that the pairwise rule would have overstated the decremental benefit of Project A, as expected, even after 11 scenarios. Conversely, the selective approach used above would have revealed that a strong interdependency existed after four scenarios and would have the full set of incremental benefits for Project A after 11 scenarios. These results are presented in detail in Appendix F.

The hypothetical exercise also revealed the importance to reporting results of the grouping and testing order. The results for Project A, when the interdependency with X applies when U is present, are shown on the left of Figure 5.9 and, on the right, for Project A when the interdependency with X applies when P exists. That is, A is competing with X in both cases, but the re-routeing only occurs when a third cycleway exists, and this third cycleway is either within U (left) or P (right). The order of the incremental BCRs is the same in each graph, but the pattern of BCRs differs: the BCR for MPX (the third bar) is high on the left but low on the right, capturing that the interdependency applies earlier on the right (because it is P that is triggering the interdependency, not U). This difference in BCRs created by phasing and the graphical representation of the results will be taken up further in the next chapter.

Figure 5.9 BCR for Project A assuming AXU interdependency (left) and AXP interdependency (right)



5.7 Conclusion from case study

The case study led to model runs for 18 scenarios (with two demand years for each), a cumbersome task that would typically exceed the resources applied to most business cases. That said, if the dollar amount of the benefits is high and the project interdependency is 3-way, or higher, then this amount of modelling may be justified. In other cases, reduction in modelling will be warranted, to match the potential benefits of a robust assessment (and decision), and conversely the risks of a less-robust method, against the resources required for modelling.

A key purpose of the case study was to show and refine the identification and grouping of projects. The grouping was important because (a) it made the modelling task tractable and (b) it sorted projects into groups that provided the summary BCRs that matched institutional arrangements. Rules were applied in the case study to guide this sorting. These rules do not dictate how to judge which projects are likely to be interdependent; rather, they provide a precedent method, which included canvassing stakeholders and transport plans and building a sketch model. It is difficult to get away from expert judgement during this process, which does increase the importance of the decremental test for confirmation. The decremental test may not be treated with much confidence in the final decision if it is uncertain whether key interdependent projects will be delivered, but the test does point to the existence – or not – of potential interdependency and can thus be used to inform the requirement for further investigation. To link through to the latter stages of the analysis, grouping projects on the basis of the likelihood of project delivery is a key requirement for the presentation of interdependencies.

In this case study, the results were relatively simple: Project A is of high value. It is likely that, in a real application with only limited interdependency, further analysis of Project A would therefore be limited. Best practice would be to write down why any interaction is expected to be minimal or disproportionate to the standalone and then support this with a decremental test.

However, if Project A had been more marginal on a standalone basis, then a multiple core analysis would be necessary to further understand the interdependencies. The interdependency benefits thus identified cannot be solely attributed to Project A as they are also ‘claimable’ by the other project groups (P, U and X in our case).

If Project A had been costly and decision-makers were risk averse, then it would be necessary to test the robustness of the project benefits. This could potentially lead to the testing of a large number of scenarios unless undertaken systematically. Here we have considered a pairwise rule and a ‘selective’ modelling approach. The pairwise rule still requires a large number of scenarios to be modelled – 11 for four groups of projects – and was shown to require at least a 12th scenario if large 3-way interdependency was suspected. Situations where the pairwise rule will not hold include when re-routeing effects occur and/or when user benefits are congestible – which limits its applications. We found that a more efficient phasing can be undertaken by selective modelling using a series of incremental tests.

Our analysis of the Group P projects led to similar findings. Likewise, the Group X local cycleway projects were of value, given a low cost, and any interaction with P and A was minor. It is the Group U projects that offered both benefit in their own right and complementary value to the rest of the MCR programme, but these results suggest the combined value (in terms of the monetised benefits assessed) was likely to be relatively modest.

Presentation of the interdependency analysis results to decision-makers is critical. Our view is that graphs are best and three important attributes of the interdependency benefits should be conveyed:

1. They are conditional on other parts of the network being developed.
2. They are shared between projects.
3. They are uncertain.

We have explored the use of different graphs to present this information and see merit in the ‘waterfall’ style. However, it may not always be appropriate. This will be taken up further in the next chapter when recommendations for the MBCM are provided.

6 Recommendations

6.1 Introduction

Project interdependence leads to conditional outcomes and hence multiple benefit–cost ratios (BCRs) to be used in the decision-making process. In some situations, the multiple BCRs could be brought together as an expected value and an expected variance. However, these situations are few in transport economics, both now and in the foreseeable future. More pragmatic processes are required to deliver decision-makers with a small number of insightful BCRs estimated in a consistent and transparent manner. This challenge is taken up in this chapter by re-emphasising the context for a cost–benefit analysis (CBA) and refining the method developed. The chapter is intended as a standalone summary that could be used as a standalone report.

6.2 Context

This research project is about a CBA, which has a strong theoretical basis. However, the CBA is preceded by an option-sifting process and is followed by a decision, with this wider system influencing the inputs to and outputs from the CBA. The matching of the theoretical concepts and the practical processes is discussed in this section. The upshot of these considerations is that the rest of the chapter leads to recommendations that:

- nudge Waka Kotahi towards reporting a range of BCRs within their priority scoring method (note, this is out of the scope of this project)
- identify situations where the modelling of interdependencies could materially change and improve decisions
- show how, in such situations, the modelling task can be reduced without undue loss of information
- show how the results around interdependency can be communicated
- bring interdependency more in focus during the early stages of a business case.

6.2.1 The theoretical context

There are two key parts to project benefit interdependency.

First, if interdependency exists, the benefit of a project will depend on the completion of one or more other projects. This implies that the standard practice of estimating a standalone BCR will likely mispresent the value of a project. Where it is certain that all projects will ultimately be completed – say, a programme that was relatively independent of other transport projects – then the analytical response is to calculate the decremental benefit of each project. Doing so will lead to a sum of benefits that differs from the combined benefit of all projects, presenting an attribution issue, but it is the decremental benefit in this case that provides an accurate measure of the marginal value of each project. In terms of modelling, the decremental benefit is calculated by assuming the programme excluding the candidate project is the ‘Do Minimum’ (DoMin) scenario and then calculating the incremental benefit of the project – but this only applies when the completion of the programme is certain or at least highly likely.

Second, and importantly, the certainty about future interdependent projects is often not known, which in turn creates uncertainty as to whether the decremental benefit will be realised. This calls for another approach based on incremental analysis.

One approach is to calculate the incremental benefit of the candidate project for all permutations of future projects and then apply probabilities to determine the expected benefit – that is, calculate the probability-weighted average benefit. To complete this analysis, a distribution of benefits for a project would also be calculated and the decision-maker would then have to weigh up the central expectation versus the possibility of lower or higher outcomes.

Again though, there are difficulties with such an approach: the probabilities are typically unknown, and this requires a decision-making process aligned to expected values *and* risk. Both problems exist within Waka Kotahi, as will be discussed below.

An alternative approach is to present a range of feasible benefit scenarios. The practical challenges are to choose a small number of scenarios, so as to enable focus on a decision, but to choose these scenarios to be representative of the range of possible outcomes and in a manner that is transparent to the decision-maker. The decision-making then requires a system that enables decisions under uncertainty to be made.[19]

It is this multiple scenario approach that is recommended here – namely, to systematically create a range of BCRs that are readily understood by decision-makers. In particular, the range of BCRs recommended are a series of incremental BCRs based on outcomes of decreasing certainty. Their purpose is to convey both (a) the potential size of interdependency benefits vis-à-vis standalone benefits, and (b) the ordering of the likelihood of benefit realisation. This, we believe, requires institutional rules around defining the scenarios and consistency in the presentation of the scenario BCRs.

The last major factor to influence the following recommendations is that modelling many transport scenarios is costly. So, it is important to understand when it is of value to undertake this expense and how the modelling task can be reasonably reduced. This advice is also provided below.

6.2.2 The Waka Kotahi decision-making context

The business case process at Waka Kotahi follows the internationally applied 5-case approach – namely, developing a strategic case, an economic case, a commercial case, a financial case and a management case. As normal, the CBA sits within the economic case.

There are two steps relevant to project interdependency that sit before and after the CBA.

Before the CBA, and also within the economic case, there is the ‘optioneering’ process where a long list of options is created and then sifted to form a short list, which is to be subjected to a CBA. The sifting process will often include a multi-criteria analysis. Issues that project interdependency raises within this optioneering process are discussed in section 6.4.5 below.

After the CBA, and after completion of all five cases, the proposed investment will be considered for funding, along with other proposed investments. At this stage, Waka Kotahi (2020b) focuses on three attributes of the proposed project, namely its alignment to the current transport strategy, its scheduling criticality and its efficiency, the last being measured by the BCR, although all aspects of the proposed investment brought forward in the business case are potentially of importance. Currently Waka Kotahi grades projects on a ‘Very High’ to ‘Very Low’ scale for each of the above attributes, following pre-set guidance, and then combines these grades into a priority score (1–12), using a matrix that is partially shown in Figure 6.1 below.

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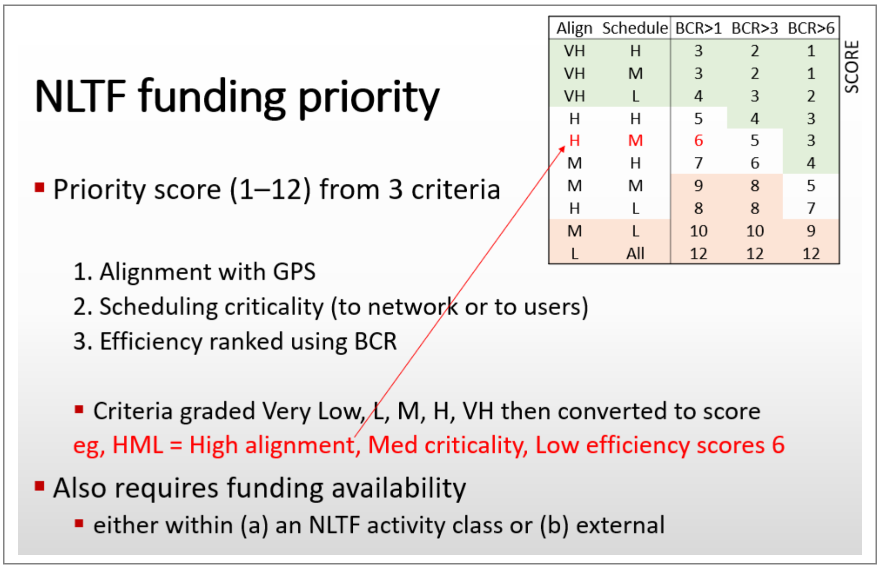
[19] For example, diversification, risk minimisation, trading off return, risk and other non-monetary factors.

Figure 6.1 The Waka Kotahi National Land Transport Fund (NLTF) funding priority process



NLTF funding priority

- Priority score (1–12) from 3 criteria

1. Alignment with GPS
2. Scheduling criticality (to network or to users)
3. Efficiency ranked using BCR

  - Criteria graded Very Low, L, M, H, VH then converted to score

eg, HML = High alignment, Med criticality, Low efficiency scores 6

- Also requires funding availability
  - either within (a) an NLTF activity class or (b) external

Align	Schedule	BCR>1	BCR>3	BCR>6
VH	H	3	2	1
VH	M	3	2	1
VH	L	4	3	2
H	H	5	4	3
H	M	6	5	3
M	H	7	6	4
M	M	9	8	5
H	L	8	8	7
M	L	10	10	9
L	All	12	12	12

The funding for investments will largely come from the NLTF, a portfolio that currently accumulates nearly $4 billion per annum from road use duties and charges, which is then apportioned into several funding streams (Waka Kotahi, 2020d). Supplementary funds, which from time to time are provided by other central government sources, are also subjected to the same approval process. Investments may also be co-funded by other parties, primarily local authorities, who have their own approval processes.

The priority scores provide a ranking for proposed investments within each funding stream, but Waka Kotahi staff or board members, depending on the nature of the investment, will use discretion, based on all the information available, as to which investments are approved by Waka Kotahi. Note, approval here pertains to the NLTF and other funds for which Waka Kotahi has been granted authority but excludes any co-funding from local authorities. In recent months, it has been typical for an investment with a priority score of 1–4 to be approved for funding, for those scored 8–12 to be declined, and for those with scores between 5 and 7 to have had a diminishing chance of approval (note that this is a generalisation only – there are exceptions).

6.2.3 Bringing theory and process together

The aforementioned Waka Kotahi process has several implications for the reporting of CBA results.

- The process currently does not formalise risk and/or uncertainty into the priority scoring, although it is part of the general information available to decision-makers.
- Related to this, the priority scores are presented as a discrete number, but it would be simple to adjust the current scoring system to include a band (eg, priority score of 4–5), although this still does not inform the decision-maker as to how to weight this variability within the funding decision.
- The BCR feeds directly into the efficiency criteria, but there is also potential for the modelling of project interdependency to influence the grades given to the other two key criteria, and potentially all information in the business case informs the funding decision – in other words, the modelling of project interdependency is more than just producing a more accurate BCR.
- That said, the modelling of project interdependency will most likely affect the funding decision if a project was otherwise considered as ‘Medium-High’ in terms of alignment and scheduling and has a BCR near 3 or less. Note that project interdependency can be complementary or competing, and hence extra modelling of project interdependency could lead to either an upward or downward adjustment to the priority score otherwise obtained; this is not a one-way street.

6.3 Lessons learnt

The other major input into any recommendation is the learnings from this research project. The learnings reported in Chapter 3 from exercises with a sketch model are updated in Table 6.1 below with learnings gleaned from the case study.

Table 6.1 Combined lessons from sketch modelling and case study

Sketch modelling lesson	Case study
1. Many model runs are required if all project interdependencies are to be fully measured.	Confirmed. Grouping of projects was necessary – and possible – to make the modelling task tractable.
2. Graphical representation of benefit measures is required to improve communication.	Confirmed. However, as below, an 'expected BCR' is not possible and adding 'target BCRs' could be deceptive. Also, there may be little to gain by showing the effect of the competing project as a separate BCR.
3. A model run that includes all interdependent projects is required to accurately estimate the full benefit of a programme when project interdependency exists.	Confirmed but with proviso. The decremental does provide the marginal value of each project but often it is not known with certainty that all projects within a programme will be completed, *plus* there will often be similar uncertainty about potentially interdependent projects that sit outside the programme. Thus the 'decremental' used becomes conditional also.
4. The level of congestion was not the only primary determinant of interdependency.	Not addressed.
5. Project interdependencies can be large, can be both positive and negative, and can change from positive to negative as demand changes.	Confirmed. Positive and negative interdependencies were found, but overall, these were modest in the case study.
6. Interdependency influences the likely investment path as demand grows and more funding become available.	Partially confirmed. The budget affects the optimal pathway for projects, but demand growth was not an issue with the cycleway (although this may in time change).
7. Path dependency issues point towards some programme-level analysis being required to be able to develop the optimal development of a network.	Confirmed. Albeit the programme may need to be extended to fully consider optimality.
8. The standalone measure only provides a true measure of a project's benefit when there is no interdependence.	Confirmed. Although the case study interdependencies once netted were modest, the benefits are very likely to be higher than the standalone benefits as probable projects are delivered when interdependency is complementary and could be lower with competing projects.
9. The standalone benefit of a project can significantly overstate its true benefit when a competing project is likely.	Not confirmed in case study but no reason offered to dispute earlier finding.
10. The pairwise measure of interdependency benefits captures the majority of the interdependency for the complementary projects when there is no re-routeing and no congestion.	Confirmed in this case study where re-routeing and congestion were low.
11. The pairwise measure of interdependency benefits is likely to be inadequate when project re-routeing occurs.	Confirmed in this case study, although only due to a hypothetical situation.

12. Induced demand can play an important but ambiguous role in interdependencies, leading to positive interdependency benefits if congestion is ameliorated, but also potentially exacerbating congestion, thereby dampening down interdependency benefits and in extreme situations potentially leading to negative interdependencies.	Not addressed but likely to be important in some project contexts, especially where there is feedback between congestion, time-of-day choice and destination choice.
13. Re-routeing plays a large role in the interdependency effects and was more significant at higher levels of congestion.	Partially confirmed. Re-routeing was shown to potentially be an issue within the extended cycleway, but this was due to congestion in this case.
14. The decremental measure gives a true measure of the marginal benefit of one project if all the others were committed.	Not confirmed in case study but no reason offered to dispute earlier finding. However, the case study did highlight that often a true decremental will not be possible as there may exist other projects that may cause interdependence.
15. The incremental measures can vary significantly. These different measures depend on the ordering of projects but give an indicator as to how project interdependencies vary.	Not confirmed in case study but no reason offered to dispute earlier finding.
16. Projects can have expected benefits that exceed standalone benefits when other projects are uncertain.	Confirmed.
17. A project's expected benefits and the expected distribution of the benefits are very dependent on the probabilities assumed. This is an important evidence gap, and more research is needed on it.	Confirmed that probabilities unknown. As an addendum, where judgement is used to estimate probabilities, this process should be made transparent.
18. If undertaking project-level appraisal, decision-making processes need to be cognisant of several projects having a claim to 'the' interdependency benefits.	Confirmed.
19. Projects proceeding on the basis of a probability-weighted expected benefit will produce outcomes with low or negative NPVs sometimes.	Not confirmed in case study but no reason offered to dispute earlier finding.
20. Major investment errors can occur if negative interdependencies are ignored.	Not confirmed in case study but no reason offered to dispute earlier finding.
21. A sketch planning model could be useful as a pre-cursor to full traffic modelling.	Confirmed, both as possible in this case and as a potentially useful tool for other cases, especially to signal the materiality of interdependency effects.

The case study confirmed many of the learnings from the sketch modelling phase and did not refute any previous findings. The case study did, though, bring attention to:

- the difficulties in defining the projects to include in a decremental analysis, largely due to the uncertainty around future projects but also due to ambiguity as to how widely to search for interdependent projects
- the usefulness of the 'decremental' analysis, being the incremental BCR when the candidate project is added to all the others, as a tool to gauge the potential for project interdependency even if it is difficult to define
- the time-consuming and costly nature of traffic modelling and hence the advantages of project grouping and scenario phasing
- the importance of establishing a process to determine when extensive modelling will be required, especially as it is difficult to pre-judge project benefit interdependencies

- the importance of developing institutional rules for the collation and presentation of multiple BCRs.

6.4 Integration of results into Waka Kotahi process

The recommendations are now presented by working backwards, from what would be required in the funding decision, to which options are developed in the early stages of a business case.

6.4.1 The funding approval

As described above, the current priority assessment puts emphasis on one BCR, then on three grades, of which one is directly derived from the BCR, and then on one priority score. A wider set of factors also influence the decision-maker, but as is common, the initial ranking method is of huge influence.

The key finding of this research project is that multiple BCRs may be required to describe the monetary value-add of a project. This result will also generally apply to other uncertainties, such as those relating to land use and the general operating environment. These issues are beyond the scope of this research project, but it is noted that the methods recommended here could be extended to include a wider treatment of BCR uncertainty.

A simple way to adapt the current funding approval process would be to provide BCRs and priority scores as a range rather than a point estimate. We have provided a method here that could be used to transparently and consistently provide a BCR range which, in turn, can directly feed into a range of priority scores. This has the advantages of (a) more directly feeding project interdependency into the decision-making process while (b) only making minor changes to current processes. However, it still has the disadvantages of (a) not fully representing the range of possible interdependency outcomes, (b) not representing the range of possible outcomes due to other uncertainties, and (c) not providing decision-makers with a method to weight variable outcomes against more certain outcomes.

Many of these issues lie outside of the scope of this research project but, importantly, the method proposed here is consistent with the wider decision-making process, and the process can be further researched and refined to better account for variability of outcomes.

6.4.2 The reporting of CBA results

Key findings of this research project are that multiple BCRs are appropriate when the future is unknown and that a discrete set of scenarios is appropriate when the probabilities surrounding future factors are also unknown.

The results recommended to report when large[20] project interdependency exists are:

1. the standalone BCR
2. the incremental BCR should projects very likely to be delivered in the next, say, 3–5 years be taken into account
3. the incremental BCR should interdependent projects within 10-year plans also be taken into account.

The case study showed how it was possible to produce these three numbers for a project that was interdependent with a large number of other projects.

This method could be extended to include a fourth incremental BCR by taking into account the interdependent projects that sit within the 10–20-year horizon when 30-year plans exist, and also a fifth BCR by taking into account the 20–30-year interdependent projects as well. These extensions beyond the 10-year

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[20] What is large is expected to be contextual.

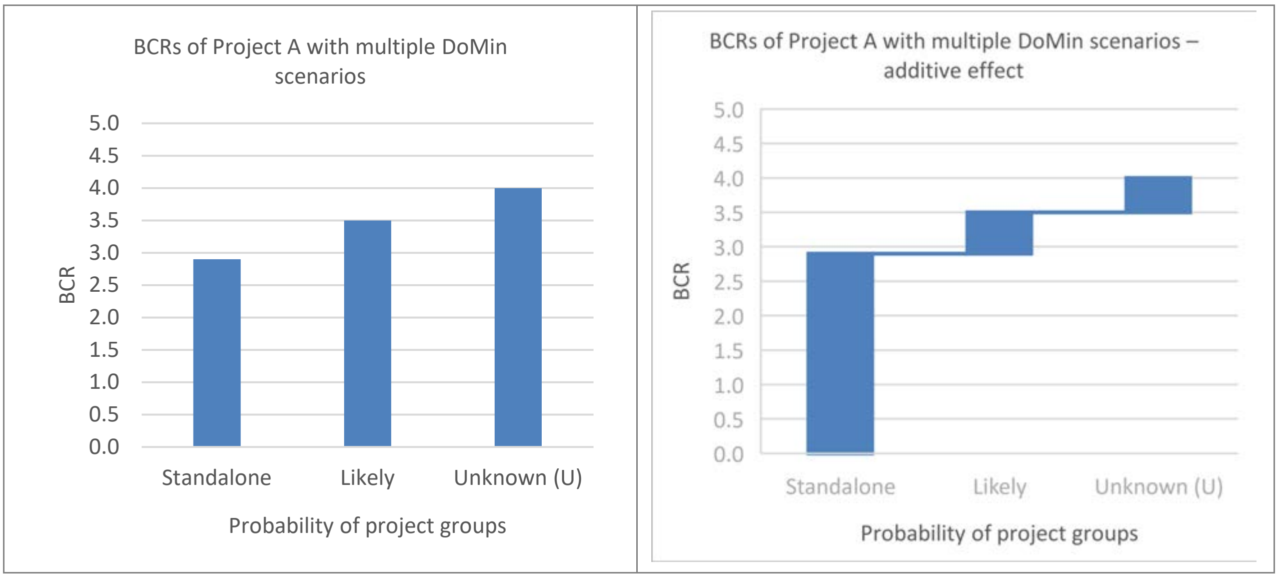
horizon were not tested here, and they do come with two major challenges: how much credence can be put on outcomes that are subject to increasing degrees of uncertainty and, from a practical perspective, how to model and measure effects within what may be a very different transport network by then and effects that will extend beyond periods of the standard period of analysis.

The recommendation of this research project is to put in place active consideration of projects that exist within the 10-year horizon of current transport plans when project interdependency is expected but to proceed cautiously with projects further into the future.

Consideration in this research project was given to weighting the multiple BCRs thus derived, effectively producing one BCR that could be taken through to the funding priority stage. However, the supporting evidence for a weighting method, whether it be based on probabilities or risk preference or another factor, does not exist at present, and furthermore, reducing the range of BCRs to a point estimate does not communicate the uncertainty around this result, so it may actually undermine the decision-making process.

The recommended method to report the multiple BCRs are (a) the graphs shown in Figure 6.2 and (b) the range created by the multiple BCRs (to be taken through to the priority score).

Figure 6.2 Illustrative multiple BCRs for key transport project scenarios (copy of Figure 4.2)



Consideration was also given as to whether to add a ‘BCR target’ as a horizontal line in the graph. There is no specified target used by Waka Kotahi, so adding such a line to the graph may confuse and potentially misinform people. There is also the added disadvantage that this number may become a target in the sense that analysts are tempted to be creative about producing results that cross (or not cross in some cases) this line. Hence the preference for the figures above. We also considered adding a low and high scenario (eg, left-hand graph in Figure 4.5), but this too was dismissed because the negative benefit effect of competing projects will already show in the decremental BCR. Extending the BCRs reported to include a ‘Moderate’ BCR or ‘Unknown 20yr’ BCR are not recommended because probabilities for the associated DoMin scenarios are simply unknown.

The exact wording to enter into the *Monetised Benefits and Costs Manual* (MBCM) is not provided here, but mention should be made of two particular sections.

First, the recommended method is a type of scenario analysis. Scenario testing is discussed in the MBCM (Waka Kotahi, 2020c, p. 25). It could be that this section of the MBCM is expanded to explicitly mention project interdependency. It could also be the case that this section is expanded to prescribe other multiple BCRs for other forms of uncertainty, although that sits outside the scope of this study.

Second, incremental analysis is also presented in the MBCM (Waka Kotahi, 2020c, p. 191). While following similar principles, the incremental analysis in the MBCM is about analysing different options in an incremental fashion. The incremental analysis of the method recommended here is designed for one option, which is then considered against alternative DoMin futures. This difference should be laid out to avoid confusion when reference is made to an incremental BCR.

There is one further matter to highlight when reporting multiple BCRs that has the potential to cause confusion. When project interdependency exists, the sum of any individual project BCRs will not equal the BCR of the combined projects, such as in a programme. Where the interdependency is predominantly complementary, the sum of the standalone BCRs will be less than the BCR of the programme, while the sum of the decremental BCRs will be greater than that of the programme. The converse will hold when project interdependency is largely competitive. The missing 'benefit' in both cases is the interdependency benefit, which does not 'belong' to any one project. The analytical response is to use the programme BCR to describe the programme and the individual BCR when considering whether to include each project within the programme. Any other approach, such as devising a rule that apportions the interdependency benefit, is *not* a measure of an economic benefit of the project but rather is a cost accounting exercise.

6.4.3 The modelling

The modelling task for interdependent projects is potentially immense. Scale reduction is likely required. There are three prongs to the scale reduction recommended here and used in the case study:

1. Group projects (and sub-projects) to bring focus to the key projects of interest and to enable a tiered interrogation of interdependency, if required.
2. Phase the scenario modelling to accumulate information as to how much more modelling is required.
3. Use a sketch model to improve insights into project interdependency and inform the first two prongs.

The use of a sketch model will depend on the situation, both in terms of what projects are being considered and what models may be readily available. In our case study we were able to build a spreadsheet model based off a catchment approach already reported by Waka Kotahi and using results derived by earlier cycle modelling for the MCR programme. In other cases, the road sketch model set up in SATURN for Chapter 3 could be adapted to the circumstances or it may be that a similar simple traffic model is built from scratch, or alternatively a systems dynamic or more general economic model is created or adapted. It is not clear which model would suit each situation, but it is clear that attempting to crudely model interdependencies brings a focus to interdependencies and provides a way to formulate prior expectations and hypotheses, which in turn can influence the phasing of scenario modelling and potentially reduce the number of runs of the more extensive, but time-consuming, transport model.

The second advantage of the sketch model is that it can be calibrated once the more extensive modelling is underway, again creating the potential for fine-tuning the phasing of scenario modelling. In the case study, the more extensive zone-to-zone modelling allowed a project-to-project dependency matrix to be inserted into the sketch model, which in turn enabled quick assessment of higher-order interdependencies.

The grouping used in the case study, and recommended for general application, was to group projects as 'very likely', 'unknown likelihood within programme', 'unknown external same mode' and 'unknown external different mode'. The split between 'very likely' and 'unknown likelihood' was made primarily by setting a 3-year planning limit, although some projects planned beyond 3 years were added as it was known that contractual commitments had been made even though the detail of the funding had yet to be specified. In other situations, it may be more appropriate to make a 1-year or 5-year cut-off instead of the 3-year cut-off used here – the key point is that current planning is used to inform the likelihood split, thus tying the results reported to an institutional behaviour, which improves the transparency around the results being reported.

The case study did show that grouping, when used for the phasing of scenarios below, enabled the analysis of project interdependency to be undertaken within a reasonable budget, but this required sorting the projects into only 4–5 project groups. It is questionable whether modelling costs will be reasonable if the number of groups increases beyond this level, although this is context specific.

The appropriate phasing of scenario modelling will depend on the situation. The phasing used, and the logic behind this phasing (see Table F.3 in Appendices), should be of aid to others. One key finding was that an early run of the complete project set and its comparison with standalone benefits provided an early indication of the potential scale of the interdependency effects, although care is required when competing projects exist. This test has been referred to as the decremental test, although it is only the ‘decremental test’ based on the chosen set of projects. It would only provide the unique decremental if (a) the full set of *interdependent* projects has been correctly identified and (b) it is certain these projects will be delivered.

One facet of the method that created a challenge in the case study was the use of the current Waka Kotahi DoMin. There is ambiguity as to what should be included in the current standalone DoMin. It is likely that the use of a more precisely defined DoMin for the standalone BCR, similar to that of the Department for Transport, and the use of rules such as above to define a ‘Likely’ BCR will provide more transparent and consistent BCRs – that is, the standalone is as per international norms while the ‘Likely’ BCR is that expected to occur once uncommitted projects that are very likely to proceed are in place as well. Of course, if such a system were already in place, the extension here for interdependent projects is to add a third BCR for projects within the 10-year planning horizon that are uncommitted and of unknown certainty.

6.4.4 The identification of interdependent projects and scale of analysis

The reporting and analytical needs of the method described above requires, before any CBA, that (a) an assessment is made as to the scale of the analysis required and (b) projects are identified, if a need for interdependency modelling is determined, that are potentially interdependent with the candidate project, or with each other.

It is hard to escape from the fact that expert judgement will be required in this early step, and hence there is the risk of behavioural bias. Such a risk can be reduced by establishing standard processes to follow. An important element of such a process is a checklist that reassures Waka Kotahi that the analyst has at least (a) considered a wide set of projects and (b) canvassed a wide set of stakeholders. It is noted that in this case study, in spite of people in the research team having working knowledge of most (if not all) of the potential universe of interdependent local projects and that the candidate project already sat within a defined programme, the research team still made a large checklist of the potential projects of interest, including those outside the programme, and made a judgement as to the likely interdependency effect of each project.

More analytically, the use of sketch models, select link analysis and interdependency tables were – and will be – key tools to use.

A helpful guide in the above search process would be a set of examples of large project interdependency. This list will naturally accumulate as new business cases are undertaken. As a starting point, large project interdependency can be expected:

- when significant re-routeing or mode shift is expected
- when demand growth is strong enough to cause congestion
- when strong network effects are strong – induced demand for other parts of the network can create either complementary or competing effects.

6.4.5 The search for options

The previous steps establish a method to calculate and report the key BCRs when project interdependency exists, built around the traditional traffic modelling and CBA process. However, prior to such extensive analysis, there is typically a long list and sifting process to identify which projects are worthy of such attention. The question is: How can project interdependency be taken into account during this pre-CBA phase?

It lies outside the scope of this research project to fully address this question, but the following preliminary comments are offered as a guide to future research.

First, as within the CBA, expert judgement plays a large role, and hence process is important.

One addition to the current process is to require two questions to be answered, ensuring project interdependency is at least considered:

1. Which projects sitting within current 10-year/30-year plans are likely to *increase* the benefit of the option being suggested?
2. Which projects sitting within current 10-year/30-year plans are likely to *decrease* the benefit of the option being suggested?

Second, it is noted that the current Waka Kotahi process does include opportunities for project interdependencies to be considered. The Early Assessment Sifting Tool[21] and multi-criteria analysis[22] guides ask that ‘Synergies and conflicts between alternatives and options should be considered if packaged together’. However, these sifting tools do not readily lend themselves to the assessment of uncertain outcomes and is a matter for further research.

Third, there are programmes that exist at present, and projects within these programmes are a likely starting point when judging interdependency. However, existing programmes have been formed for many reasons that have little to do with benefit interdependency, so a search beyond any existing programme is likely to be needed.

Fourth, there is a danger during early assessment that project alternatives are filtered out prematurely when they may be highly beneficial should other projects (or events) occur. Conversely, there is also a danger that benefits are overstated due to non-consideration of competing projects (or events), although errors of this second nature should be revealed within the subsequent CBA.

6.5 Applicability to multi-modal transport situations

The processes and methods described above apply to both unimodal and multi-modal transport situations. Project interdependency can occur within one mode: the sketch model showed examples of induced demand and re-routeing causing interdependency within a general traffic situation, and the case study also showed induced demand and re-routeing arises within a cycleway. Interdependency can also occur between modes: the case study tested for competing effects between the cycleway and planned road projects, albeit the effect found was small, but a similar test applied to, say, a public transport system competing with new roads would find larger effects. The same methods discussed above apply in all these situations – namely, identify expected interdependencies, both within and beyond any programme that might exist, and seek to efficiently model the benefits from the pertinent project permutations.

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[21] https://invest.nzta.govt.nz/pluginfile.php/757/mod_resource/content/4/EAST%20User%20Guidance%20August%202020-FINAL.pdf#:~:text=INTRODUCTION-,The%20Early%20Assessment%20Sifting%20Tool%20(EAST)%20supports%20an%20initial%20’,criteria%20analysis%20(MCA)%20exercise

[22] https://www.nzta.govt.nz/assets/resources/planning-policy-manual/docs/multi-criteria-assessment-user-guidance.pdf

7 Conclusion and further research

This chapter summarises the research findings. It is structured around the objectives of the research project and offers recommendations for future research.

7.1 Concluding comments

Project interdependency occurs when the benefit and costs of candidate projects depend on the undertaking and completion of other projects. This research project has focused on the *benefit* interdependency of *transport* projects, although similar principles could be applied to wider interdependency, such as between project costs or non-transport projects, policies and events.

The key issue raised by project interdependency is the focus on the conditional nature of a project outcome. The implicit uncertainty leads to multiple outcomes to report and to more complicated identification and analysis of effects.

We have identified a method that (a) can address these issues and (b) has a reasonable fit with the current Waka Kotahi process. We note, though, the method may require adaptation if applied to local government transport activities that do not entail Waka Kotahi approved funding.

The key steps in the method are:

1. Use process to guide experts, and possibly sketch models, in the identification of projects that are expected to be interdependent.
2. Combine projects into groups for the CBA.
3. Phase the transport modelling, progressively providing the results required and informing whether further modelling would change the results materially.
4. Report multiple (incremental) BCRs, plotted in order of declining certainty of completion and using institutional rules around the DoMin in each BCR.

The advantages of the method are that project interdependency is searched for and taken into account in a manner that is efficient and provides a transparent result to decision-makers. Two disadvantages of the method are the reliance on expert judgement at stages within the analysis and that the range of BCRs reported still does not accurately capture the range of possibilities being faced, although both components appear to be an inevitable part of any approach to uncertainty. It is also assumed that wider non-monetised interdependency issues are being addressed within the wider business case process.

The recommended method addresses the research questions posed for this study as follows.

1. *Set out a theoretical framework on how interdependent schemes and packages can be identified and how interdependency benefits can be assessed.*

Identification of interdependent projects occurs on two levels: a quantitative and a qualitative level.

The quantitative framework for the identification of project interdependency is that of incremental BCRs calculated by transport modelling. Logic informs us that interdependency benefits can be identified by comparing different combinations of projects. To identify interdependency of A+B would therefore need a comparison of project benefits from the project combination with the standalone benefits of A and the standalone benefits of B. Where interdependency A+B is significant, then we can view Projects A and B as interdependent. We have shown how transport modelling can be used to identify those projects that have benefit interdependency, primarily through the selective phasing of scenario analysis. For projects on uncongested networks and where re-routeing is also not expected to be significant, a pairwise rule can be adopted instead. Here it is only necessary to model pairs of projects, even if there are many projects that could be interdependent. The number of applications to which the pairwise rule is likely to be applicable is considered to be small.

However, to undertake this quantitative analysis, there is also a prior requirement to identify projects *expected* to be interdependent, and this must be qualitative. There is no specific theoretical framework for identifying project interdependency prior to modelling. It was found that project interdependency was contextual, and it was shown that this context can change over time – for example, demand growth leading to congestion and re-routeing effects. Thus, there will be a reliance on expert judgement in the early stages of an assessment and on adaptive testing during the CBA, which implies the need for process, both to reduce the risk of behavioural bias and to provide efficient phasing of scenarios. The recommended method addresses the issues of bias and scale, plus will enable precedent examples to be accumulated of where project interdependency has occurred, and hence can be expected in future.

2. *Identify and develop techniques and methods to assess the benefits of interdependent transport interventions.*

The recommended method outline provides a consistent and transparent way to assess the benefits of interdependent transport projects, which has been derived from the strong theoretical base of CBA. An important conclusion is that for project-level appraisals there is no single measure of project benefits that can also encapsulate interdependency benefits. This is because interdependency benefits are conditional on future network configurations that are uncertain. The treatment of uncertainty therefore is integral to the method of assessing the interdependency benefits of transport projects. Important tests on project interdependency are the incremental and the decremental. The incremental test considers what a project adds to a set of other projects, whilst the decremental test considers what added value a project brings to a programme but does require certainty about full programme delivery.

3. *Determine how schemes that are interdependent can be grouped into programmes and what the criteria should be for grouping schemes into programmes.*

The research project reveals that many types of programmes exist and that these programmes are often formed for reasons other than benefit interdependency, such as ease of administration or coordination of construction/implementation. It is judged that it was not necessary to combine schemes or projects into a formal programme to complete a CBA. In fact, it would be premature to assign projects to programmes on the basis of benefit interdependency until such time as quantitative interdependency assessment (eg, transport modelling) was undertaken – a type of ‘chicken and the egg’ situation. Instead, a more pragmatic response is to model *expected* interdependent projects that sit within approved 10-year or 30-year plans, irrespective of whether each project sits within the same programme. The projects shown by modelling to be heavily interdependent can then be grouped as a formal programme, if appropriate, or remain as projects across existing programmes. Given the nature of programmes, it is also important to look outside the programme for the assessment of interdependency benefits. For example, in our case study, the MCR programme had interdependencies with cycle projects that sat outside the programme, though we found it had limited interdependencies with the road investment programme.

The transport modelling challenge increases exponentially as the number of interdependent projects increases. Grouping of projects for the CBA is therefore necessary, and our method encapsulates this. Two criteria are relevant during this grouping stage. Ideally, project groups should serve similar markets (eg, by mode or origin–destination), and secondly, they should have a similar likelihood of occurring. The latter is important due to the treatment and presentation of uncertainty.

4. *Determine how to treat uncertainty of uncommitted schemes.*

A key judgement of the researchers is that consistency and transparency around the treatment of uncommitted schemes or projects is important. In theory, probability analysis could be used to summarise the effect of uncommitted schemes by presenting an expected value of project benefits and a distribution of benefits. However, in practice, the probabilities are not known and may not even exist (ie, the event may be uncertain rather than risky). The method recommended here sits within the wider field of scenario analysis, but given the ad hoc manner that scenarios can be created and reported, it is judged that decision-makers would be better served by scenario outputs that were quickly recognised and understood. In this case, the scenarios to present are specific multiple BCRs that include near-term uncommitted schemes. The scenarios are linked to the transport planning framework and how advanced the planning is of the different transport projects. For example, projects that have passed early gateways in the business case would be viewed as more probable than projects that have not had any form of business case developed. Projects sitting in a 10-year transport plan might be viewed as more likely than ones sitting in a post-10-year plan, or a post-20-year plan. Of course, this still leaves wider uncertainties to be considered within a business case. Uncommitted schemes beyond, say, 10 years could fit into that category.

5. *Outline how benefits of schemes should be correctly attributed to ensure that there is no double counting.*

At a project level, there is no one measure of benefit that will apply in all reporting situations when project interdependency exists, and again, context matters. It is recommended that the benefit of a programme (or groups of projects) is the primary means of reporting the combined benefits and that incremental benefit BCRs are used to test whether a project is adding value within a programme (or group of projects). Where a programme clearly includes all projects that are interdependent *and* where all projects are certain to be completed, then the decremental BCR provides the appropriate test of the marginal value-add of a project. Where, more likely, the set of interdependent projects is not so clearly defined or known, then a series of incremental BCRs will provide practical measures of the marginal value-add, albeit these measures are subject to what can at times be considerable forecast error. The risk of double counting can be reduced by always including a programme-level (or grouped project level) summary of benefits, even when reporting individual projects. A related issue to also be aware of, and guard against, is where gaming of the funding system is possible – for example, sinking a high-cost, low-value project and then claiming its interdependency benefits on the next (proposed) project, should interdependency exist and the initial standalone benefit be low.

6. *Outline how the developed methodology be included in the Waka Kotahi MBCM.*

The recommend method can be inserted into the MBCM by expanding the scenario analysis section to require multiple BCRs when material project interdependency exists. It is important that a qualitative description of the likelihood of the different scenarios is presented alongside the different BCRs. A number of different graphical methods for presenting these BCRs have been provided.

7.2 Further research

As to be expected with a topic such as ‘interdependency’, there are many facets to further research that could improve the understanding and account of interdependency.

1. First, should the recommendations of this report be accepted, then there is likely to be detail around how, when and where to apply these methods.

2. There is further investigation recommended as to how to better build project interdependency into the optioneering process. Tools such as multi-criteria analysis are not well suited to uncertainty, but quantitative tools such as transport modelling can be very costly, so alternatives are required.
3. Sketch modelling was found to be useful in this research report. A survey of sketch models and their uses could raise analysts' awareness of the usefulness of this approach.
4. Research into the probabilities surrounding the completion of a project given its stage within the planning process, including uncommitted projects beyond the 10-year planning horizon, would help decision-making when large projected interdependency is expected beyond the near-term. The availability of probabilities would allow the testing of the usefulness of an expected value approach in line with economic theory.
5. It is recommended here that a range of BCRs is taken through to the prioritisation for funding but that does not resolve how decision-makers should weigh up expectations against uncertainty – this remains a topic worthy of further research.
6. Institutional reporting rules around scenarios for other forms of uncertainty could be established that are similar to the multiple BCRs recommended here.
7. The research touched upon the issue of optimising a series of projects, possibly within a programme but not necessarily, and concluded that there were too many factors unrelated to monetised benefits that were required to inform an optimisation exercise – this also is a matter worthy of further research.

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Appendix A: Projects and programmes

The theme that ties this appendix together is 'the programme'. Programmes often involve interdependent projects. Programmes already have established methods to group projects. The method used to analyse interdependent projects within a programme can also be generalised to other groups of interdependent projects. Hence, programmes are of interest to this research. It also provides an opportunity to define a few terms.

Projects have a long history (Carayannis et al., 2005), where a 'project' is taken to mean that implementation is broken down into a discrete set of tasks, responsibilities and schedules to deliver a specified output. Projects proved so successful that they became a major supplement to, or in some cases a replacement for, the traditional divisional line-management processes, including for IT changes, software development, new product development, performance improvement, research, strategy deployment and construction (Maylor et al., 2006). The extensive use of projects has brought with it the need to coordinate and balance projects. It is to this end that programme management has evolved (Pellegrinelli, 2011).

However, the lines between projects and programmes are blurry. Projects can be programmes (eg, mega-projects), and programmes can be projects – the terms do have definitions, but those definitions differ and practitioners apply terms imprecisely (Berechman & Paaswell, 2001; McGrath & Whitty, 2019). Just as projects are now many things, programmes, it turns out, have evolved to fit different purposes, requiring different characteristics (Maylor et al., 2006). The feature of interest to this study is the interdependency of projects that often comes within a programme. Interdependency, in turn, creates challenges when it comes to the estimation and attribution of expected programme and project benefits, which is the core topic of this study.

These issues are taken up below, starting with some definitions. Material has been drawn from various papers, as referenced below, plus more generally from two industry standards – *A Guide to the Project Management Body of Knowledge* (PMBOK) (Project Management Institute, 2018) and *The Standard for Program Management* (Project Management Institute, 2017) – plus a programme management text book by Thiry and Dalcher (2015) and a programme management text with application to business by Martinelli (2014).

A.1 Project terminology

The following notes are not necessarily complete definitions of each term but are those commonly understood within the project community,[23] albeit not always used consistently.

An **activity** has been explicitly defined in the Land Transport Management Act 2003 to mean 'a land transport output or capital project'. This is similar to the PMBOK's definition: 'A distinct, scheduled portion of work performed during the course of a project' (Project Management Institute, 2018, p. 520).

The PMBOK definition of **project** is 'a temporary endeavour undertaken to create a unique product, service, or result', and a **subproject** is 'a smaller portion of the overall project created when a project is subdivided into more manageable components or pieces' (p. 535).

A **scheme** is defined to be 'a total plan of physical treatments and other measures for a street, group of streets, or area' (Austroads, 2015, p. 136). The term appears to be used interchangeably around the world with 'project'. This is the case also in New Zealand, but it is also used to refer to sub-projects that, for this

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[23] A larger set of definitions is given at http://www.maxwideman.com/pmglossary/index.htm

research project, are sufficiently important to require separate transport modelling. The term 'project' is used in this report to apply to both schemes and projects.

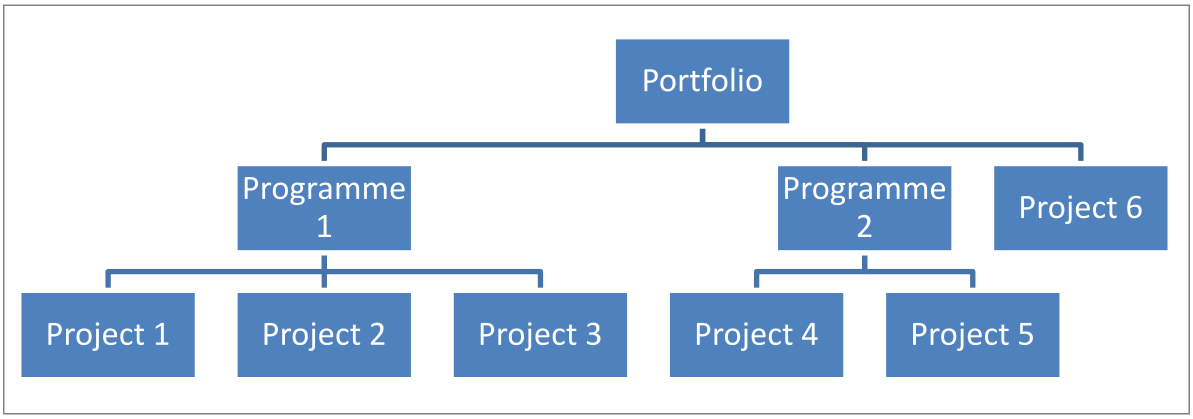
An important component of activities, projects and schemes is that they produce an **output**, which the PMBOK defines as 'a product, result, or service generated by a process. May be an input to a successor process' (Project Management Institute, 2018, p. 532).

There are various ways that projects may be grouped. A generic term is a **programme**, which the PMBOK defines as 'a group of related projects, subprograms, and program activities managed in a coordinated way to obtain benefits not available from managing them individually' (p. 534).

Specific terms are also applied to various groupings of activities. The term 'package' is used in two ways. There are **work packages**, defined by the PMBOK as 'the work defined at the lowest level of the work breakdown structure for which cost and duration can be estimated and managed' (p. 544). Waka Kotahi (2020, p. 3) also uses the term **package** to differentiate programmes (referred to as 'a defined group of land transport activities') where the nature of the project relationship is one of interdependence, preferring to refer to groupings of interdependent projects as *packages* and otherwise groupings of interrelated but independent projects as *programmes*. This is not a distinction that is applied internationally and is not applied in this research report.

Another grouping is a **portfolio**. A portfolio is a common term used in finance to mean the group of shares and other assets held by an investor. Its importance tracks back to Markowitz's theory of portfolio optimisation where the mix of assets held is chosen to maximise expected return given the investor's specified risk tolerance. The investor is allocating his/her resources across a set of companies, say, being one common financial asset, over which they typically have no operational control. The portfolio definition used in the PMBOK – 'Projects, programs, other portfolios, and operations managed as a group to achieve strategic objectives' (Project Management Institute, 2018, p. 533) – sits neatly with this understanding in the finance industry. The PMBOK considers the hierarchy to be that organisations allocate their resources across portfolios, which can be programmes consisting of projects or of projects themselves (see Figure A.1), whereas team leaders apply resources within programmes and projects *plus* control the operations.[24]

Figure A.1 Hierarchy of portfolios, programmes and projects to be used in this report



One application of programmes is to provide focus on an **outcome** as distinct from an **output**, with the latter tending to be tangible while outcomes relate more closely with performance – for example, a bridge may be a project output while the reduced travel time between the relevant origin and destination is the outcome

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[24] See also Thiry and Dalcher (2015, p. 32) for expanded comparison of project, programme and portfolio.

delivered by the project. As further distinction, it is the value being placed by people on an outcome that is of pertinence to a CBA.

A feature common to all programmes is **interrelatedness**, defined within the *Oxford English Dictionary* to be 'closely connected and affecting each other'. As Martinelli (2014, p. 5) puts it, we are interested in projects where 'they are not just related, but rather highly interrelated'. Some dictionaries refer to interrelated as being reciprocal – this is a little academic for this research project as it is the interdependency between projects that is the key feature for a CBA.

A.2 Programmes of projects

The topic of this study is sometimes referred to as programmatic appraisal. Interdependent projects often sit within programmes, so a CBA of a programme is typically the appraisal of interdependent projects, although not all dependency need be internal. In a rather circular manner, it is also of interest to establish how the nature of the interdependency between projects can inform the creation of a programme.

Programmes are widely applied today within many companies and across many sectors. Early examples include the Manhattan Project in the 1940s that was used to create the atomic bomb, termed a project but in fact consisting of several large and small-scale projects, and, more recently, Intel used a programme approach to be the first to develop multiple capabilities on a single integrated circuit (Martinelli, 2014).

This widespread use partly explains why there is so much variation between programmes, albeit the one common feature is collaboration. Various authors have offered ways to categorise programmes.

Pellegrinelli (2011) refers to three types of programmes:[25]

- First, there are programmes for managing a portfolio of projects. Here the emphasis is on allocating a budget across a group of projects, where the aim is typically to achieve a balance of projects that align with a strategic objective. There is little control exercised over individual projects (Van Buuren et al., 2010). The fine-tuning comes in the selection of projects to undertake.
- Second, there are programmes that aim to share costs associated with a group of projects. Cost management can include financial, legal and administrative services but also technical services. The key focus is on coordination and cost savings across projects (Pellegrinelli, 2011).
- Third, there are programmes where the focus is on the overall programme outcome. There are likely interdependencies between projects and possibly coordination required amongst stakeholders and project teams, and there may be adaptation of projects and/or the programme over time to maintain alignment with the desired programme outcome.

Thiry and Dalcher (2015) refer to Pellegrinelli's first two groupings as being in fact ongoing operations, quoting the example of large government programmes. Note, a transport safety programme is likely to fall within this category.

Another perspective is given by Martinelli (2014) for programmes that exist within an organisation, namely that there are four distinct stages:

1. an administration-focus, where programme management is largely about administration, data-gathering and activity-monitoring
2. a facilitation-focus, where projects are more linked organically rather than strategically and only a low level of cross-project communication and collaboration is required

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[25] Maylor and Turkulainen (2019) offer a similar typology of either a portfolio, chain or network of projects.

3. an integration-focus, where the primary programme management roles are integration and synchronisation of work flows, outcomes and deliverables across multiple projects
4. a business-focus, where programmes are tightly linked to strategies and the programme manager is both empowered and accountable for realising business goals.

A similar contrast is offered by Busscher (2014) for programmes that span organisations. At one extreme is the traditional approach used within transport circles and recommended by guides such as the PMBOK. These approaches essentially consider a programme as a scaled-up project and apply a similar linear approach to creating an output. At the other extreme are programmes that sit closer to strategic management whereby the emphasis is on adaptation of projects to ensure re-alignment with the programme goals whenever the external context and the internal feedback require. Thiry and Dalcher (2015) refer to the nexus as predictive planning contrasting with adaptive planning.

Before looking closer at programmes at the strategic end of the spectrum, a measure possibly of how far programmes have evolved is reported by Lycett et al. (2004), who list 15 ways that programmes were being shaped to improve goals but all but one of these ways were about the delivery of projects.

Put another way, many existing programmes are likely to have little in the way of benefit interdependency, let alone a role for adaptation of interventions.

Turning to the strategic-type programmes, Martinelli (2014) lists the characteristics of such programmes within a large organisation. Strategic programmes:

- exist to realise particular benefits, namely those aligned to the business goals
- provide coordinated management over a cross-discipline and cross-functional set of project teams
- coordinate projects, which extends beyond schedule coordination to include also the compromises that may be necessary to ensure the projects, individually and combined, remain aligned to the desired result
- are for a finite period of time, a view that is considered contentious, but is justified by the requirement of a result and by questioning what differs programmes from normal business operations
- establish ownership and accountability for the realisation of the desired programme results from the set of underlying projects
- are strategic in nature, being a mechanism that links execution to strategy
- align functional goals, which risk being aligned to interests of a project team, to the strategic goals
- foster cross-project and cross-disciplined integration, in effect working across the typical traditional hierarchical line management structures
- enable distributed collaboration, not typically a large feature of infrastructure projects but a key strength when working on a global IT or R&D programme.

Martinelli (2014) also suggests that the interdependency of interest is if one project were to fail, or cannot be bypassed, then the programme fails. This may be the case in product development, the core topic of his book, but this does not generalise to all infrastructure programmes. The following example will illustrate this point.

Busscher (2014) reports similar features as above in inter-agency programmes and discusses the Netherlands National Collaboration Programme on Air Quality. The interdependency here is typically the conflict between air quality and traffic. It is not so much that higher emissions preclude higher traffic levels but rather the dis-benefits and benefits of each, in a CBA approach, are required to be weighed against each other to optimise the transport solution. For completeness, it would be possible in this example for the emissions component of the programme to be pivotal if the objective was to increase transport benefits subject to an emissions constraint.

Interestingly, one of the reasons for the creation of the Netherlands air quality programme was to deal more constructively with the conflicts that had been experienced in previous attempts to collaborate across different organisations on air quality issues. The programme not only became a platform for consensus to be reached but it also shifted the focus of all parties to the larger objective and to the need for joint action, with the aim of adapting the programme as context and programme information evolved. Thiry and Dalcher (2015, p. 43) refer to this process as using 'a stakeholder value chain approach to create a flow of learning and performance that enables ongoing delivery of benefits and re-evaluation of requirements and expectation, based on the analysis of results'. This process enables programme management to combine adaptiveness with the predictive methods of project management.

A further point raised by Martinelli (2014) is his view that a programme has a fixed term. This leads to the issue of agile project management techniques that entail shorter iterations, regular reconsideration of methods and engagement with stakeholders (Pellegrinelli, 2011). Thiry and Dalcher (2015, p. 20) describe both programme management and agile management as evolutionary, pointing to the measure of their value as being their responsiveness.

In sum, there are a range of programmes. Many will be largely administrative and/or are mainly to do with achieving efficiencies during implementation. These programmes are less likely to include projects that have benefit interdependency (in the sense that the total outcome depends on the mix of projects). There are also programmes that are inherently highly adaptive. These will make the prediction of the outcome of any particular project challenging but, in theory at least, should improve certainty about the overall outcome. Within these two extremes there will be programmes where the mix of projects will significantly influence the outcome. These are the programmes – or portfolios or projects if so-called by others – that are of key interest to this study. They are more likely to be found in programmes towards the strategic goal end of the spectrum, but interdependency will probably only be revealed on a case-by-case basis.

New Zealand, as elsewhere, has a wide range of transport programmes. Examples involving Waka Kotahi are shown in Table A.1. There are programmes that are largely administrative, such as the Safe Network Programme and the low cost, low risk programmes. At the other extreme are programmes of highly interdependent projects such as the Let's Get Wellington Moving (LGWM) programme. Noticeably, the transport programmes are just that – programmes of transport projects only. New Zealand programmes involving projects across sectors are rare at this stage.

Table A.1 Examples of New Zealand transport programmes

Safe Network Programme[26]	Low cost, low risk programmes[27]	State highway corridor programmes	LGWM programme
A $1.3–$1.5 billion pool of Waka Kotahi funding over 3 years to be made available to local councils for safety projects, which aims to quickly apply standard safety treatments. Effectively creates a portfolio of largely unrelated projects that collectively increase the safety standard across the network.	Local councils submit a group of road or public transport improvement projects, each < $2 million, for Waka Kotahi funding. Effectively creates a portfolio of small projects for Waka Kotahi and provides a group of often unrelated projects for local councils that for administrative purposes are called a programme.	Regional councils coordinate a set of state highway and local road activity programmes every 3 years. These programmes are largely administrative, although they may lead to a programme within the corridor that contains interdependent activities (eg, the proposed Piarere-to-Taupō programme).	A programme that includes 6 key interdependent projects near the Wellington CBD: • State highway improvements, including new tunnels • New mass rapid transit network • Place-making in the CBD • Improved cycleways • Parking availability and pricing • Traffic demand management

This leads to the question, can the nature of the interdependency inform the formation of a programme?

In part this is already happening, although other factors have a large influence on what constitutes a programme, even when programmes are restricted to those towards the strategic end of the spectrum. Thiry and Dalcher (2015) describe programme formation in terms that are similar to the Better Business Case methodology applied in New Zealand (and the UK and Australia to name a few other countries). An outline proposal is created by bringing together stakeholders to agree on issues, expectations and objectives. The Better Business Case requires interdependencies to be identified at this strategic phase, including those influences that sit outside the project or programme. Then follows a long-listing and short-listing process. Thiry and Dalcher (2015) refer to a similar process as creating a blueprint that includes the functional specification.

There is also a thread of research that explores how to create an optimal set of projects within a portfolio given a budget or more general resource constraint. These approaches sit within four groups:

- those considering how to select a project from a set of mutually exclusive options
- those considering how to select a portfolio from a group of independent projects
- those that consider this same exercise when projects are interdependent
- those that consider each of these previous situations when uncertainty prevails.

This process of selection is further complicated depending on whether the selection of the candidate projects involves a programme that is already started or one yet to be started. In portfolio selection, these are known as dynamic and static problems respectively (Eilat et al., 2006).

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[26] https://nzta.govt.nz/safety/our-vision-of-a-safe-road-system/safe-network-programme/

[27] https://www.nzta.govt.nz/planning-and-investment/planning-and-investment-knowledge-base/201821-nltp/activity-classes-and-work-categories/local-road-regional-and-state-highway-improvements-activity-classes/wc-341-low-cost-low-risk-roading-improvements/

The formation of a portfolio from independent projects and from interdependent projects is often described as the knapsack problem in the operational research literature. This is discussed further in Appendix B. In principle, algorithms are applied to establish the combination of projects that provide the largest benefit for the given constraint.

Unfortunately, also, the selection process is complicated by uncertainty around the benefits, both of projects and combined projects, and ambiguity around the objective. Introducing probability and multi-criteria are the two ways that have been used to address these problems. Dutra et al. (2014) reviewed methods of project selection and suggest an integrated economic and probabilistic approach. Other methods using R&D project scoring on multiple criteria (eg, risk, efficiency and balance) have been suggested by Eilat et al. (2006) and Nowak (2013). Worobei and Flämig (2014) suggest a further sophistication when programmes unfold in an organic fashion.

In practice, benefit interdependencies do not appear to be the primary factor in drawing up transport programmes. Network management issues, delivery of investment and decision-making are more relevant matters. Hence the papers above are noted and may inform methods used to analyse project interdependencies but are not expected to be a major part of transport programme formation.

A.3 Programmes and cost–benefit analysis

What has been written about CBA of programmes? What challenges do programmes present for CBA?

We were unable to find research – other than discussed in the next appendix – that explicitly considered the challenges that programmes present for CBA. Instead, the following notes draw out issues arising from papers referred to above.

First, programmes are unlikely to capture all interdependencies within the programme. Programmes are formed for various reasons of which interdependency is only one, and even when programmes are established around a set of interdependent projects, there will still likely be interdependencies that exist outside the programme.

Second, programmes do not necessarily make benefit realisation more certain. A CBA is an ex-ante analysis that requires an unknown future to be predicted, which ex-post analysis reveals is challenging. In simple projects it may be reasonable to extrapolate forward traffic patterns to provide a BCR with some confidence. Even in simple cases (eg, an intersection improvement) there will be uncertainty about future land use and traffic demand over the next few decades – in this sense the benefit realised is dependent on future events unfolding in a predictable pattern. One such event might be the potential construction of a new route that feeds onto the intersection that would significantly change the outcome to expect. The response, as suggested by the literature above, is to combine the intersection upgrade and the new route (if likely to be near-term) as a programme to ensure the desired outcome (presumably less accidents and quicker travel) is attained. In doing so, the expectation is that the programme provides more certainty about future benefits. If further projects were also interdependent with the intersection upgrade, then this logic can be extended and thus the programme builds – both increasing the scale of the project and, as in the Busscher (2014) example, increasing the breadth of projects within the programme. To repeat the key point above, in theory, programme management has made the desired benefits more certain. Unfortunately, ex-post analysis shows that programmes – and large projects – do not necessarily deliver on the benefit assurance that formed part of the raison d’être (Svejvig & Schlichter, 2020). Two reasons have been shown for mega-projects not being delivered: because more complexity and scale means there is more opportunity for the implementation to go wrong, and because cost over-runs can lead to ad-hoc value engineering that reduce overall benefits. The same issues are likely for programmes. Unfortunately, whether undertaking a CBA of a complex programme or its constituent projects, the benefit prediction can still be challenging.

Third, a CBA is typically tractable because it is marginal analysis that compares several discrete options. This presents several problems for programme appraisal. More complex situations can mean it is difficult to define the DoMin scenario. In general, there is also the issue as to what activities are included in any option. This is an even greater problem in an adaptive programme where the options are evolving.

Fourth, and related to above, the bundling of activities to form the programme (and also within the constituent projects) that happens prior to the CBA is a political process. Typically this occurs as a result of engagement, sense-making and sorting by key stakeholders along with engineers (in the case of transport programmes), entailing a process of compromise. This was a key reason for creating the Busscher (2014) air quality programme. As mentioned above, the programme provided the platform for compromise. It is not known whether the preferred programme to emerge from this process was subjected to a CBA, but in principle the stakeholders have taken into account the different values that different people are placing on the components of the programme when compromising on their preferred bundle. From this perspective, a CBA of the components is redundant. However, it is also usual to check the value-add of key components, and refine as appropriate, but part of the value of a component – say a project or scheme within a programme – may be a hard-to-measure interdependency benefit and could simply be the reduced transaction cost benefit of re-negotiation. In other words, each project within a programme has arrived at the point of a CBA having come through a political process and judgements of network effects that, at least, should be acknowledged as being of potential value.

Fifth, a CBA is a comparison of benefits and costs. Interdependencies on the cost side are reasons for the formation of many programmes, which invariably leads to value-engineering processes within the programme. This in principle is a good thing, but it is important that benefit interdependency is understood and preferably estimated when cost cutting is sought.

Last, the issues involved in undertaking a CBA where interdependency – and uncertainty more generally – exist do require considerable time and modelling. If, say, the solution to the benefit identification problem for the sketch model of Chapter 3 is to undertake appraisal at a programme level, this may imply a wide study area approach, which will increase the data requirements, the necessary model calibration (if such an area-wide model even exists) and the challenges of model validation. The information costs associated with this work can be high and will not always be justified. Part of the aim of this study is to identify the appropriate level of analysis.

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Appendix B: Economic theory

The core topic of this research project is the CBA of interdependent projects. An understanding of how interdependency might occur and how this affects the CBA is required. This chapter serves that purpose. It draws heavily on the Arup and Institute for Transport Studies (2019) study (see also Bruce et al., 2019), with comments not necessarily referenced specifically and some inferences reached by the authors of this report from the results of the Arup and Institute for Transport Studies study.

CBA looks to identify investments where the expected benefits exceed the costs. This is made more complicated when the budget is constrained and when the investments are both interdependent and uncertain, as can occur with programmes. The following notes build up the logic of how these complications occur and how economic theory would suggest that decision-makers can deal with these complications, starting first with projects with certain (ie, risk-free) outcomes within a budget-constrained programme.

B.1 Decision-making with cost–benefit analysis

B.1.1 Independent projects

The overarching objective in CBA is to select projects that maximise the net social surplus to society. This leads to a decision criterion that maximises NPV (Boardman et al., 2011, pp. 13–14; de Rus, 2010, pp. 131–132). The NPV includes changes in welfare on all those impacted by the project: users, operators, government and third parties (eg, externalities such as noise and CO_2). The investment costs of the project would appear in the government component (if government is funding the project). If market failures in secondary markets are present, then the additional surpluses arising in these markets should also be taken into account. These are also known as wider economic benefits (WEBs).[28] In what follows, we abstract from the important practical problem that some relevant project impacts cannot be monetised.

For independent projects – that is, those for which benefits and costs are invariant no matter which projects enter the programme and all projects can potentially enter the programme – the preferred project is the one with the largest NPV (Boardman et al., 2011, pp. 13–14; de Rus, 2010, pp. 131–132). If there is no budget constraint then all projects with a positive NPV (ie, social surplus) at the relevant discount rate would enter an investment programme.

However, if a budget constraint exists, as is the case for public sector expenditure, then the BCR is used as a decision criterion. BCRs can be defined in different ways, but in this context, the rationed item forms the denominator – in this case the funding authority's expenditure.[29] The social surplus of the investment programme is maximised if independent projects are selected according to their BCR until the budget is exhausted.[30] Analytically, this 'problem' is known as the knapsack problem. 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 (see Figure B.1).

If investment funds are scarce but there is no defined budget, then the lowest BCR that would be acceptable for a project to enter an investment programme would be the BCR of the funding authority's marginal project

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[28] See Wangsness et al. (2017) for a review of WEBs within national transport appraisal guidelines.

[29] A number of authors (eg, Boardman et al., 2011, pp. 33–34; de Rus, 2010, pp. 131–132) argue that the BCR is open to manipulation of the cost items that appear in the denominator. Care therefore needs to be made to ensure that it is the 'rationed' cost that appears in the denominator.

[30] The marginal project should be small relative to the size of the overall budget for this to hold.

(across all areas it is active in: transport, education, defence, economy, etc). This cut-off BCR represents the opportunity cost of the investment.

This argument is the rationale for public sector agencies to use BCRs as a decision criterion for projects to enter an investment programme, including the Waka Kotahi (2020) MBCM and the UK Department for Transport (2017) Value for Money Framework. It is, however, contingent on the projects under consideration being independent. When they are mutually exclusive or are interdependent, alternative decision-making criteria are required.

Figure B.1 The linear knapsack problem

You have a 'knapsack' with capacity/budget W. You can choose from n items that have costs $\{c_1, \ldots, c_n\}$ and benefits $\{b_1, \ldots, b_n\}$ respectively. How do you 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' (ie, 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.

Source: Adapted from Arup and Institute for Transport Studies (2019, p. 19)

B.1.2 Mutually exclusive projects

Mutually exclusive projects would include different alternatives to solve a particular transport problem. This could include different route alignments between two towns, different junction designs, or different design standards. Once again, project selection should be based on maximisation of NPV (see Boardman et al., 2011, p. 33–34 for an example). If there is no budget constraint, then project selection is simply based on picking the project that gives the largest net benefits.

However, if there is a budget constraint and projects are mutually exclusive, an iterative procedure can be adopted utilising an incremental BCR (see Figure B.2) to identify the preferred project from a set of projects. This is because with mutually exclusive options ranking by BCR alone is not guaranteed to maximise social surplus. The incremental BCR is defined as the incremental benefits between two mutually exclusive alternatives over the incremental costs.

Minken (2016) presents a different algorithm that achieves the same outcome. This algorithm is a type of continuous knapsack problem. Arup and Institute for Transport Studies (2019, Appendix B) show the equivalence between the incremental BCR algorithm used in the Waka Kotahi MBCM (and also the UK Cost Benefit Analysis (COBA) manual; Department for Transport, 2002, Part 3) and that proposed by Minken.

Minken also shows the application of this algorithm in the context of an investment programme formulation (eg, a National Transport Plan). That is, the algorithm can be used to select the best-performing projects, some of which are mutually exclusive, to form an investment programme subject to an overall budget constraint. The decision criterion used is the marginal BCR of the programme (similar to the target incremental BCR used in the MBCM BCR incremental analysis). Minken does not identify an automated process to identify the full size of the investment programme, but instead advocates an ad hoc search where the marginal BCR of the programme (ie, target incremental BCR) is adjusted to ensure the investment programme fits within the budget.

The discussion in Boardman et al. (2011, p. 34) also effectively proposes a knapsack search type algorithm, though in this instance the search is trivial as there are only six projects to choose between. The approach can be easily automated where multiple projects exist that can form a programme. Gühnemann et al. (2012) use an automated incremental BCR approach in the appraisal of 405 alternatives to 264 projects (ie, includes mutually exclusive alternatives) to form an investment programme for the National Secondary Road network in Ireland.

Figure B.2 Using incremental BCRs to select between mutually exclusive projects

The following procedure should be used to calculate the incremental BCR of mutually exclusive options:

1. Rank the options in order of increasing cost.
2. Starting at the lowest-cost option, consider the second-to-lowest-cost option and calculate the difference between the present value of the benefits of the lowest-cost option and the second-to-lowest-cost option. These are the incremental benefits.
3. Next, calculate the difference between the present value of the costs of the lowest-cost option and the second-to-lowest-cost option. These are the incremental costs.
4. Calculate the incremental BCR by dividing the incremental benefits by the incremental costs.
5. If the incremental BCR is equal to or greater than the target incremental BCR, discard the lower-cost option and use the second-to-lowest-cost option as the comparison basis with the next higher-cost option.
6. If the incremental BCR is less than the target incremental BCR, discard the higher-cost option and use the lower-cost option as the basis for comparison with the next higher-cost option.
7. Repeat the procedure from steps (2) to (6) until all options have been analysed.
8. Finally, select the option with the highest cost that has an incremental BCR equal to or greater than the target incremental BCR.

Source: Adapted from Waka Kotahi MBCM (Waka Kotahi, 2020, section 6.3)

B.1.3 Interdependent projects

When projects are interdependent, interactions between the projects create additional benefits or costs that would not occur otherwise.[31] In Figure 2.2 these benefits are shown by the areas A+B, A+C, B+C and A+B+C.

Project selection with interdependencies should again be based on maximisation of the NPV. Boardman et al. (2011, p. 33–34) give an example of a selection between five projects of which two have interdependency benefits (C and D). Their treatment of the decision process is to classify the joint Project C and D as a separate project, so effectively the choice is between six projects (A, B, C, D, E and C & D). This effectively is a 'brute force' method, which turns each combination of projects into an additional project, and the search is then between these different 'projects' to identify the preferred one, potentially subject to a budget constraint.

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[31] From a mathematical programming perspective, mutually exclusive projects are a type of interdependency as when the two mutually exclusive projects are 'implemented' the net benefit is zero.

In terms of developing a programme of multiple projects subject to a budget constraint, this optimisation issue has been researched under the heading of the network design problem (NDP). The literature identifies more sophisticated knapsack routines that accommodate pairwise (the quadratic knapsack problem) and higher-order interdependencies and time dependency – see, for example, Carazo et al. (2010) and Kellerer et al. (2004). Efficient search algorithms are needed where the large numbers of alternatives need to be compared rapidly. Brute force approaches can be adopted – ie, ones where each combination of projects is identified as a project in its own right (as per Boardman et al.) – but will be more resource intensive and therefore take a longer time to identify the correct solution than the efficient algorithms. Even the efficient search algorithms require 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.

Network Design Problem for Transport

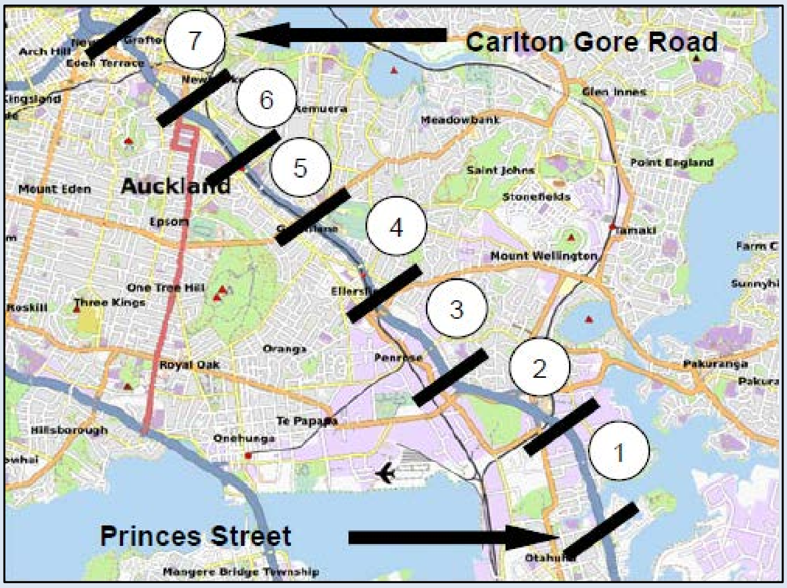
- How to optimise transport network investments for a given budget constraint (eg, minimum travel cost)?
- May involve a discrete number of projects (discrete NDP) or a continuous series of projects (continuous NDP)
- Typically involves many transport model runs
- Algorithms exist to reduce the number of runs, such as the knapsack algorithms
- But the number of model runs required can still get large quickly
- Complicating matters further, the algorithms can end at multiple solutions that may not necessarily be the optimal solution.

Source: Arup and Institute for Transport Studies (2019, pp. 21–25)

An example of an application of an algorithm addressing pairwise interdependencies (ie, solving the quadratic knapsack problem) in a transport appraisal is given by Raith et al. (2011) for a set of cycling initiatives in Auckland. Here, by taking account of adjacent pairwise interdependencies, one would choose to take forward different sections of the cycle route upgrade which otherwise, if treated as independent, fail the decision criterion. This is presented in more detail in Figure B.3. Whilst an improvement over a discrete analysis of each section, their analysis has limitations in that not all pairwise interdependency benefits are analysed (only those between adjacent projects) nor are the higher-order interdependency benefits analysed. Doing so would of course result in the need to model the demand and benefits of many combinations of cycle route sections – in this case 127 (= 2^7 – 1).

Figure B.3 Case study of project selection amongst interdependent cycle infrastructure

Raith et al. (2011) consider the upgrading of a cycle corridor route in Auckland. It has seven components, as illustrated in the figure below. They augment the transport modelling and appraisal of the corridor sections with a demand model and decision criteria that accounts for interdependencies.



They demonstrate that with a project budget of $3.5 million that treating each route section as discrete would lead to sections 3, 6 and 7 being constructed. However, taking into account pairwise interdependencies between adjacent schemes would result in the preferred programme comprising sections 5, 6 and 7. They use a linear quadratic knapsack algorithm and program it in the open-source solver COIN-OR CBC.

Source: Adapted from Raith et al. (2011, p. 11)

B.1.4 The curse of dimensionality

The modelling and appraisal of a large number of potential combinations is a real constraint on the appraisal of project interdependencies. This is because a significant amount of effort is involved in the modelling of each project variant and combination of projects, and the number of project combinations can very quickly become very large. For example, if there are two decision options for each project (build or not to build) then there are 2^n possible project combinations (including the Do Nothing), where n is the number of projects that could be considered as part of the investment programme. Thus, if there are 7 route sections (as in the Raith et al., 2011), there are 127 project combinations plus the Do Nothing. If two different infrastructure standards were also available for each section, then this would increase to 3^n possible project combinations (including the Do Nothing), which for the Raith et al. (2011) example would be 2,187 possible combinations. Adding in potential variations on phasing or timing of project combinations and different demand growth scenarios increases the potential combinations further. This rapid proliferation of project combinations is an example of the 'curse of dimensionality'. To what extent the dimension of the analysis challenge can be reduced by methods – for example, applying expert judgement – is to be explored in the next phase of this research project.

In comparison to the computational and resource effort of modelling and analysing the different project combinations, the effort involved in applying the economic decision criteria to identify the best-performing combination of projects is likely to be small, even if brute force methods are utilised. For example, Gühnemann et al. (2012) use Visual Basic for Applications (VBA) code in a spreadsheet to sort and rank 405 project alternatives (including mutually dependent options) in seconds of travel time savings per representative hour.

B.2 User benefits and congestion

There has been little work on how user benefits due to interdependencies may vary in either linear or non-linear ways. The recent Arup and Institute for Transport Studies (2019) work addressed this and sets out relationships, based on theory, about how the size and sign of interdependency benefits may be related to each other and project type. A summary is provided below (see also Bruce et al., 2019).

The framework for the following discussion is the standard transport supply–demand diagram, used to show the interaction of induced demand and congestion. The demand curves represent demand for trips between fixed origin and destination points with no presumption about the route (or potentially mode) taken. The supply curves are derived from a set of possible origin–destination routes to represent the minimum travel cost between the origin and destination. As per Mackie (1996), the elasticity of the demand curve does allow for change in activities at each destination and each origin, but only to the extent that changing transport costs give rise to a location change. Note that not all the induced demand depicted below is currently captured within the fixed land-use transport modelling analysis that is typical at present.

There is a line of research that questions whether lower travel costs can indeed occur due to the likelihood of induced demand. Mackie (above) discusses the particular conditions that would be required for induced demand to completely offset all benefits from an intervention intended to cut travel costs. Empirical research examining this phenomenon on the US interstate highways by Graham et al. (2014) shows the extent of induced demand can be high, whilst that by Duranton and Turner (2011) shows that induced demand has in places offset entirely the initially planned congestion relief when considered at an aggregate level, but more recently, Chang et al. (2020) show this effect to vary when viewed in a more disaggregated manner.

B.2.1 Linearly additive generalised cost functions and a pairwise heuristic

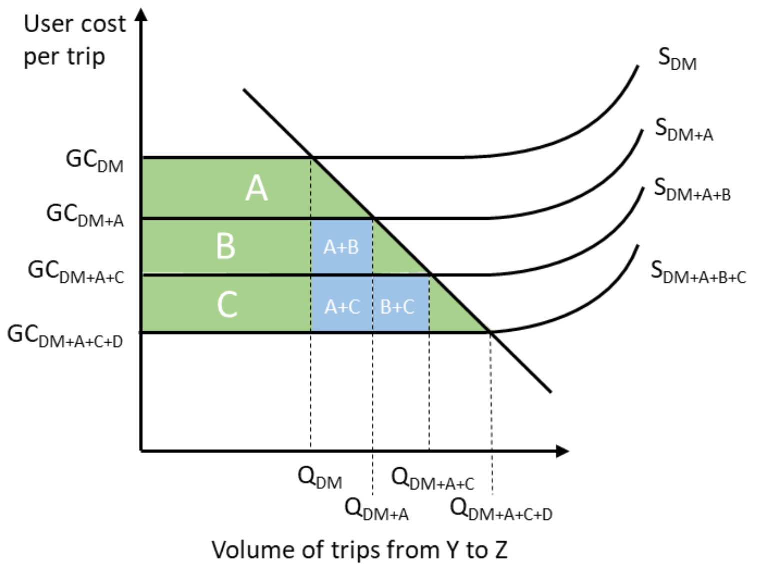
Consider, say, three discrete projects – A, B and C – where each is an upgrade (eg, lane widening) of different sections of a route. The existing route is of similar standard along its entire length. The route itself is uncongested but is slow. The proposed route upgrade via Projects A, B and C increases journey speed. The upgraded route is itself also uncongested. The consequence of these upgrades is that each route section induces traffic, which in itself will then derive benefits from the upgrades on the other sections. It is the induced traffic therefore that creates the interdependency benefit.

Other similar examples include additional safety features introduced in different projects along a route or adding a small number of extra bus stops or services (add too many though and network effects may dominate).

The discussion in Arup and Institute for Transport Studies (2019) shows that under these circumstances the generalised cost reductions produced by each of the three projects are linearly additive when the projects are all implemented. This arises due to a lack of congestion. If the demand curve, taken to be the demand for each origin–destination pair and not simply for the route itself, is also linear, then the total interdependency benefit of implementing all the projects is the sum of the pairwise benefits. This is illustrated in Figure B.4. This is a very useful finding as it implies that it is not necessary to model every combination of projects, therefore being ‘cursed by the dimensionality’, but instead it is only necessary to model each project independently and its interaction with each of the other projects in a ‘pair’. Arup and Institute for Transport Studies (2019) termed this the *pairwise rule*.

The assumptions of a linear demand curve and additivity of the project cost reductions (as a consequence of zero congestion) mean that the triple interdependency benefit arising from implementing all three projects (area A+B+C in Figure 2.2) is zero. Relaxing the linear demand curve assumption would, using a demand curve convex to the origin, result in a positive value for this triple interdependency benefit. Exactly how large it is would depend on the elasticity of the demand curve and the size of the generalised cost function. Whilst there is a literature on the accuracy of the rule of half in transport appraisal, which includes discussions on the error attributed to the linear demand curve (see, for example, Nellthorp & Hyman, 2001; Laird, 2010; de Jong et al., 2007) this does not address the issue as to how the interdependency benefits vary with demand curve elasticity and the size of the generalised cost reduction. This specific aspect represents an evidence gap that this study aims to explore in the subsequent stages of work.

Figure B.4 Consumer surplus of the programme comprising complementary Projects A, B and C where generalised cost reductions from each project are additive



Note: In this example the triple interdependency between Schemes A+B+C equals zero. This is a function of the shape of the cost curve and the additive properties of the cost reductions (arising from the lack of congestion before and after).

Source: Adapted from Arup and Institute for Transport Studies (2019, p. 53)

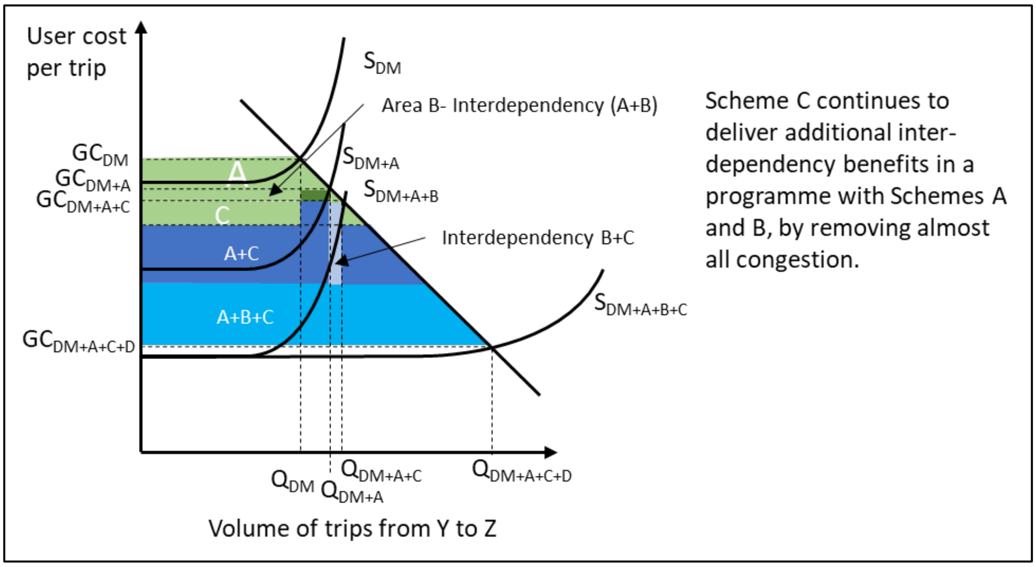
B.2.2 The case when generalised cost reductions between projects in a programme are not additive

Arup and Institute for Transport Studies (2019) identify four situations, repeated below, where the generalised cost functions for each intervention are not linearly additive. In these situations, there is no simple heuristic like the pairwise heuristic that they were able to identify for easily modelling interdependency benefits.

1. **Re-routeing or mode choice brought about by complementary projects.** Here the upgrade of a route corridor through a combination of projects may attract new traffic onto that corridor from a parallel corridor that individual projects would not. This arises because each project in isolation does not lower generalised cost on the corridor in question to attract any re-routeing traffic. It is only when all the projects are implemented together that the generalised cost on the upgraded corridor is low enough for the traffic to re-route and the interdependency benefit is then generated (eg, think travel time for the alternative route falling below the threshold created by the originally preferred route). In a general traffic situation this could be upgrading a road and bridge, with both required to make the route the fastest between an origin and destination pair. In mode choice terms this could be the equivalent of requiring a whole route upgrade of a public transport network to attract patronage from the car.

2. **Complementary projects in heavily congested conditions.** Let's consider a similar example to the uncongested case in section B.2.1, but instead there exists a bottleneck in section C. In this case Projects A and B generate traffic and make the congestion worse in section C of the corridor (eg, higher travel demand due to intercity route improvements may cause more congestion at the city entrance (section C), thus constraining the intercity demand growth implicit in the current demand curve). In combination therefore they deliver less benefits than if they had been implemented by themselves. They therefore compete. It is only when Project C is delivered that this congestion dissipates and significant benefits occur. We can therefore see that apparently complementary projects that give rise to congested conditions in the Do Something erode each other's benefits – that is, interdependency benefits are negative. This is illustrated in Figure B.5. The significant triple interdependency benefit (A+B+C) indicates that the pairwise rule identified in the previous section is likely to fail in heavily congested conditions. However, it is not clear at what level of congestion the pairwise rule will become unreliable.

Figure B.5 Consumer surplus of the programme comprising complementary Projects A, B and C with a congestion bottleneck at C



Scheme C continues to deliver additional inter-dependency benefits in a programme with Schemes A and B, by removing almost all congestion.

Source: Adapted from Arup and Institute for Transport Studies (2019, p. 58)

3. **Competing projects – no congestion.** This is most easily seen in the context of route choice between parallel routes. If Project A lies on Route A between two cities (Y and Z), whilst Project B lies on Route B between the same two cities, then Projects A and B will abstract demand from each other and impose negative interdependency benefits on each other. It is not immediately apparent from consumer surplus diagrams whether the pairwise rule that has been identified would hold in these circumstances. This therefore needs to be examined further in the next stage of this study.
4. **Competing projects – congestion.** Taking the preceding competing route example, if both routes are congested, then a project on Route A will deliver benefits to traffic on Route B. The non-linear nature of congestion costs, however, would mean that the congestion costs are unlikely to be additive, but again it is unclear whether there are circumstances under which the pairwise rule may hold.

Bringing this together, the following table (Table B.1) may be developed. Here we see the sign of the interdependency benefits depends on whether the project induces demand for other projects in the programme (complementary), abstracts demand (competing), is uncongested or is congested. Furthermore, if it is congested, it depends on whether the congestion is alleviated or it remains. There exist a number of evidence gaps in this area associated with the conditions under which the pairwise rule will remain a valid approximation.

Table B.1 Interdependency benefits and congestion

Interdependent project	Type of interdependency if network is:	
	Uncongested	Congested
Induces traffic on project being appraised	**Complementary**	**Complementary** if congestion is ameliorated. **Competing** if congestion is worsened.
Abstracts traffic from the project being appraised	**Competing**	**Complementary** if congestion remains in the Do Something and both routes using either project are viable. **Competing** if sufficient capacity on one route is created such that that route dominates route choice.

Source: Adapted from Arup and Institute for Transport Studies (2019, p. 62)

B.2.3 Wider economic benefits

In discussing wider economic benefits (WEBs) we need to distinguish between changes in economic outcomes in the broader economy (eg, changes in GDP, employment, etc) and welfare impacts that are additional to user benefits in a transport CBA.[32] They are of course interrelated, and both are of interest to decision-makers. The WEBs can be calculated within a Land Use Transport Interaction model or can be calculated in a more piecemeal fashion; the method employed may affect the workload required but will not change in principle how interdependency affects WEBs.

GDP impacts are closely related to business and freight user benefits. If user benefits are therefore expected to be affected by project interdependencies, then we would expect that GDP impacts that arise from improved transport efficiency to be likewise affected. Complementary projects that increase user benefits above those that would occur if the projects are implemented individually would therefore also be expected to generate additional GDP impacts.

WEBs due to *imperfect competition* would be likewise affected, as these are treated as proportional to business user benefits in transport appraisal (Waka Kotahi, 2020, section 3.12).

WEBs due to *employment* would also be expected to experience similar levels of additionality to interdependencies as the user benefits. The employment WEBs are not directly related to user benefits, as the imperfect competition WEBs are, but they are a function of the change in transport costs, in the same way that user benefits are (Waka Kotahi, 2020, section 3.11). Where transport costs decrease by more than would be expected due to project interdependencies, then employment WEBs would also increase by more than expected, and vice versa.

Transport investments may also expect to increase the effective density of *agglomeration* in a region. Transport appraisal practice has therefore broadened to include the assessment of agglomeration impacts on changes in productivity (Venables, 2007; Wangsness et al., 2017). This field remains an emerging area, and uncertainties exist in the estimation of the productivity-related agglomeration benefits of transport investments. This uncertainty is reflected in the MBCM by requiring the presentation of a National BCR with and without WEBs (Waka Kotahi, 2020, section 6). From an interdependency perspective, agglomeration benefits, as currently codified into appraisal guidance both in New Zealand and internationally, are interesting as they vary non-linearly with transport costs due to the decay formula used to calculate

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[32] See Laird and Venables (2017) for an overview.

economic density (Waka Kotahi, 2020, section 3.10). It is not therefore clear *a priori* whether agglomeration benefits will increase or decrease given a set of complementary or competing interdependent transport projects. We are not aware of any work exploring this issue and see that the development of an understanding as to when interdependent projects will lead to an increase in agglomeration benefits and when they will lead to a decrease as an area that could be explored further in this study.

Threshold effects and the unlocking effects of transport investments have been recognised at a conceptual level (eg, SACTRA, 1999). In this context, small transport investments can lead to large changes in economic outcomes. Threshold effects can also lead to the opposite, as large transport investments may lead to limited changes in economic outcomes if at an insufficient scale. Venables et al. (2014, Appendix 4.1) identifies the 'lumpy' or non-marginal nature of the private sector investments that follow a transport investment as the source of these threshold/unlocking effects, and in a theoretical framework identify the WEB associated with this. The context for Venables et al. was a dependent development. The existence of threshold effects has implications for interdependency benefits. Take Projects A and B. Each project may in itself be sufficient to overcome the threshold, permitting development to occur, thereby resulting in the economic impact of a joint implementation of Projects A and B being less than the sum of the economic impacts if each was implemented individually. Alternatively, neither Project A nor B could be sufficient to overcome the threshold required for the development to proceed. In this case it is only through a joint implementation that the development would occur. In this instance, the interdependencies between the two projects give rise to a greater cumulative economic impact than the summing of the individual project benefits would have suggested. A third alternative is that Project A may unlock land-use change in one area of a city and Project B may unlock land-use change in an alternative area but each project is only effective if the other is not present. The benefit resulting from the two projects existing will be less than each as a standalone project. Importantly, being aware of this interdependency is required to reasonably represent the benefit of each project (which may not be readily apparent without a city-wide view of projects being taken).

These threshold/unlocking arguments are examples of land-use change resulting from transport investment. The MBCM refers to this as *dynamic land use*. It is therefore easy to see that dynamic land-use impacts of interdependent transport investments may be greater or less than the sum of the dynamic impacts associated with the individual projects – context dependent. The area of dynamic land-use impacts and transport-related thresholds to development clearly sits on the knowledge frontier. Reflecting this, Waka Kotahi has recently published a report on working groups on the transformative impacts of transport investments with a particular interest in dynamic WEBs and land-use benefits and costs (Waka Kotahi, 2019). Here transformative is defined as where 'an investment is expected to result in significant changes in the places where people live and work'. Transformational in an economic context is taken to be a unidirectional, irreversible change.[33] In this context, 'significant land-use change' is being seen as unidirectional and irreversible. Clearly, for significant land-use change to occur, it may require a whole set of interdependent transport projects plus complementary policies in other sectors: investments in education and skills and supportive government policies towards housing development and land-use change more generally (eg, Banister & Berechman, 2001). This is clearly a substantial research field, and Waka Kotahi is taking work forward in this area in a parallel research study to this.[34]

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[33] Note, there is a distinct field in development economics concerned with *economic transformation*. In development economics, economic transformation is concerned with the shift from an economy characterised by low productivity (typically an agricultural economy) to one with much higher productivity. This involves structural change and typically industrialisation.

[34] For example, ART 19/21 – Capturing dynamic clustering and structural change impacts in cost–benefit analysis (https://www.gets.govt.nz/NZTAHNO/ExternalTenderDetails.htm?id=22533517)

B.2.4 Safety, health and environmental externalities

Safety; health impacts related to physical activity and noise; and greenhouse gas and air pollution environmental impacts are monetised within the CBA (Waka Kotahi, 2020). In line with the discussion on user benefits and WEBs, these benefits/costs will be expected to exhibit competing and complementary effects between interdependent projects.

Whether interdependent projects generate competing or complementary effects is likely to be context specific. The re-routeing example in section B.2.2 could generate complementary safety benefits if the projects re-route to a ‘safer road’, but if they are re-rerouted away from a longer motorway-type route, then the projects could erode the safety benefits at a programme level. Similarly, the impact of air pollutants will depend on the locality in which the pollutants are emitted, whilst greenhouse gas emissions are dependent on fuel consumed, which is, in the main, dependent on changes in total VKT. Health benefits are dependent on the increase in physical activity, and interdependent projects that reinforce such behaviour will clearly be complementary in this regard.

Simplistically we can therefore see that interdependent projects that between them reinforce a reduction in VKT and remove traffic from urban areas will likely be complementary in terms of safety, health, noise, air pollution and greenhouse gas emissions, whilst increasing VKT and increasing traffic in urban areas are likely to erode these benefit categories at a programme level.

There is no reason to expect these benefit/cost categories to all be complementary or all competing. A set of interdependent projects that reduce greenhouse gas emissions may lead to a reduction in physical activity, and/or may increase noise levels.

Non-linearities in how benefits ‘sum’ between different projects that are aimed at addressing environmental or safety issues can also create interdependencies. Looking at safety in particular, motorcycle training and protection are strongly complementary (Morrison, 2018).

The above discussion has focused on the marginal benefits of changes in safety, health or environmental impacts. However, where the environment is concerned, the absolute impact may be relevant. If populations of a flora or fauna species dip below certain levels, they may never recover. Environmental thresholds therefore become important, and can form part of the decision-making process (Polasky et al., 2011). In the context of transport infrastructure appraisal, this is most likely to be of most relevance to new infrastructure that impacts on waterways and fragile eco-systems. The larger debate on greenhouse gas emissions also has to be seen in this context. In this context it is the cumulative impacts of many investment decisions that are important – that is, projects can be interrelated, not because they are proximate to each other, but because they are each contributors towards the transgression of an environmental threshold. None of this is new. Nearly 30 years ago the SACTRA committee advised the UK Department for Transport to include ‘strategic’ level environmental appraisals much earlier in the decision-making process to capture this cumulative impact (SACTRA, 1992). By ‘strategic’ they meant environmental appraisals at a route corridor or programme level. In their evidence to SACTRA, Nash et al. (1990) enunciate this distinction very clearly:

> *We believe that the environmental effects of road construction are conveniently viewed under two broad headings. The first consists of those effects which may be viewed as strategic – i.e. the consequences of the decision to provide for a given volume of traffic, rather than to use pricing or other demand management measures to reduce the volume. Thus for instance the contribution of road transport to the production of greenhouse gases will* ***be sensitive to the overall national and worldwide transport strategy, but not to decisions about individual road projects*** *[emphasis added]. The second consists of the local effects of policies and projects, including those of providing for that volume of traffic by the construction of particular projects.* (Nash et al., 1990, p. 1)

B.3 Decision-making with risk and uncertainty

The future is never certain, but nonetheless decision-makers have to choose investments on the basis of future outcomes. The following section discusses how interdependency interacts with future events, with a distinction made between events that are risky and events that are uncertain. In practice, uncertainty is more pervasive. The practical implications are that even more transport model runs are required for a complete CBA and the reporting of only a few model results will be prone to spurious accuracy.

B.3.1 Interdependency benefits and uncertainty

From our perspective the treatment of risk and uncertainty is of interest because interdependency benefits are contingent on two or more projects being constructed. Typically, investment decisions are phased, with decisions on the latter stages of an investment programme being indirectly contingent on expectations of future performance of the transport network in terms of traffic levels and congestion and the economy in terms of land use change and budget availability. Political priorities may also change, which may affect rates of investment in public infrastructure and the types of public infrastructure, also affecting likelihoods of investment in the latter stages of a programme. The different stages of an investment programme may therefore be subject to uncertainty. Thus, interdependency benefits have a degree of uncertainty associated with them.

Economic theory typically distinguishes between risk and uncertainty. Risk is when probabilities of future states are known (eg, probability of flooding based on historical rainfall patterns). On the contrary, uncertainty is when we do not have a set of probabilities. Within the CBA framework, risk is most easily accommodated, whilst uncertainty often needs to be managed in the decision-making process. In this section we look at risk in the first instance and then at uncertainty.

B.3.2 Treatment of risk

When the probabilities of future states can be satisfactorily estimated, the *expected value* of the investment can be calculated, by summing the products of the probability of each potential state with expected value of the investment in each of the potential states. This is indicated in Figure B.6 for both a programme and for a project within that programme.

Figure B.6 Expected value of a programme and a project within it

If we consider a programme of n projects with two potential variants for each project (build or no build), then there are 2^n potential project combinations with the Do Nothing as one of those. These are the potential states s. In each of these states the programme will differ – that is, different combinations of schemes will be constructed. Each of these potential combinations has an associated probability of being constructed p_s. The future states s are mutually exclusively and the probabilities p_s sum to 1. The NPV of each potential project combination, NPV_s, has been estimated. The expected NPV of the programme $E[NPV^{Programme}]$ is then given by:

$$E[NPV^{Programme}] = \sum_{s=1}^{2^n} p_s . NPV_s$$

Here the Do-Nothing counterfactual does not contain any potential projects in it. It is the same across all potential Do-Something counterfactual states.

If we think about a particular project within the programme, Project A, then its expected NPV is given by:

$$E[NPV^A] = \sum_{s=1}^{2^n} p_s . NPV_s^A$$

Here the Do-Nothing counterfactual for estimating the NPV of Project A will vary with the potential state – as it will contain the other elements of the programme other than A. Additionally, some of the potential 2^n potential project combinations will not contain Project A. The NPV of Project A in these states is zero, and they can be dropped from the calculation for simplicity.

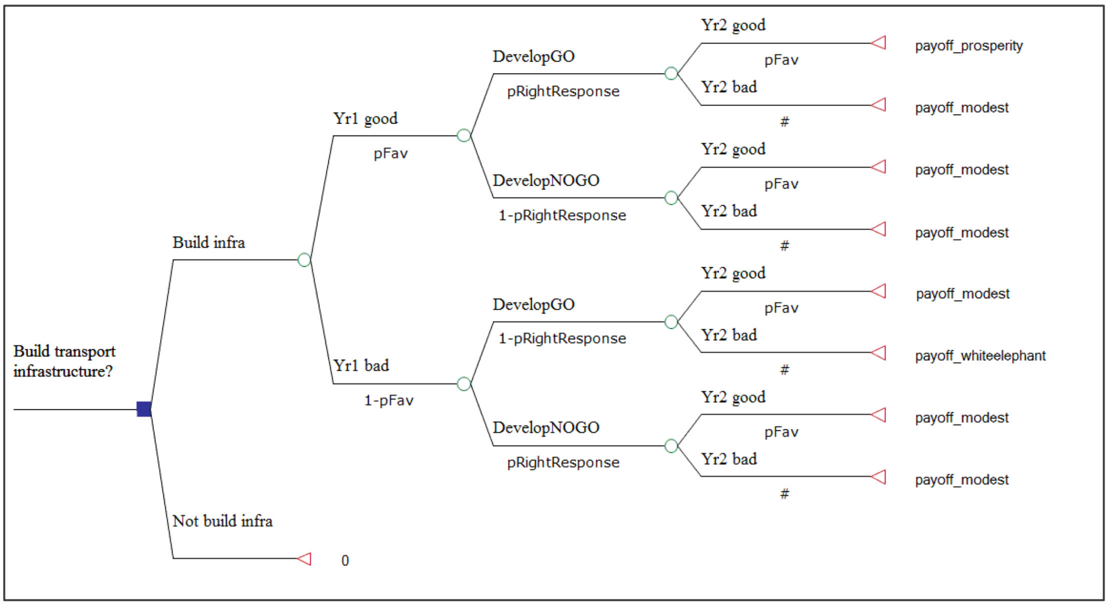
Both of the examples in Figure B.6 assume that all the projects in the programme are constructed simultaneously, or at least the phasing is fixed, and that no project is itself contingent on another project being constructed first. If, however, the phasing itself is variable, then the number of project combinations increases. To emphasise the significance of this, more project combinations require even more transport model runs than what may already be a high number, even for only several interdependent projects. For example, if each programme element could be constructed in time period $\{1, \dots, t\}$, then the number of project combinations increases. Increasing the number of project variants to 3 (partial or full implementation or two different route alignments) increases the number of project combinations further still. However, not all of the project combinations are possible – if Project A exists in time period 1, then it must exist in all subsequent time periods. Similarly, if partial implementation in time period 1 is selected, then full implementation can be selected in a later time period, but the opposite is not plausible (ie, moving from full to partial implementation in a later time period).

Thinking in terms of project phasing raises the possibility that certain projects act as programme enablers, an issue to which we will return later. A particular bottleneck in the transport system could be an example where an enabler project is required before other projects in the programme can be constructed. These enabler projects would need to progress early in the phasing of the programme.

When probabilities in one time period are conditional on what occurs in previous time periods, the basic expected value procedure in Figure B.6 cannot be so directly applied. A more flexible framework is required. This is often termed *decision analysis* (Boardman et al., 2011, p. 174), but is also known as *decision tree analysis* (for a review, see Byett et al., 2017). The approach can be summarised in two stages. The first is the construction of a decision tree, which is a diagrammatic form of representing sequences of decisions and realisations of contingencies. The second is a process of backwards induction. This process works backwards from final outcomes to the initial decision, calculating expected values of net benefits across contingencies. These decision trees can easily become complex, and as a consequence software exists for their application. Byett et al. (2017) give several transport examples, though none relate to interdependencies within a transport investment programme. The relatively simple decision tree example in

Figure B.7 relates to a joint development scenario (transport infrastructure development by the public sector and land-use development by the private sector), but illustrates the main points regarding how the benefits at each decision point are contingent on the decisions that have previously been made and the probabilities associated with different occurrences.

Figure B.7 Decision tree of a joint transport infrastructure and land-use development scenario



Source: Reprinted from Byett et al. (2017, p. 58)

Multi-time-period analysis also offers the *option to learn*. Delaying investment decisions until new information becomes available reduces the uncertainty, possibly eliminating it. The expected value of information gained by delaying an irreversible decision is called a *quasi-option value*. The learning can either be exogenous (ie, imparted to the decision-maker through a form of passive learning) or it can be endogenous (ie, a form of active learning). Whilst some analysts consider the quasi-option value to be a separate benefit category, it 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, p. 190). Quasi-option values are also known as ‘real option values’, and as such have parallels with real options analysis and financial options analysis.

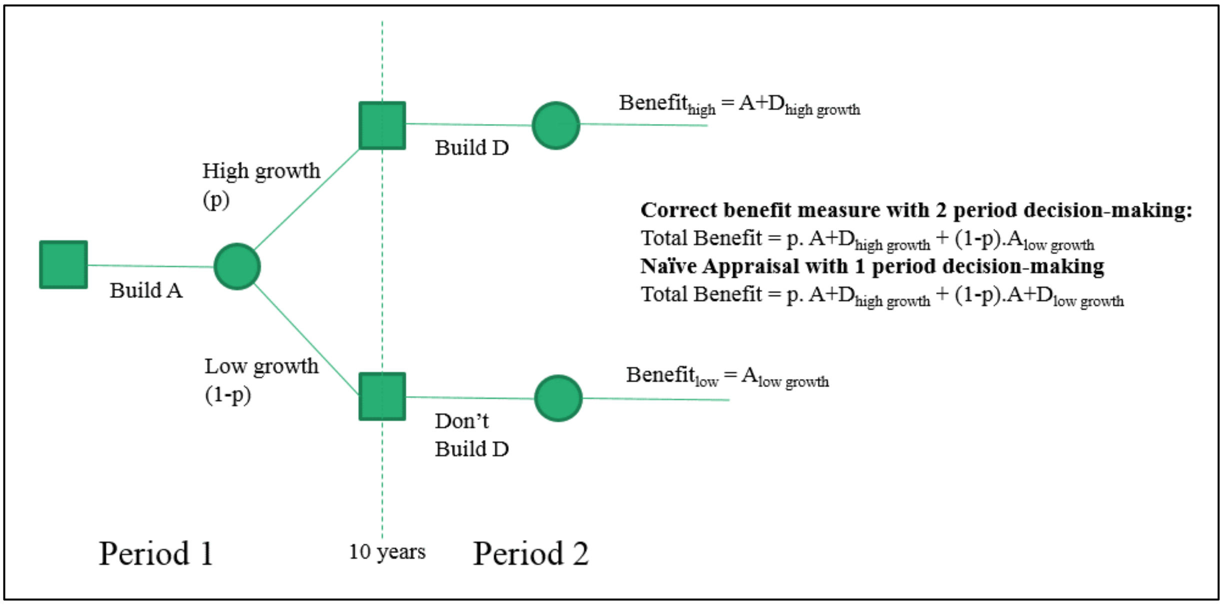
We can illustrate the quasi-option value with a simple programme consisting of Project A and Project D. Project D is only justified under high traffic growth that occurs with probability p. The total benefit of Project A is contingent on high traffic growth (and therefore high user benefits) and the delivery of Project D. A naïve appraisal based on 1-period decision-making would, however, combine the benefits of constructing Projects A and D under both low and high growth (with the respective probabilities). If Project D really only has value when high growth occurs, then this naïve appraisal would lead to an overestimation of the benefits of Project A by including the interdependencies with Project D when these may not be delivered. This is illustrated in Figure B.8.

In this case the learning process is *exogenous* (or passive). After a period of, say, 10 years after constructing Project A, we learn that traffic growth has either been high or low. Alternatively, we could think of a scenario where the learning process is *endogenous* (or active). For example, Project A is expected to generate traffic that will benefit Project D. However, at the planning stage it is uncertain how much traffic Project A may generate (as it may, for example, be contingent on a significant land-use response – as in Figure B.7). After a period of time, more information on the level of induced traffic will become known and a better informed decision can be made. Byett et al. (2017) give the Auckland Northern Busway as an example of a transport project that entailed an endogenous learning, although they do not calculate the quasi-option value.

With respect to the size and relevance of quasi-option values, the conventional wisdom is that they tend to be large for no ‘development in cases of exogenous learning and large for limited development in cases of endogenous learning’ (Boardman et al., 2011, p. 193).

There are limited applications of real options in the transport literature. In their review, Byett et al. (2017) identified 10 transport-related papers at the time. 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 Figure B.8, these are $\text{Benefit}_{\text{high}}$ and $\text{Benefit}_{\text{low}}$. These scenarios will require modelling, which was something Byett et al. were not able to undertake. There is also a need to quantify the uncertainty in the demand growth and relate that to the likelihood of a project being chosen for investment.

Figure B.8 Quasi-option value for a two-project programme



Source: Reprinted from Arup and Institute for Transport Studies (2019, p. 34)

Boardman et al. (2011, p. 194) advise that if there is insufficient knowledge to explicitly formulate the decision problem, then it is better to discuss the quasi-option value (also known as the real option value) as a source of bias, rather than add an arbitrary sum to the expected net benefits.

If the decision-maker is risk neutral, then the only relevant criterion to investment is the expected value of the project. This is in line with earlier discussion on decision criteria. However, if the decision-maker is risk averse or a risk seeker, then two additional matters become relevant: the attitude of the decision-maker to risk and an understanding of the potential distribution of benefits.

A risk-averse decision-maker prefers a certain lower income over a higher ‘expected’ risky income. This gives rise to the concept of a certainty equivalent. There is therefore a social cost to receiving a risky income, which is the difference between the risky income and the certainty equivalent. This social cost is known as the risk premium. Private sector decision-makers will therefore base their decisions around the certainty equivalents corresponding to the expected value of the risky income, which will be smaller than the expected values (de Rus, 2010, p. 157).[35]

For the public sector decisions, where the risk is pooled over the collection of persons affected by the policy, treating expected values and certainty equivalents as commensurate is generally reasonable.[36] This is based around the theorem by Arrow and Lind (1970) and a consideration as to when certainty equivalents are likely to diverge significantly from expected values in the context of public sector policy investments.

Notwithstanding this textbook position on the use of expected values as a decision criterion for public sector investments, decision-makers may also prefer less risky projects over more risky projects (or vice versa) *ceteris paribus*. Understanding the probability distribution of the expected value of the project is therefore important. Underlining the importance of this is the comment by the National Audit Office (2013) in the UK on the proposed High Speed Rail 2 (HS2) investment that the Department for Transport failed to communicate the uncertainty to the BCR by quoting point estimates and not ranges. To this end a number of approaches are utilised that are considered to be forms of sensitivity testing:

- *Sensitivity analysis.* With sensitivity analysis one uncertain variable is altered over its parameter range to understand how the value of the project will alter. The difficulty with this approach is when there are several uncertain parameters.
- *Scenario analysis.* Here different scenarios are constructed where values are assigned to several uncertain variables – for example, a scenario of high growth, or a scenario of autonomous vehicles. The strength of this approach is that best case and worst case scenarios can be constructed. The disadvantage with this is that it is difficult to understand the likelihood of the best and worst case scenarios occurring because unless all the variables are correlated, it is unlikely that all the uncertain variables will simultaneously be at their worst or best levels.
- *Monte Carlo sensitivity analysis.* This analysis uses probability distributions assigned to the uncertain variables by the analyst to construct many different estimates of the value of the project. Correlations between uncertain variables would also be taken into account (eg, low fuel price and higher traffic levels). This analysis will give a probability distribution for the value of the project and give a better understanding to the decision-maker of the project being of poor value or of high value. An example of Monte Carlo results is shown in Figure B.9. A key requirement of Monte Carlo analysis is an understanding of the probability distribution of the variable – it may be that the variable is risky, rather than uncertain, but its statistical properties may be unknown. As a consequence, it is most easily applied to risk that can be measured (eg, from historical data) and reasonably extrapolated. These would include, for example, probabilities of construction costs departing from their estimated values, and risks of flooding, avalanche or other naturally occurring events.

From our perspective the **source of the risk (or uncertainty in some cases)** is *not knowing* which projects in the programme go ahead. This is what would be tested with sensitivity analysis. As stated earlier, this is likely to be correlated with traffic growth and budget availability.

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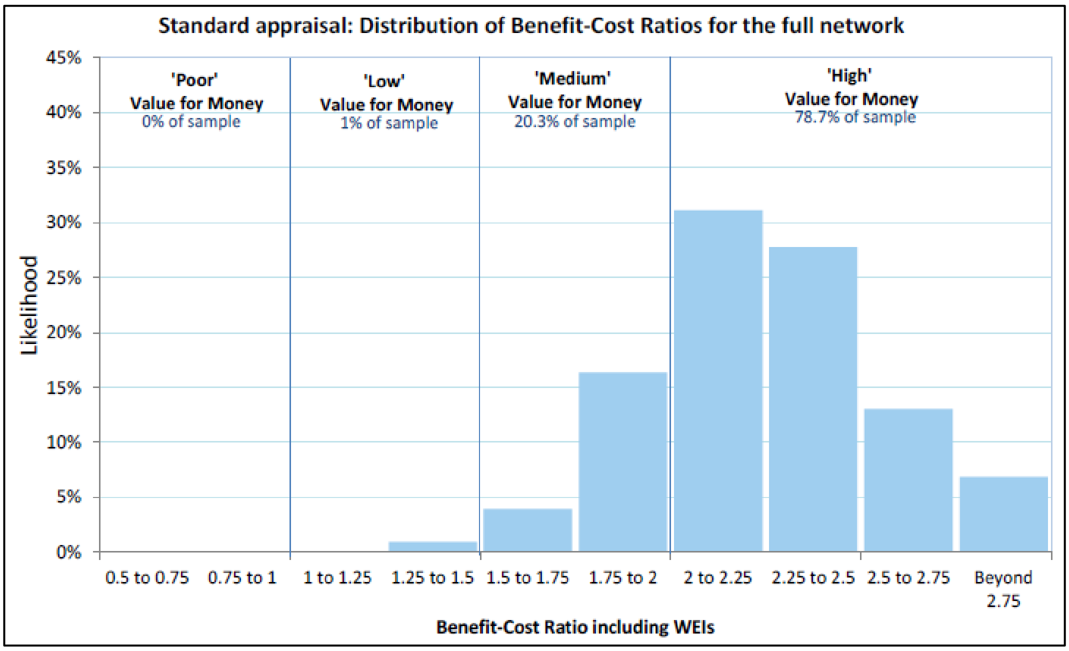
[35] An alternative to using certainty equivalents is to adjust the discount rate to reflect the riskiness of the investment. The downside of this is that benefits in later years of a project are discounted more heavily than those in the early years, when in fact it may be that the early years are more risky.

[36] For a more in-depth discussion on this issue, see Boardman et al. (2011 pp. 173, 217) and de Rus (2010, pp. 158–161). Boardman et al. give an example of a nuclear power plant as a project where a more specific treatment of risk may be needed, as this general position may not hold.

Figure B.9 Monte Carlo analysis for BCR in HS2



Source: Reprinted from HS2 Ltd (2013, p. 27)

B.3.3 Treatment of uncertainty

Uncertainty, in contrast to risk, is where probabilities cannot be associated with outcomes. As a policy area this is most pertinent to the treatment of the environment and climate change (see, for example, Polasky et al., 2011). It also arises when a series of interventions are required in a road network that are to be phased over years or possibly decades – say, a series of road sections leading to a potentially expanded bridge – but because of institutional funding arrangements it may be uncertain whether future planned phases will actually be delivered.[37]

In the face of uncertainty, as opposed to risk, there is little that can be added analytically to the CBA, which ultimately is underpinned by calculus. Instead, we argue that where uncertainty can be quantified, it is best dealt with by using the decision theory described above. Where uncertainty cannot be quantified, it is best to use a mixture of scenarios (eg, based on thresholds) as discussed above, adaptive management strategies that look closely at the decision-making process, or the use of sensitivity testing/scenarios to reveal when thresholds would be crossed. These approaches are not directly related to CBA, but would guide the governance and decision-making framework within which the appraisal and the CBA sit.

For example, with respect to adaptive management strategies, Byett et al. (2017) proposed the following decision-making framework:

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.

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[37] It is noted that this is a situation that can lead to gaming, to the extent that programme proposers leave the more contentious project until last, by which time there is little opportunity to re-jig the programme to avoid said project.

6. Probe robustness to uncertainties.
7. Crudely estimate indicative payoffs.
8. Establish threshold that favour one alternative over another.

As an example relevant to this research report, consider again the situation of Figure B.8, except now the probability of high growth (*p*) is unknown and hence the question lingers as to whether Project D will ever proceed, keeping in mind that the full benefits of Project A depend on the presence of Project D. Maybe Project A is a new bus lane and Project D is an increase in bus services (in New Zealand these projects would be undertaken by separate parties) and the uncertainty pertains to future demand for public transport. It is not possible in this contrived example to derive *p*, but it is often possible to deduce the minimum value that *p* must be for Project D to proceed. In some cases, knowing the probability threshold is likely low can be enough for decision-makers to judge it is worth the risk (or too high and not worth the risk). In other cases, it may be possible to re-shape Project A to increase the probability of, in this case, public transport growth or to generate extra benefit in the interim, which in turn increases the expected benefits of Project A. In our example, maybe the new lane is restricted to high-occupancy-vehicles in the near-term, nudging the propensity for single-person cars, while not reducing non-public-transport travel costs in the interim (due to the extra lane). The point is that a reasonable estimate of expected benefits may not be possible due to uncertainty, but framing the decision in terms of the key uncertainties and the threshold probabilities can (but not always) be sufficient to either make a decision or to focus attention on project options that reduce the sensitivity to key uncertainties. However, as with the analysis of more interdependent projects, the number of transport model run permutations can get high when more scenarios are added to explore the effect of uncertainties.

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Appendix C: Transport modelling and appraisal practice

The previous appendices have pointed to programmes as being a suitable place to consider projects that are interdependent and have discussed ways that project interdependency can occur. Potentially a CBA could consider the many permutations of projects, but identifying which projects to include in and the computational scale of such an analysis present difficult challenges. This appendix looks at how practitioners are dealing with these challenges at present.

C.1 The development of programmes and the understanding of interdependencies

Good practice in transport investment decision-making requires the development of transport investment projects that address identified problems or weaknesses in the transport system and that also meet broader economic and social goals. As a result of this, it has become conventional to think of a ‘cycle’ of decision-making that starts with objective setting (based on an assessment of need and goals) and proceeding through option development and ex-ante appraisal. This is then followed by implementation, evaluation that feeds back to lessons learnt. See, for example, Nellthorp (2017) for a broader discussion. The ex-ante appraisal typically takes the form of an option-sifting process to go from a long list of options to a short list, followed by a more detailed appraisal of the short list. CBA techniques usually form part of the latter detailed appraisal, but can sometimes be part of the option-sifting process.

As discussed in Appendix A, investment programmes are themselves quite varied in their nature. Some are just a collection of potentially unrelated projects that are being invested in by government and are more of a financial administrative grouping, others may be interrelated around a common theme (eg, safety, but otherwise unrelated), others may be physically related to each other (eg, a corridor investment programme or a city investment programme), and others still may form part of a mechanism for delivery. The decision-making cycle should take into account interdependencies in the formation of these differing programmes. In the early part of the decision-making – the option generation and option sifting, when there typically has been little quantitative analysis – interdependencies are likely to only be able to be incorporated into the decision-making in a qualitative way. At the more detailed appraisal stage, where a set of short-listed options are analysed, a more quantitative analysis is likely to be employed. This is what we have found from our research of the literature and speaking with practitioners.

In the UK, examples of problem identification and solution approaches can be seen for roads in England in Highways England’s (2015) route strategies, for rail throughout the UK in Network Rail’s Control Period investment plans (see, for example, Control Period 6 plans at Network Rail, n.d.) and in Scotland in the Scottish Transport Projects Review (Transport Scotland, 2009).

Our discussions with practitioners indicate that identifying interdependencies within a programme are most tractable when the programme components are defined. This is because for transport modelling purposes a relatively firm specification of the project has to be defined. Having said that, there still may exist substantial modelling challenges due to the sheer number of scenarios that will need to be analysed. Qualitative judgements will therefore likely be necessary in almost all circumstances: either due to the size of programmes or due to the uncertainty regarding the components of a programme. Judgements about whether projects are interdependent can be based on consideration of geographic location, size of the project (ie, expect geographic impact) and the market served (eg, long distance market, business market, commuter market). This could involve data analysis, analytical modelling, and expert knowledge. The limited literature on this topic also identifies the role of experts, albeit not in a transport context (see, for example, Roland et al., 2016, and de Almeida & Duarte, 2011).

One method used to both form and report judgements on interdependencies is the creation of a 2-way dependency matrix, which can be summarised in a matrix form if this aids presentation (see Table C.1, where the benefit of the row project is dependent on the column project – eg, a 'Tram extension to the south-west of a city' would be expected to reduce the benefit of the 'Bus rapid transit project in the south-west' due to providing competition for patrons).

Table C.1 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 bus rapid transit. Will also increase public transport market.	Will compete leading to lower patronage for bus rapid transit.	Required to provide termination point for bus rapid transit.
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 public transport 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 public transport market.	Potentially minor reduction in passengers using interchange.	

Source: Adapted from Arup and Institute for Transport Studies (2019, p. 29)

The NDP literature (see Appendix B) makes it clear that it is a complex task to optimise a large investment programme taking into account all the interdependencies, possibly too complex in practice to undertake with current levels of knowledge and computing power. Simplifications are therefore likely to be necessary. The above 2-way dependency table is one such simplification. Haas and Bekhor (2016) extended this idea by proposing a pairwise heuristic, based on identifying the interdependency benefit that arises from pairs of projects. Their heuristic then identifies the projects that would constitute the programme by firstly identifying the projects that deliver the highest benefit, and then adding in further projects based on least cost. They apply this approach to single (standalone), pairwise and triplet treatments of projects within the programme, and find that the total network travel time of their proposed programme is close to the total network travel time of the optimal programme. The more interdependencies that are considered, the better the approximation is. However, Arup and Institute for Transport Studies (2019) found that this heuristic fails where congestion is large. Interestingly, the finding that different programmes can have similar minimum cost times is consistent with anecdotal evidence from practitioners. The implication is that, provided alternative investment programmes are all reasonably sensible, they may have similar global BCRs. However, it would seem implausible that this would hold all the time, and tests of the programme components would be necessary – as to be discussed below in section C.1.

The difficulties in identifying and optimising a large investment programme have led practitioners to consider projects as independent but then test that when the projects are combined, the entire programme meets appropriate economic and social goals (see, for example, Gühnemann et al. (2012) for an application in Ireland, and Roberts (2016) for a regional transport investment programme). Each project is therefore justified in its own right, and overall, the whole programme is justified. The Strategic Transport Projects Review in Scotland (Transport Scotland, 2009), by considering corridor investments (where relevant), also simplified the programme identification process. In that national study, by looking at corridors, interdependencies between individual projects were captured, although interdependencies between corridors were not captured explicitly in the quantitative analysis.

At a national level, interviews reported by Arup and Institute for Transport Studies (2019) regarding practices in developing the five-year national transport plans in Norway and Sweden identify similar practices. That is, projects are treated as independent, aside from where obvious interdependencies exist (eg, along route corridors where they are treated in a combined manner), followed by testing that the whole national transport plan meets economic and social goals.

If the issue of handling interdependencies within a programme is not complex enough, a point also raised by practitioners is that there can be cross-sectoral interdependencies. Policies outside of the transport sector on de-carbonising and on the rollout of high-speed broadband to all households can significantly affect the prices and costs on the transport network as well as prices and costs for activities that may be substitutes for travel (eg, work from home). These ‘scenario’ interdependencies could just affect the overall size of the investment programme, or they could actually make the programme look very different in terms of the sorts of projects that it comprises.

C.1.1 The development of investment programmes in New Zealand

The development of programmes in New Zealand follows a similar mix of structured and unstructured approaches found elsewhere. Many groupings of projects and activities as programmes are largely for administrative purposes or for coordination of implementation. However, benefit interdependency is possible even within these types of programmes. For example, the benefits of a national safety programme can be increased by considering the interaction between treatments, such as the strongly complementary effect of combining motorcycle protection with motorcycle training (Morrison, 2018).

The structured approach to programme formation comes from the planning cycle applied for New Zealand state highways and local roads and the assessment required for funding from the National Land Transport Fund (which is 100% for state highway projects and typically around 50% for local road projects).

The planning phase involves regional land transport committees establishing a 10-year and 3-year programme of regional activities every three years. This entails aligning existing and newly proposed activities with (a) a national policy (the GPS), (b) existing state highway programmes, (c) existing local council transport programmes, and (d) local council wider plans, with each also re-set every three years. This collaborative and coordinated process naturally leads to interdependencies between future transport activities being considered regularly – sometimes formally by way of transport modelling but often by expert judgement. The transport activities from these regional plans that are to be funded by Waka Kotahi also enter the 3-year National Land Transport Programme, going through a prioritisation step that requires each activity to be scored (High/Medium/Low) on its criticality for, or interdependency with, other activities in a programme or as part of the network.[38] Sitting within this process are requirements – and funding mechanisms – to consider activities on a corridor basis and/or a safety basis and/or for bridges specifically. These combined processes will lead to programmes that may contain interdependent projects. For example, the 2018–2028 Auckland to Levin[39] Corridor Management Plan had led to several programme business cases, including a Piarere-to-Taupō programme business case[40] where interdependencies were to be explored via a stakeholder workshop process.[41]

The assessment phase follows a standard business case approach (Waka Kotahi, 2020b). Tools such as multi-criteria analysis and a recently added checklist approach termed the Early Assessment Sifting Tool are used in the screening of options. CBA forms a major component of the economic appraisal of the preferred option.

While there exist several opportunities in the planning and assessment phases for interdependency to be considered, the general low content in business cases and the tendency to run limited traffic models hints that the institutional process described above (and in Table C.2 below) is not fully addressing interdependency at present.

The less-structured approach to programme formation can emerge in various ways. For example, the Southwest Gateway Programme in Auckland was created to better coordinate the traffic modelling and implementation of two projects – one a road widening and the other a public transport project – which shared a common section of a road. The Christchurch Northern Corridor Programme, which coordinated local road changes to influence through-traffic movements, was a Waka Kotahi and Christchurch City Council response to downstream issues that became apparent after a Route of National Significance upgrade to the northern state highway approach to the city. The Let's Get Wellington Moving (LGWM) programme in part emerged from the structured process described above but differs in that difficulties with scale, interdependencies and collaboration led to the formation of a cross-agency programme that effectively sits above the GPS-led process (see Figure 3 in GPS 2021; New Zealand Government, 2020).

Table C.2 shows some steps that are traditionally taken to form a state highway corridor programme and how, in this case, the LGWM programme knits in with this process.

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[38] Other factors influencing priority are alignment with the current GPS and the BCR (or similar) for the activity (see Waka Kotahi, 2020a).

[39] Around 10 towns and 1 city lie within the 550 km between Auckland and Levin.

[40] https://www.nzta.govt.nz/assets/About-us/docs/oia-2017/SH1-Piarere-to-Taupo-programme-business-case.pdf

[41] https://www.nzta.govt.nz/planning-and-investment/learning-and-resources/network-operating-framework/

Table C.2 New Zealand state highway corridor plans, programmes and plans

Nationwide state highway planning and implementation process	**Government Policy Statement (GPS)**[42] The Government's priorities for investment in land transport over the next 10 years from the National Land Transport Fund (NLTF), administered by Waka Kotahi, are outlined in a GPS every 3 years.	**10-year corridor plan**[43] A 10-year plan for each of 30 state highway corridors is prepared each 3 years, aligned to the GPS. These plans, plus those of local councils, are brought together in a Transport Agency Investment Proposal (TAIP).[44]	**10-year corridor programme** A 10-year programme of activities is established for each corridor, comprising projects that are (a) committed, (b) proposed and (c) projects to be re-evaluated (for alignment with current GPS).	**3-year corridor programme** A 3-year programme of activities is established, to be considered for funding in the current 3-year window. State highway activities are considered along with local road activities by 16 regional transport committees to form 16 Regional Land Transport Programmes. Projects of interregional significance are explicitly identified within each regional programme.
Let's Get Wellington Moving (LGWM) programme fit with above process (LGWM involves state highways and local roads)	LGWM is mentioned in the GPS for 2021–2031, including $3.8 billion NLTF funding expectation over 20 years and 40% local council co-funding.	LGWM state highway improvements were considered as a corridor strategy in 2015 and then as 'proposed' as part of the wider Wellington programme in the 2018 TAIP.	LGWM expected to emerge as a programme consisting of six key projects in the 2021 10-year regional programme.	Some LGWM projects expected to emerge as being implemented within the 2021 3-year regional programme.

C.2 Tests for interdependency benefits

Having established a programme of projects, it is relatively straightforward in principle to undertake a programme CBA. However, there are many practical problems such as an agreed definition of the projects within the programme and a transport model that spans the affected road network (see end of this section). This sort of top-down analysis may be sufficient to decision-makers.

However, even within a programme the question is often asked as to whether all projects provide value-for-money, while in situations where interdependent projects span several (or no) programmes, then bottom-up analysis is required. Section C.3 explores bottom-up methods being used at present.

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[42] https://www.transport.govt.nz/multi-modal/keystrategiesandplans/gpsonlandtransportfunding/

[43] https://www.nzta.govt.nz/roads-and-rail/highways-information-portal/processes/corridor-management/corridor-management-plans/

[44] https://nzta.govt.nz/assets/planning-and-investment/docs/Draft-Transport-Agency-Investment-Proposal-201827.pdf

Our review work has not identified any appraisal guidance that formally sets out any forms of tests or analysis for interdependency benefits. However, drawing together practitioner experiences and drawing in particular from the review work undertaken by Arup and Institute for Transport Studies (2019), we can identify that key techniques and tests used by analysts for the identification of interdependency benefits include:

- incremental test/analysis
- decremental test/analysis
- pairwise analysis
- higher-order analysis.

An **incremental test/analysis** assumes that no other projects will be constructed after the project being appraised. So, if there are three projects (A, B and C) within a programme, and we are considering the CBA of Project A, and the phasing of the programme is Project B, A and then C, there would be two scenarios and model runs: DoMin+B and DoMin+B+A (where DoMin is the ‘Do Minimum’). In this type of analysis, a sequencing or ordering of the projects is required. A comparison of the two scenarios shows the ‘incremental benefits’ associated with the addition of Project A.

In a **decremental test/analysis**, the project being appraised is ‘taken away’ from the whole programme. So, with the same three projects there would be two scenarios and model runs: DoMin+A+B+C and DoMin+B+C. The ‘decremental benefit’ is the difference between the scenarios.

In **pairwise analysis**, the projects are appraised in pairs. So, with the same three projects there would be two pairs of projects with interactions with Project A – our project of interest. This gives two scenarios and model runs: DoMin+A+B and DoMin+A+C. Pairwise analysis can be used to get a sense of how each of the projects are dependent on each of the others.

In a **higher-order analysis**, the projects are appraised in either triples or larger combinations – for example, DoMin+A+C+D.

Examples in New Zealand are largely of an incremental and/or decremental nature. That is, a project or scheme or activity is often analysed using CBA to consider whether it adds sufficient extra benefits to justify the extra cost, the analysis often resulting from budget pressures within the programme or project. An example is the Auckland Manukau Eastern Transport Initiative, a busway project (which has the characteristics of a programme) that is part of a public transport network joining a populous south-eastern suburb to the Auckland CBD. Split into three phases to be implemented over approximately 10 years, the project was at one stage estimated to cost substantially more than initial estimates, leading to a process of value-engineering that involved the calculation of incremental BCRs for some components. Likewise, the Auckland City Rail Link project (strong similarities to a programme) included the construction of two new rail stations along new track and tunnels to complete a rail circuit in the inner suburbs. Decremental CBA was used to test the additive effect of each new station. On a smaller scale, a recent business case for a cycle and walking lane added to an 11 km state highway that connects (through rural, hilly country) the two major suburban areas of Wellington provided BCRs for lanes on specific segments of the highway and for the highway in total, showing a complementary benefit if extra lanes were constructed along the full route.

Outside New Zealand, as already indicated, there is no formal appraisal guidance that we have identified, but there are practitioners who are currently working in this area, or have previously worked in this area. They are currently applying two types of project-level appraisals:

1. A programme-level appraisal is compared against the sum of all the discrete or standalone project-level appraisals. The difference between the two is the total interdependency benefits of the entire programme

– however 'programme' is defined. Supplementary analysis on pairwise and triple-level interactions between projects then identify which projects are interrelated with each other.

2. Two incremental analyses are undertaken in addition to the discrete or standalone project-level appraisal. The first is against a counterfactual, termed a reference case, that includes a set of projects that are viewed as firmly committed but have not yet received final ministerial approval, whilst the second is against an alternative reference case containing a set of identified projects that have a degree of commitment behind them for which some early-stage business cases are available. These steps enable interdependency benefits to be calculated for each project, the first being the interdependency with projects that are certain to proceed and the second with projects that are very likely to proceed. Not calculated are any interdependency benefits with projects that are neither certain nor very likely.

Decremental analysis is also utilised in the tests in other countries. The strength of a decremental analysis indicates whether a project has any added value to a programme. The weakness in a decremental analysis is that the interdependency benefits identified from it are dependent upon all the projects in the programme being constructed. Decremental analysis has therefore been used to test whether each element of a programme was a net contributor to that programme in some transport modelling and appraisal applications (Arup & Institute for Transport Studies, 2019).

Practical experience also indicates that within a project there can be contrasting impacts of the interdependencies. Projects that complement early in the appraisal period may compete later in the time period (and vice versa), whilst it is possible for some project benefits to complement whilst others to compete. An example of the former was found by Arup and Institute for Transport Studies (2019) in their case study. For the latter, an example was cited to us of a programme-level investment where time savings and WEBs were complementary, whilst safety and reliability benefits were competitive. Arup and Institute for Transport Studies (2019) also identified that in congested networks it can be a complex process to identify the interdependency benefits, due to the presence of large network delays, complex routeing patterns and possible model convergence issues.

Practical experience also identifies several transport modelling and appraisal challenges. Firstly, it is only possible to assess programme interdependencies in a transport model that has sufficient geographic coverage. For large infrastructure projects with large geographic impacts, these may require very large regional- or national-level models. Such models in themselves have idiosyncrasies and characteristics that can hamper an investigation. Two relevant ones are that model noise in parts of the network may 'swamp' benefits in the areas of interest (the project being appraised and its interdependent projects). This was very relevant in the Arup and Institute for Transport Studies (2019) case study. The second is that such models will not have a full network representation and, as one of the practitioners we spoke to identified, this may lead to project-level benefits being omitted compared to an appraisal based around a project-specific transport model. Thus, a programme-level appraisal in such large models may underestimate the total benefits of the programme. In such a situation it may be necessary to combine the results of models of different scales to identify either the total benefits of a programme or the total benefits of a subset of the programme. Obviously, this then increases the analytical effort.

C.3 Treatment of uncertainty

Uncertainty or risk in the delivery of the interdependency benefits is one of the two defining issues surrounding the appraisal of interdependency. As previously mentioned, there are no specific national transport guidelines that we have been able to identify on the treatment of interdependencies between projects, therefore there is no specific treatment of the uncertainty surrounding interdependency benefits.

The New Zealand system for dealing with uncertainty has similarities with those overseas. With regard to uncertainty about future transport projects, the coordinated and collaborative process of forming 10-year and

3-year plans and programmes does increase certainty about future transport projects, but this process does not provide surety, as evidenced by the re-evaluation of state highway programmes[45] following policy changes introduced in the 2018 GPS. Creating longer-term funding commitments for Auckland (the Auckland Transport Alignment Project[46]) and Wellington (the LGWM programme) are efforts in recent years to raise expectations about major projects in Auckland and Wellington, but key components of these programmes still remain subject to confirmation – or not – from the business case process and are also subject to availability of funds when project implementation comes around. With regard to non-transport uncertainties, the MBCM (Chapter 7) recommends sensitivity and scenario testing of benefit and cost estimates. In practice, cost estimates are often subjected to a probabilistic treatment while the analysis of benefit uncertainty is mixed, at least to date, ranging from a scant ±20% calculation to a fuller consideration of key assumptions. The refined manual is expected to lead to a fuller analysis of benefit uncertainty. In all cases, a risk register is required and provided.

In England, uncertainty and risk in project-level benefits are addressed through the use of a risk register, sensitivity testing and scenario analysis. This is set out in *TAG Unit M4 Forecasting and Uncertainty* (Department for Transport, 2019). Arup and Institute for Transport Studies (2019) therefore proposed that this should be the framework in which project-level uncertainties should be analysed within. Two difficulties acknowledged within their work exist with such an implementation. Firstly, there remains the need to present the results of a large number of scenarios, and secondly, each of these scenarios has to be categorised by likelihood. The large number of scenarios increases the analytical burden but also makes it hard for the decision-maker to understand all the data. The categorisation of scenario likelihood is also problematic as TAG indicates that all projects without a full business case are classed as uncertain. Thus, all the interdependency benefits are classified as uncertain. In reality, projects are at different stages of development, with some at fairly advanced stages of design and with a high degree of commitment behind them, whilst others remain more conceptual without necessarily any stakeholder support. This has led to discussions and analytical work undertaking a reduced number of scenarios that include projects that are under active consideration but have not yet received approval (see section C.1 for these scenario definitions). How to convey this uncertainty to decision-makers still remains exploratory work.

In Scotland, the Strategic Transport Projects Review analysis has led to an identification of the projects that will form the basis of investment from 2012 to 2032. This gives a degree of commitment to different projects. Additionally, it has also led to the identification and commitment to route improvement strategies. The A9 Perth to Inverness corridor is an example. Here there is a commitment to upgrade the road to dual carriageway throughout its length. This reduces the uncertainty associated with project interdependencies within the route corridor to more of a timing-related issue. In countries where national transport plans are developed (eg, Norway and Sweden) the national transport plans also give a high degree of certainty, particularly over the early project years, which are often the most important in terms of project benefits (due to the effect of discounting).

C.4 Presenting interdependency benefits to decision-makers

There is no particular recommended manner in which interdependency benefits are presented to decision-makers as far as we have been able to ascertain.

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[45] https://www.nzta.govt.nz/planning-and-investment/national-land-transport-programme/project-re-evaluations/

[46] The Auckland Transport Alignment Project's (ATAP) founding report describes the ATAP as a project, package and programme all in the one sentence: 'The ATAP package is a transformative transport programme' (Auckland Transport, 2018, p. 4).

In the UK, there is recognition at the Department for Transport that the economic case project-level appraisals cannot contain interdependency benefits without double counting. The interdependency benefits and the added value the project contributes to a programme can be discussed and presented in the strategic case. This is not entirely satisfactory, and there is pressure from stakeholders to also include CBAs for alternative scenarios in the economic case. Such alternative scenarios could be programme-level comparisons, or incremental analysis based on interdependent firmly committed or partially committed projects.

Whilst it will also be the case that there will be project-level appraisals that suffer these difficulties in Scotland (eg, station openings), as the major investments come out of the Strategic Transport Projects Review, the Scottish Ministerial decisions on these are at a strategic (programme/route) level, which in the main internalises the interdependency benefits and their associated uncertainty. Similarly, for national transport plans, which include combinations of projects, the interdependency and associated uncertainties are also internalised into the decision-making.

The principal difficulty with the treatment of interdependency benefits and their presentation to decision-makers therefore concerns project-level appraisals, where decision-making is at a project-by-project level and projects may be interrelated and give rise to interdependency benefits. Here it is useful to consider the situations in which these are likely to be relevant to the decision. Arup and Institute for Transport Studies (2019) give the following useful summary.

First, consider a situation where a project has low value for money. Then:

- if the project is central to the programme (it is an enabler), then the project *and* the future of the programme are contingent on the interdependency benefits
- if the project is peripheral to the programme, then interdependency benefits are relevant to whether the project progresses.

Second, consider a situation where a project has high value for money. Then:

- Whether the project is central (an enabler) or peripheral to the programme is largely irrelevant to whether the project will progress. It may not therefore be necessary to assess interdependency benefits in more than a qualitative way. The exception would be where it competes with other projects to such an extent that its value for money is weakened.

A refinement is to consider for further project-level appraisal only those projects that are costly, there being little value-add likely from a costly appraisal on a low-cost project.

This implies, for project-level appraisals, that a quantitative assessment of interdependency benefits in the CBA is most relevant to decision-making when project value for money is weak and the project cost is high. It will be particularly relevant if the project is seen as an enabler. For projects with high value for money as a standalone, it is likely that a quantitative assessment of interdependency benefits in the CBA would only be necessary if a qualitative assessment of interdependencies identified strong competition with other projects in the programme. How this project-level appraisal information on interdependencies should be conveyed succinctly to decision-makers remains, however, work in progress.

The reporting of interdependencies in New Zealand business cases has been mixed but in the main minimal. One example of the reporting of interdependency is the 2015 Business Case for the Auckland City Rail Link, where several benefit and several construction interdependencies were presented and discussed, without quantification reported. More often, even less information is reported on the nature and effect of interdependency.

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Appendix D: Sketch network analysis

The results of a sketch model developed to test issues of project interdependency are presented here.

D.1 Sketch network description

A simple three-zone, eight-link network was devised. The network is shown in Figure D.1 and the critical links A, B, C, F and G are described in Table D.1. Links A, B and F are thought of as low-quality state highway links with free-flow speeds of 80 kph and a capacity of 1,600 vehicles/hr. Speed at capacity is 45 kph. Links C and G are thought of as urban links with free-flow speeds of 45 kph and capacities of 1,200 vehicles/hr. Speed at capacity is 5 kph. Links C and G easily become congested. Projects A and B upgrade the state highway Links A and B to Dual 2 Motorway standard (note, projects share the same letter as the link). Project H is a new motorway bypass of similar standard to Projects A and B. Projects C and G represent an upgrading of the urban links to dual carriageway urban links. These projects represent significant step changes in capacity, at probably a fairly extreme level, and are designed to help identify any patterns in interdependencies.

Figure D.1 Sketch network

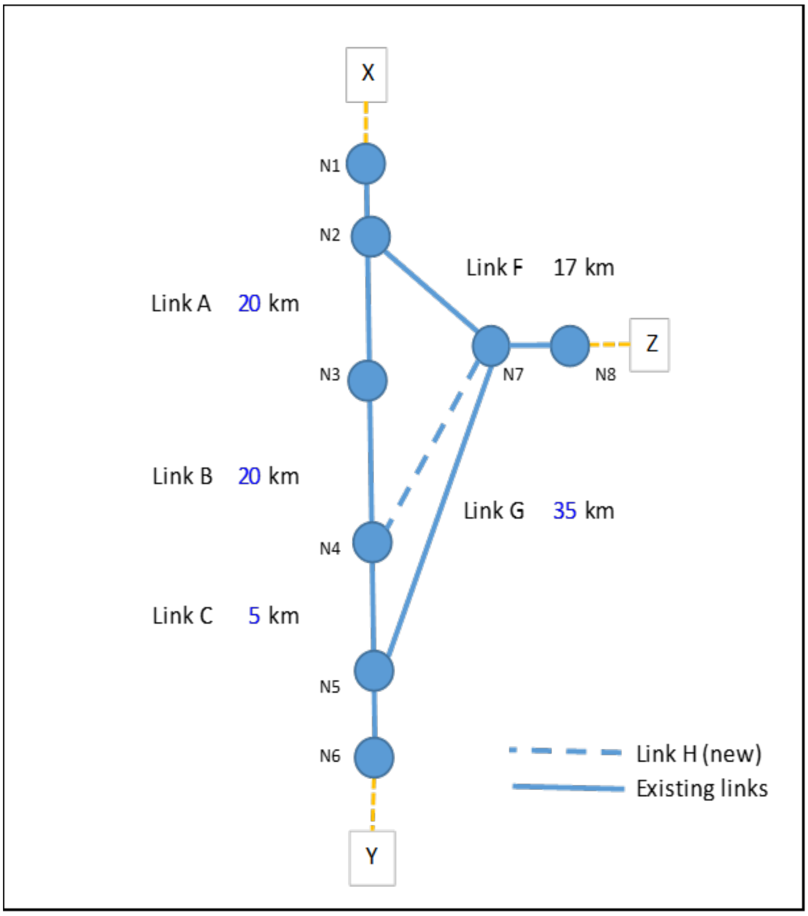

Table D.1 Sketch network description

	Do Nothing	Do Something
Link A (and Project A)	• 80 kph state highway (limited-access road) • capacity 1 • 600 • max = 80 • 1 lane (speed/flow curve 281)	• 100 kph 2-lane motorway segment • capacity 4 • 400 (speed/flow curve 112)
Link B (and Project B)	• 80 kph state highway (limited-access road) • capacity 1,600 • max = 80 • 1 lane (speed/flow curve 281)	• 100 kph 2-lane motorway segment • capacity 4 • 400 (speed/flow curve 112)
Link C (and Project C)	• Collector 1,200 capacity • 45 kph • 1 lane (speed/flow curve 641)	• 60 kph minor arterial • max = 60 • 2 lanes • capacity 3 • 400 (speed/flow curve 562)
Link F	• 80 kph state highway (limited-access road) • capacity 1,600 • max = 80 • 1 lane (speed/flow curve 281)	• No change
Link G (and Project G)	• Collector 1,200 capacity • 45 kph • 1 lane (speed/flow curve 641)	• 60 kph minor arterial • max = 60 • 2 lanes • capacity 3 • 400 (speed/flow curve 562)
Link H (and Project H)	• Doesn’t exist	• 60 kph minor arterial • max = 60 • 2 lanes • capacity 3 • 400 (speed/flow curve 562)

The sketch network modelling was undertaken in the SATURN traffic modelling suite. The speed/flow curves used were based off Christchurch Assignment and Simulation Traffic model speed/flow curves (Quality Transport Planning [QTP], & Sinclair Knight Merz [SKM], 2010) with adjustments to speeds at capacity to 15 kph aside from the urban Links C and G, which had speeds at capacity of 5 kph. A power of 10 was also used for Links C and G. The effect of lowering speeds at capacity is to increase congestion on the links.[47] The effect of raising the power variable on the urban Links C and G is twofold: at lower volumes of traffic it flattens the speed/flow curve out, but as the link approaches and exceeds capacity there is an exponential increase in cost as volume increases. This generates a bottleneck type effect. It is worth stressing this is indicative-type modelling and is not designed to fully represent any particular network.

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[47] In the Christchurch Assignment and Simulation Traffic model, congestion on the network is determined principally by junction capacity, which is not modelled in the sketch network. Hence, there is a need to ensure the speed/flow curves give rise to congestion.

In essence, therefore, we have some state highway rural links that are not of a particularly high standard that feed into an urban area, which will give rise to bottlenecks and high travel times when capacity is exceeded.

If we consider that project interdependencies will follow the way that projects may compete for traffic or re-enforce each other with increased amounts of induced traffic, this gives rise to the following table of interdependencies at uncongested traffic levels. Projects A, B and C will complement each other. Projects G and H are partial substitutes for each other and will compete. Project G also competes with Projects A, B and C. Project H also competes with Projects A and B, but it complements Project C as the two work together to improve traffic movements between Y and Z. Note, these expected interdependencies may change with congestion.

Table D.2 Sketch network interdependencies at uncongested traffic levels

	Project A	Project B	Project C	Project G	Project H
Project A		+ve	+ve	−ve	−ve
Project B			+ve	−ve	−ve
Project C				−ve	+ve
Project G					−ve
Project H					

+ve = complementary at low traffic volumes
−ve = competitive at low traffic volumes

To model the impact of congestion on demand, an elastic demand function was used. This was implemented directly within SATURN using the elastic assignment options. Initial demand was set at 500 trips between each of the three origin–destination pairs. Higher demand scenarios were also created. At 500 trips some congestion was present, so a lower demand scenario was created (called Scenario 0.5). Each scenario is interlinked in that the scenario demand matrix is a function of the initial demand matrix but constrained to the capacity of the network.[48]

Figure D.2 depicts the demand and supply curves for the base and project combinations involving Projects A, B and C for the X to Y origin–destination movement. What is obvious from this graph is that at low demand levels the network is uncongested and the supply curves are flat, but these increase very steeply as demand approaches 1,000 trips between X and Y. The substantive nature of Projects A, B and C lead, in uncongested conditions, to a reduction in transport time costs of 22%, and an induced demand of 28%. In heavily congested conditions there is a 46% reduction on time costs, and induced traffic is some 83% of the demand in the base. This analysis has only considered changes in travel time and has used a constant elasticity demand curve with an elasticity of 1.0. This could be viewed as quite elastic; therefore, the induced demand effects may be overly generous. A constant elasticity model is akin to the use of elasticities set out in the MBCM to analyse changes in demand in response to changes in transport costs.[49]

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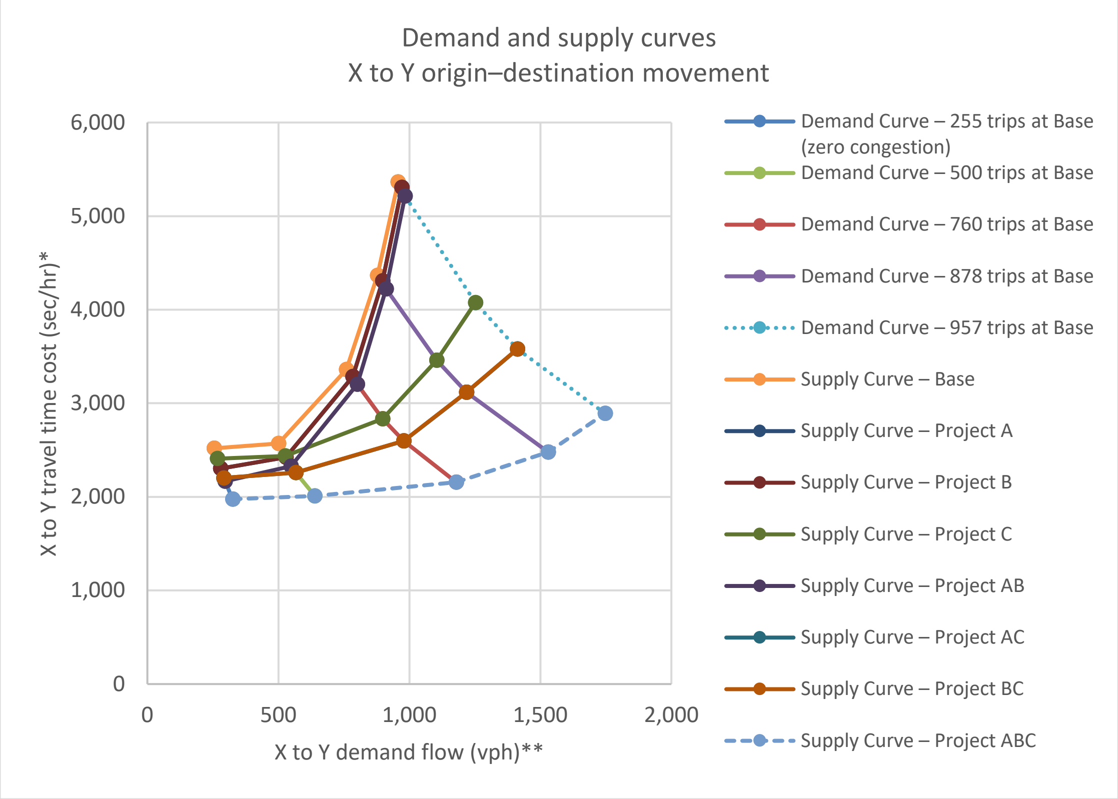
[48] In the case of the lower demand scenario, demand was not constrained by capacity limits because demand fell below the level at which congestion effects begin.

[49] The analysis also tested a negative exponential demand curve with an elasticity of 1.0 in the base scenario with 500 trips. It found similar results. The negative exponential demand curve is slightly more linear, and the demand elasticity increases as one moves along the curve (towards higher demand levels). The remainder of the analysis uses the constant elasticity function.

Figure D.2 Zone X to Zone Y demand and supply curves



* sec/hr = seconds of travel time savings per representative hour
** vph = vehicles per hour

A final point to make is that if the different demand growth scenarios were thought of as presenting different points in time, then the traffic growth across these scenarios would span many years. For example, at a growth of 2% per annum in a network that was unconstrained[50] from a capacity perspective, there would be 35 years of growth required to move from 250 trips/hour to 500 trips/hour and then again to 1,000 trips/hour. From a 1,000 trips/hour to 1,500 trips/hour would require a further 20.5 years of growth, and then from 1,500 trips/hour to 2,000 trips/hour would require a further 14.5 years of growth.

The sketch model has then been used to model the 32 different network combinations associated with the five projects (A, B, C, G and H). The results are presented in Table D.3 (shown as time savings in seconds per representative hour). Each project combination is treated as its own project. Thus, if A, B and G are implemented, that would constitute Project ABG. The interdependency benefits for all the different project combinations are presented in Table D.4. These have been separated into standalone, pairwise, triple, quadruple and quintuple interdependencies. A positive number indicates complementarity of projects, and a negative number indicates substitutability of projects. Having said that, the net interdependency benefit is given by the sum of all the relevant pairwise and triple, etc interdependencies. Thus, the net interdependency benefits of Project ABG are the sum of the pairwise benefits AB, AG and BG plus the triple benefit ABG. For completeness, the total benefit of Project ABG is given in Table D.3 (738,403 minutes for

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[50] The highest demand growth scenario is associated with an unconstrained demand of 2,000 trips/hour. Capacity constraints in the base case reduce this to 957 trips/hour.

Demand Scenario 0.5) and can be found as the sum of standalone (A+B+G=725,991) and interdependency benefits (AB+AG+BG+ABG=12,441) from Table D.4.[51]

Table D.3 User benefits (seconds of travel time savings per representative hour) by demand scenario for all sketch network project combinations

Demand scenario	Project A User benefits	Project B User benefits	Project C User benefits	Project G User benefits	Project H User benefits
0.5	115,720	115,720	57,807	494,551	735,288
1.0	284,328	284,322	257,509	1,244,112	-243,778
2.0	208,996	209,187	1,557,986	4,048,255	282,930
3.0	147,449	147,827	3,048,719	7,578,710	603,057
4.0	113,927	113,872	4,767,241	11,263,518	2,108,250

Demand scenario	Project AB User benefits	Project AC User benefits	Project AG User benefits	Project AH User benefits	Project BC User benefits	Project BG User benefits	Project BH User benefits	Project CG User benefits	Project CH User benefits	Project GH User benefits
0.5	259,709	218,262	610,267	813,864	218,265	610,267	813,923	552,359	1,188,379	735,288
1.0	471,567	590,416	1,453,282	-167,323	590,415	1,453,282	-167,343	1,393,408	2,572,537	809,041
2.0	461,798	2,335,906	4,272,171	449,159	2,335,921	4,272,625	449,160	4,937,216	6,253,085	3,861,688
3.0	444,097	4,422,148	7,794,832	729,067	4,422,150	7,794,832	729,056	9,594,156	10,498,821	7,578,736
4.0	460,770	7,126,261	11,477,944	2,424,518	7,126,246	11,477,013	2,424,504	14,393,969	15,046,233	11,269,587

Demand scenario	Project ABC User benefits	Project ABG User benefits	Project ABH User benefits	Project ACG User benefits	Project ACH User benefits	Project AGH User benefits	Project BCG User benefits	Project BCH User benefits	Project BGH User benefits	Project CGH User benefits
0.5	491,838	738,403	894,117	674,510	1,309,091	813,864	674,510	1,309,091	813,923	1,188,379
1.0	1,032,748	1,674,012	-95,016	1,639,941	2,792,347	1,000,353	1,639,940	2,792,347	1,000,353	2,572,537
2.0	3,831,703	4,492,857	605,566	5,476,217	6,579,918	4,149,567	5,476,216	6,579,918	4,149,484	6,253,085
3.0	7,281,858	8,016,218	867,064	10,465,593	10,921,563	7,795,142	10,465,512	10,921,774	7,794,893	11,266,501
4.0	10,829,733	11,686,764	2,756,161	15,641,067	15,719,485	11,481,092	15,641,067	15,719,572	11,481,089	18,229,488

Demand scenario	Project ABCG User benefits	Project ABCH User benefits	Project ABGH User benefits	Project ACGH User benefits	Project BCGH User benefits	Project ABCGH User benefits
0.5	811,655	1,444,206	894,117	1,309,091	1,309,091	1,444,206
1.0	1,925,965	3,039,684	1,208,689	2,792,347	2,792,347	3,039,684
2.0	6,306,954	6,984,454	4,473,356	6,579,918	6,579,918	6,984,454
3.0	12,206,262	11,505,674	8,016,454	11,870,485	11,870,766	12,908,585
4.0	18,283,325	16,814,506	11,689,092	18,901,186	18,901,217	20,324,215

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[51] It may help to think of the numbers in Table D.4 as analogous to the main and interaction terms in a regression analysis.

Table D.4 Interdependency benefits (seconds of travel time savings per representative hour) by demand scenario for network Programme ABCGH

Demand scenario	Total programme-level user benefits	Standalone benefits				
	Programme ABCGH	A	B	C	G	H
0.5	1,444,206	115,720	115,720	57,807	494,551	735,288
1.0	3,039,684	284,328	284,322	257,509	1,244,112	-243,778
2.0	6,984,454	208,996	209,187	1,557,986	4,048,255	282,930
3.0	12,908,585	147,449	147,827	3,048,719	7,578,710	603,057
4.0	20,324,215	113,927	113,872	4,767,241	11,263,518	2,108,250

Demand scenario	Pairwise interdependencies									
	AB	AC	AG	AH	BC	BG	BH	CG	CH	GH
0.5	28,268	44,735	-4	-37,143	44,738	-4	-37,085	1	395,284	-494,551
1.0	-97,082	48,579	-75,158	-207,873	48,585	-75,151	-207,887	-108,212	2,558,806	-191,293
2.0	43,615	568,924	14,920	-42,766	568,749	15,183	-42,957	-669,025	4,412,169	-469,497
3.0	148,820	1,225,980	68,673	-21,440	1,225,604	68,295	-21,829	-1,033,273	6,847,046	-603,031
4.0	232,971	2,245,093	100,498	202,342	2,245,134	99,623	202,382	-1,636,789	8,170,743	-2,102,181

Demand scenario	Triple interdependencies									
	ABC	ABG	ABH	ACG	ACH	AGH	BCG	BCH	BGH	CGH
0.5	84,850	-15,849	-26,651	-38,300	-2,599	4	-38,302	-2,661	4	-1
1.0	206,508	108,642	92,954	-11,217	94,775	190,014	-11,223	94,790	190,028	-944,606
2.0	674,246	-47,299	-53,438	-253,840	-408,321	106,730	-254,119	-408,145	106,384	-2,909,733
3.0	1,337,459	-143,556	-136,822	-570,664	-929,248	21,724	-570,369	-928,649	21,864	-5,174,726
4.0	1,111,495	-237,646	-217,583	-1,212,421	-1,888,110	-205,262	-1,211,531	-1,888,049	-204,375	-4,341,294

Demand scenario	Quadruple interdependencies				
	ABCG	ABCH	ABGH	ACGH	BCGH
0.5	-82,274	-72,064	15,849	38,300	38,302
1.0	-178,575	-174,851	-87,489	-103,640	-103,654
2.0	-378,826	-586,720	93,114	132,190	132,552
3.0	-473,411	-1,188,299	136,713	661,510	661,522
4.0	288,339	-705,201	218,755	1,315,632	1,314,673

Demand scenario	Quintuple interdependencies
	ABCGH
0.5	82,274
1.0	157,422
2.0	333,010
3.0	752,932
4.0	60,168

Insight as to what is providing the interdependencies can be found by considering the traffic volumes accommodated and the travel times for project and demand permutations.[52] Figure D.3 shows the project effects (ie, project less DoMin) on average vehicle travel time and number of vehicles between X and Y and between Z and Y (the changes between X and Z are not shown as they were relatively small albeit important

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[52] Standard graphical model outputs could also be used to show these and more effects.

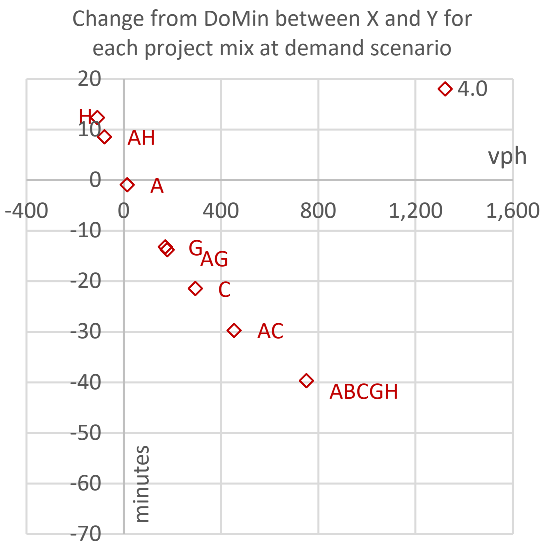
at times). The projects in the graphs were selected with the question in mind: if Project A were committed, then what is the benefit of choosing Project C, G or H as a second project (at this stage ignoring project costs)? The results are shown for Demand Scenario 4.0, when the DoMin travel time between X and Y has increased to 89 minutes from a DoMin of 42 minutes in the uncongested Demand Scenario 0.5 and between Z and Y to 110 minutes from 51 minutes uncongested.

Not shown in the graphs below, the direction of the effect was usually the same for any particular project combination under a low-demand and a high-demand scenario, but there were exceptions with project combinations that involved Project H (eg, Project AH increased volume slightly for X–Y journeys when congestion was low but otherwise led to lower X–Y volumes when congestion was higher).

The graphs show that projects have travel time and induced demand effects, and these effects are complicated by the re-routeing of journeys between nodes in some cases.

These issues are taken up further in the following sections.

Figure D.3 Traffic statistics for selected project combinations under Demand Scenario 4.0

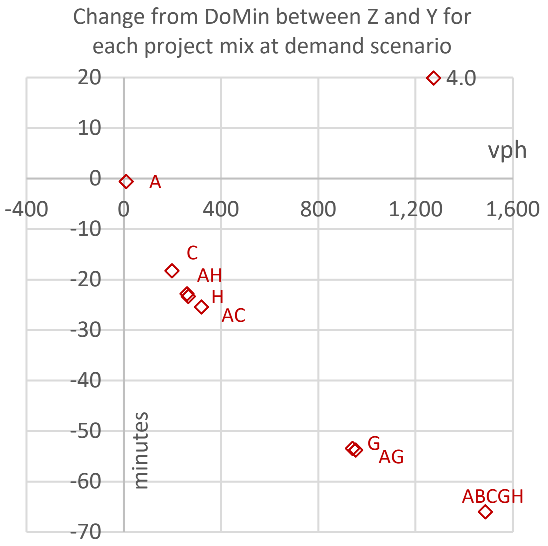


Project A would have small beneficial effects – that is, more traffic (vph) and fewer minutes travel (minutes) – on X–Y trips when the route is congested (Demand Scenario 4.0).

Adding Project H (ie, combined Project AH) creates X–Y congestion as a result of re-routeing. Project A would dampen that.

Alternatively, adding Project G to Project A has beneficial effects on X–Y travel but no more or no less than had Project A not existed (since Project G re-routes more X–Y trips re-routed via Links F and G).

Alternatively, adding Project C to Project A also has a large beneficial effect, and having Project A in place amplifies this effect – an example of a complementary interdependency.



Meanwhile, on the Z–Y sections, which form the major part of the potentially competing journey for sections ABC, Project A has also had a small beneficial effect.

Adding Project H is beneficial to the Z–Y journey, but Project A has little extra effect.

Alternatively, adding Project G to Project A again shows only the effect of Project G and no interdependency with Project A.

Alternatively, adding Project C is beneficial for Z–Y trips, with Project A amplifying the effect (ie, consistent with re-routeing of Z–Y trips via X and ABC links).

Note, should all projects be undertaken (ABCGH), then the effect comes through as large reductions in travel time *and* large increases in traffic volumes, with the effect largest on the Z–Y journey. (Not shown are also modest changes on the X–Z link.)

D.2 A search for rules on interdependencies

The initial 120 model runs are discussed further below, along with further runs to explore specific questions. All results tabled in this section follow the convention of the earlier Table D.4 – that is, presenting user benefits as seconds of travel time savings per representative hour for each standalone, pairwise, etc effect (eg, benefits shown for the ABC-triple is the total benefit of an ABC sub-programme less the standalone (A, B, C) and pairwise benefits (AB, AC, BC)).

D.2.1 Complementary schemes, the pairwise rule, congestion and re-routeing

A consideration of economic theory identifies that in uncongested conditions, pairwise benefits are good indicators of the interdependency benefits from complementary schemes. This leads to the concept of a pairwise rule for assessing interdependency benefits. The literature also identifies that under congested conditions where a bottleneck exists up or downstream, complementary projects may compete with one another. Furthermore, re-routeing effects can increase interdependency benefits. We look at complementary Projects A, B and C under a variety of different demand conditions to consider whether these pointers from theory appear generalisable.

The three scenarios are:

- **Scenario All**: Demand between each of the three zones (X, Y and Z) is the same. This scenario effectively means that in congested conditions all links in the network are congested. See Table D.5 for user benefits.
- **Scenario No-Z**: Demand between zones X and Y is the same, but there is no demand to/from Z. This scenario effectively gives rise to the scenario that when Links A, B and C become congested, a route via Links F and G becomes viable and this route is not congested. That is, at high traffic levels two traffic routes are possible, but one is congested and the other is not. See Table D.6 for user benefits.
- **Scenario XY-Only**: Demand between zones X and Y is the same, but there is no demand to/from Z and traffic is not to travel on Links F and G. This is the same demand level as Scenario No-Z, but all traffic, no matter what the conditions, has to route via Links A, B and C. See Table D.7 for user benefits.

A quick glance at the aforementioned tables indicates that there are a number of competing interactions that are occurring, and these vary with both the demand scenario and the supply scenario. To understand what is happening, it is useful to look at the simplest scenario – Scenario XY-Only in Table D.7. Here we can see the error based on pairwise benefits at low levels of demand (Demand Scenarios 0.5 and 1.0) is low. This is also the case where re-routeing can occur under congested conditions. In fact, the results for demand levels 0.5, 1.0 and 2.0 in both Scenarios No-Z and XY-Only are the same.

Differences start to occur as the network becomes more congested. Focusing again on Scenario XY-Only we can see that as congestion starts to build, then, as predicted by theory, the complementary Projects A and B start competing. This can be seen by the negative pairwise benefit AB. The high levels of congestion on Link C are causing a serious bottleneck in the network, resulting in Projects A and B generating very little traffic at high congestion levels – hence the standalone benefits of Projects A and B remain static as the demand scenario increases and the pairwise benefit AB, having gone negative, tends to zero. At high levels of congestion, the programme benefits become dominated by Project C.

Scenario No-Z differs significantly from this situation as re-routeing via Links F and G when the network is congested in Demand Scenarios 3.0 and 4.0 acts as a ‘safety valve’ on travel costs. This is because Links F and G are not congested in this scenario. For Demand Scenario 3.0, traffic re-routes back to Links A and B if both Projects A and B are implemented, but not if only one of them is implemented. This is a re-routeing complementary effect. This gives rise to the positive pairwise benefit AB. However, by the time demand is at levels associated with Demand Scenario 4.0 there is not sufficient capacity on Link C to permit this re-routeing to occur. Therefore, the pairwise benefit AB has gone back to being negative, and the standalone benefits of A and B are small.

The situation differs significantly in Scenario All (see Table D.5), where travel demand exists between all zones, and in the high demand scenarios all links are congested. At low levels of demand in Scenario All we get similar standalone benefits as with the other scenarios; however, the pairwise benefits differ significantly. The pairwise benefits are a lot higher – particularly associated with Project C as this encourages re-routeing for traffic from Z to Y to switch to the longer route via Links A, B and C. This additional re-routeing traffic therefore makes Links A, B and C more congested than in the other two scenarios at lower levels of growth. This in itself gives rise to the negative pairwise interdependency benefit AB as Projects A and B start competing in the presence of a large bottleneck on Link C. At higher levels of growth, a bottleneck also appears on Link G, and the network can be viewed as fully congested. Projects A and B then revert to being complementary. However, it can be seen that the level of congestion is such that the benefits do not increase significantly with growth, and the programme-level benefits are driven by Project C.

We can also see from the right-hand column of each of the tables that the level of error from ignoring interdependency benefits increases substantially with congestion in Scenarios No-Z and XY-Only, but seems relatively static in Scenario All. The difference is attributed to the effects of re-routeing. We can also see that the error from basing the benefit estimation on pairwise benefits only seems below 20% in the main and is always lower than excluding all interdependency benefits from the analysis.

Table D.5 User benefits (seconds of travel time savings per representative hour) for Project ABC by demand scenario (Scenario All: includes demand to/from Z, re-routeing via Links F and G is permitted)

Demand scenario	Standalone			Pairwise			Triple	Total interdependency benefits	Error based on using pairwise only	Error based on ignoring interdependency
	A	B	C	AB	AC	BC	ABC			
0.5	115,720	115,720	57,807	28,268	44,735	44,738	84,850	202,591	17%	41%
1.0	284,328	284,322	257,509	-97,082	48,579	48,585	206,508	206,590	20%	20%
2.0	208,996	209,187	1,557,986	43,615	568,924	568,749	674,246	1,855,534	18%	48%
3.0	147,449	147,827	3,048,719	148,820	1,225,980	1,225,604	1,337,459	3,937,863	18%	54%
4.0	113,927	113,872	4,767,241	232,971	2,245,093	2,245,134	1,111,495	5,834,693	10%	54%

Table D.6 User benefits (seconds of travel time savings per representative hour) for Project ABC by demand scenario (Scenario No-Z: no demand to/from Z, re-routeing via Links F and G is permitted)

Demand scenario	Standalone			Pairwise			Triple	Total interdependency benefits	Error based on using pairwise only	Error based on ignoring interdependency
	A	B	C	AB	AC	BC	ABC			
0.5	115,711	115,711	57,802	12,417	6,435	6,435	2,579	27,866	1%	9%
1.0	209,379	209,379	149,466	11,665	37,500	37,500	28,108	114,773	4%	17%
2.0	225,407	225,407	899,138	-4,330	317,346	317,346	307,769	938,131	13%	41%
3.0	118,957	118,957	1,954,498	103,639	770,263	770,263	878,455	2,522,620	19%	54%
4.0	34,185	34,191	1,191,014	-8,648	1,230,215	1,230,209	1,454,510	3,906,286	28%	76%

Table D.7 User benefits (seconds of travel time savings per representative hour) for Project ABC by demand scenario (Scenario XY-Only: no demand to/from Z, no re-routeing via Links F and G)

Demand scenario	Standalone			Pairwise			Triple	Total interdependency benefits	Error based on using pairwise only	Error based on ignoring interdependency
	A	B	C	AB	AC	BC	ABC			
0.5	115,711	115,711	57,802	12,417	6,435	6,435	2,579	27,866	1%	9%
1.0	209,379	209,379	149,466	11,665	37,500	37,500	28,108	114,773	4%	17%
2.0	225,407	225,407	899,138	-4,330	317,346	317,346	307,769	938,131	13%	41%
3.0	224,575	224,575	2,064,470	-1,749	668,678	668,678	991,777	2,327,384	20%	48%
4.0	235,770	235,770	3,275,814	352	1,104,079	1,104,076	1,621,393	3,829,900	21%	51%

To summarise, for complementary schemes the sketch network analysis indicates that:

- pairwise benefits are only a good indicator for total interdependency benefits at low levels of congestion and where re-routeing is not expected to be significant
- at high levels of congestion and where re-routeing becomes significant, the manner in which projects interact changes significantly with demand levels – it is therefore difficult to see that any simple generalisations will be possible.

This might suggest that the application of the pairwise rule is limited, and that may certainly be the case with respect to highway projects. However, for a lot of active travel or public transport initiatives in the New Zealand context, overcrowding on the public transport modes or on the active travel infrastructure is not a particular issue. In that case, the pairwise rule may have a broader applicability.

D.2.2 Competing projects

Projects 'compete' in two ways. Firstly, they can compete for demand, which in this sketch model network is via re-routeing. Secondly, in combination they may impose additional costs elsewhere in the network that are not compensated for by the cost reductions on the project itself. This latter point has been identified and discussed in relationship to Projects A, B and C.

The two obvious projects that compete in our sketch network are Projects G and H, as they are parallel to each other and serve the Y to Z trip movement. Project H is a motorway standard link but re-routes traffic onto Link C, which under certain demand scenarios is heavily congested. The results of an examination of their interaction are shown in Table D.8. In this rather extreme case, at low levels of congestion Project G is redundant – no demand uses it. At very high levels of demand, congestion on Link C is such that there is no demand for Project H. These all-or-nothing type assignments are reflective of situations where projects can create dominant routes. They might be relatively rare but could be thought of as occurring between rural interurban routes or potentially for some mode choice scenarios, where they illustrate the situation where projects create imbalances between what were competitive routes. At intervening demand levels there is demand for both projects, but the congestion on Link C is imposing additional costs on the network.

Interestingly, Project H on its own actually creates dis-benefits in Demand Scenario 1.0 (second row of Table D.8). This is due to a condition known as Braess's paradox, which is discussed in more detail in section D.2.4.

Table D.8 User benefits (seconds of travel time savings per representative hour) for Project GH – interdependency analysis

Demand scenario	Total programme-level user benefits	Standalone benefits		Pairwise	Pairwise as a percentage of the sum of the standalone benefits	Note
	Project GH	G	H	GH		
0.5	735,288	494,551	735,288	-494,551	-40%	Project G is redundant.
1.0	809,041	1,244,112	-243,778	-191,293	-19%	Project G and H compete.
2.0	3,861,688	4,048,255	282,930	-469,497	-11%	Project G and H compete.
3.0	7,578,736	7,578,710	603,057	-603,031	-7%	Project H is completely redundant.
4.0	11,269,587	11,263,518	2,108,250	-2,102,181	-16%	Project H is completely redundant.

Note Braess's paradox for Project H.

A less extreme competing scheme example is given by Projects C and G. Under congested conditions, Links C and G both offer viable routes between X and Y; therefore, under congested conditions, Projects C and G compete and we see competing effects in the range of about 10% of the sum of the standalone benefits. It can also be seen that when neither route experiences congestion, the two projects do not interact (see the first line of Table D.9).

Table D.9 **User benefits (seconds of travel time savings per representative hour) for Project CG – interdependency analysis**

Demand scenario	Total programme-level user benefits	Standalone benefits		Pairwise	Pairwise as a percentage of the sum of the standalone benefits
	Project CG	C	G	CG	
0.5	552,359	57,807	494,551	1	0%
1.0	1,393,408	257,509	1,244,112	-108,212	-7%
2.0	4,937,216	1,557,986	4,048,255	-669,025	-12%
3.0	9,594,156	3,048,719	7,578,710	-1,033,273	-10%
4.0	14,393,969	4,767,241	11,263,518	-1,636,789	-10%

D.2.3 Mixed competing and complementary schemes and the pairwise rule

We now turn to the benefits of a programme comprising Projects A, B, C and G, where A, B and C complement each other and compete with Project G. Looking at the right-hand columns of the lowest part of Table D.10 we can see that the error of basing an interdependency assessment on just the pairwise interactions appears low. However, this can be seen to arise from two competing effects of large positive pairwise benefits and large negative triple interdependency benefits. The latter arise due to the re-routeing competitive effects between Project G and Projects A, B and C. We would therefore consider the pairwise rule to be inappropriate when re-routeing effects are likely to be important between competing schemes.

Table D.10 **Interdependency benefits (seconds of travel time savings per representative hour) for Programme ABCG**

Demand scenario	Total programme-level user benefits	Standalone benefits			
	Programme ABCG	A	B	C	G
0.5	811,655	115,720	115,720	57,807	494,551
1.0	1,925,965	284,328	284,322	257,509	1,244,112
2.0	6,306,954	208,996	209,187	1,557,986	4,048,255
3.0	12,206,262	147,449	147,827	3,048,719	7,578,710
4.0	18,283,325	113,927	113,872	4,767,241	11,263,518

Demand scenario	Pairwise interdependencies					
	AB	AC	AG	BC	BG	CG
0.5	28,268	44,735	-4	44,738	-4	1
1.0	-97,082	48,579	-75,158	48,585	-75,151	-108,212
2.0	43,615	568,924	14,920	568,749	15,183	-669,025
3.0	148,820	1,225,980	68,673	1,225,604	68,295	-1,033,273
4.0	232,971	2,245,093	100,498	2,245,134	99,623	-1,636,789

Demand scenario	Triple interdependencies				Quadruple inter-dependencies
	ABC	ABG	ACG	BCG	ABCG
0.5	84,850	-15,849	-38,300	-38,302	-82,274
1.0	206,508	108,642	-11,217	-11,223	-178,575
2.0	674,246	-47,299	-253,840	-254,119	-378,826
3.0	1,337,459	-143,556	-570,664	-570,369	-473,411
4.0	1,111,495	-237,646	-1,212,421	-1,211,531	288,339

Demand scenario	Total Inter-dependency benefits for ABCGH	Total pairwise benefits	Error based on using pairwise only	Error based on ignoring inter-dependency
0.5	27,857	117,734	-11%	3%
1.0	-144,305	-258,440	6%	-7%
2.0	282,530	542,367	-4%	4%
3.0	1,283,557	1,704,099	-3%	11%
4.0	2,024,767	3,286,530	-7%	11%

The inappropriateness of the pairwise rule when re-routeing occurs becomes more obvious when looking at the impact of Programme ABCGH (see Table D.11), where errors in the pairwise rule are up to 50% – though again this is likely to be heavily contingent on the types of project that are being considered and how they interact so is unlikely to be generalisable.

Now, turning to the benefits of a programme comprising Projects A, B, C, G and H, we saw earlier that there are substantial positive and negative interdependency benefits (see Table D.4), but these seem to approximately cancel out at the programme-level (see the right-hand column of the lower part of Table D.11). This is felt to be coincidental and is a property of the mix of competing and complementary schemes that are assessed in this analysis. We can also see that the pairwise rule does not give a good indicator of interdependency benefits – consistently overestimating the total interdependency benefits. This is attributed to the way that the effects of re-routeing in this network seem to become important once two or more schemes are constructed (ie, triple and quad benefits are negative). For the pairwise rule to hold, the higher-order benefit measures would need to be zero or close to zero, which they are not.

Table D.11 Standalone and summary interdependency benefits (seconds of travel time savings per representative hour) for Programme ABCGH

Demand scenario	Standalone					Sum of interdependencies			
	A	B	C	G	H	Pairwise	Triple	Quad-ruple	Quintuple
0.5	115,720	115,720	57,807	494,551	735,288	-55,762	-39,506	-61,887	82,274
1.0	284,328	284,322	257,509	1,244,112	-243,778	1,693,314	10,665	-648,209	157,422
2.0	208,996	209,187	1,557,986	4,048,255	282,930	4,399,315	-3,447,535	-607,689	333,010
3.0	147,449	147,827	3,048,719	7,578,710	603,057	7,904,845	-7,072,988	-201,966	752,932
4.0	113,927	113,872	4,767,241	11,263,518	2,108,250	9,759,816	-10,294,775	2,432,198	60,168

Demand scenario	Total interdependency benefits for ABCGH	Total programme benefits for ABCGH	Error based on using pairwise only	Error based on ignoring interdependency
0.5	-74,880	1,444,206	-1%	-5%
1.0	1,213,192	3,039,684	-16%	40%
2.0	677,101	6,984,454	-53%	10%
3.0	1,382,823	12,908,585	-51%	11%
4.0	1,957,407	20,324,215	-38%	10%

Figure D.12 (on page 157) also demonstrates the error associated with the pairwise rule, but in a graphical way. The pairwise rule would be a good indicator of benefits if projects lie on the diagonal line. As can be seen from Figure D.12, the more complex project combinations all seem to lie above the line, indicating that the pairwise rule is not a good indicator of benefits in aggregate.

Situations when complementary and competing projects may switch from complementary to competing and vice versa are shown in Table D.12 for the sketch model.

Table D.12 Interdependency benefits, congestion and sketch network examples

Scheme types (in terms of travel demand)	Sign of interdependency benefits if network is:	
	Uncongested	Congested
Complementary	**Positive** **Projects A, B in Demand Scenario 0.5**	**Positive** (if congestion is ameliorated). **Projects A with C and B with C in Demand Scenarios 2.0, 3.0 and 4.0.** **Negative** (if congestion is worsened). **Projects A and B in Demand Scenario 1.0.**
Competing	**Negative** **Project G when Projects A and B have been jointly implemented**	**Positive** (if congestion remains in the Do Something and both routes using either scheme are viable). **Projects A and B would be expected to compete with G but generate a positive triple interdependency in Demand Scenario 1.0.** **Negative** (if sufficient capacity on one route is created such that that route dominates route choice). Projects G and H in Demand Scenarios 3.0 and 4.0. Here Link C is too congested and Project H is redundant if G is constructed.

D.2.4 Braess's paradox

Braess's paradox is a situation when project improvements can bring dis-benefits to a network (Steinberg & Zangwill, 1983; Venables, 1999). We have an example of this paradox in our sketch network. Here we can see that Projects H, AH and BH create use dis-benefits in Demand Scenario 1.0. This arises as traffic between Y and Z travels along Link C when Project H is implemented. This imposes a congestion cost on traffic travelling between X and Y. In Demand Scenario 1.0 this additional cost is sufficient to make the project negative. In the other demand scenarios, dis-benefits to traffic between X and Y still occur, but the congestion benefits between Y and Z are more than the dis-benefits – thus generating a positive impact for Project H in those demand scenarios.

The following notes bring together and expand key points from this section, some already noted in the 'Sketch Lesson' boxes in Chapter 3.

- The pairwise rule is likely to only apply to uncongested conditions, where re-routeing is not likely to be overly significant.
  - For road projects, this is likely to be limiting to particular state highway improvements (eg, SH1 Christchurch to Dunedin).
  - *But* if New Zealand public transport networks are not too congested (that is, are not overcrowded in the public transport vehicles), then it may apply to those situations.
  - *Plus,* pairwise may be appropriate to active travel also, particularly if active travel and public transport improvements are on radial city routes that do not abstract demand from one another. This might point towards a certain type of case study.
- In our simple sketch network, we have examples of all types of competing, complementary and congested interactions that theory would suggests occur. In real networks this will be amplified. Ultimately it will be an empirical matter as to which effects will dominate. So, in complex networks subject to congestion, full modelling of as many permutations as possible will likely be required.
- It seems there is a limited set of projects where fewer model runs will be sufficient.

D.2.5 Induced traffic versus re-routeing traffic as a source of interdependency benefit

The interdependency benefits arise as projects induce traffic on other projects in the programme. One of our aims of the sketch network was to develop an understanding of the importance of induced and re-routeing traffic as sources of interdependency benefit. Induced traffic would include traffic that switches destinations, modes and changes in land use. Table D.13 and Table D.14 present traffic flows on Links A, B and C with Project ABC for the scenario where there is no travel demand to/from Z, and when there is.

When there is no travel demand from Z, we can see that Project ABC induces an extra 446 trips on the network. This is an increase of 54%. This is a very large amount of induced traffic and reflects a mixture of things: the reasonably elastic demand function (an elasticity of 1.0 to time only), the high level of suppressed demand in the system (base costs are defined from Demand Scenario 1.0), and the significant cost reduction that occurs (approximately 35% on the X to Y movement). Induced traffic then contributes 21% of the user benefit. It is the induced traffic that is the primary source of the interdependency benefits of Project ABC.

If there is travel demand to/from Z, we see that traffic flows on the project increase by 100% on the base traffic flows, with re-routed traffic being over half of the additional traffic on these links. Interestingly, however, re-routeing traffic contributes some 40% of the user benefits. This is because under congested conditions the re-routeing traffic obtains all the benefit of the cost reduction, whilst the induced traffic only obtains a fraction of the cost reduction due to the manner in which it arises (from re-distribution, mode shift, land use change, etc) and the application of the rule of half.

A key difference between induced and re-routed traffic, however, is how captive it is to the project. In our sketch network, the re-routed traffic is trying to avoid congested Link G. Implementing Project G therefore reduces the re-routed traffic on Links A, B and C to zero. The re-routed traffic is therefore the source of the competing interdependency effect between Project G and Projects A, B and C. The robustness of the interdependency benefits of a project to other competing projects is therefore likely to be contingent on the level of benefits that are attributed to re-routeing.

Table D.13 Project ABC disaggregation of traffic flows (vph) between base, induced and re-routed traffic (Demand Scenario 2.0)

	Traffic flows on links A, B & C					
	Base	Project ABC	Induced traffic (between X and Y on links A, B & C)	Re-routed traffic (from Z to Y via links A, B & C)	Induced traffic as percentage of base traffic	Re-routed traffic as percentage of base traffic
No traffic to/from Z	827	1,273	446	n/a	54%	n/a
With traffic to/from Z	889	1,760	418	453	47%	51%

Table D.14 Project ABC disaggregation of user benefits (seconds of travel time savings per representative hour) between base, induced and re-routed traffic (Demand Scenario 2.0)

	User benefits of Project ABC						
	Project ABC	Attributed to base traffic	Attributed to induced traffic (between X and Y)	Attributed to re-routed traffic (from Z to Y via links A, B & C)	Percentage attributed to base traffic	Percentage attributed induced traffic	Percentage attributed to re-routed traffic
No traffic to/from Z	2,288,083	1,802,138	485,945	n/a	79%	21%	n/a
With traffic to/from Z	3,831,703	1,852,555	435,528	1,543,620	48%	11%	40%

D.3 Marginal benefit of a project

As discussed previously, there is no one measure of the benefit when the project is interdependent with other projects – there are only conditional benefits. Instead, analysts have traditionally used multiple benefit measures such as the standalone benefit (conditional on no other interdependent project), the incremental benefit (conditional on some projects having commitment) and the decremental benefit (conditional on all projects committed in the programme). Each measure will give a different result.

This section explores the three measures for the projects modelled under Scenario All to show the intricacies of each measure and to continue the search for heuristics to reduce modelling.

This requires considering project benefit measures in four steps, namely:

1. What happens when decision-makers have committed to the programme (but want to consider individual project benefits)?
2. What happens when it is uncertain whether one or more projects will proceed?
3. What happens to benefits over time as demand increases, or maybe decreases?
4. What happens once costs are brought into the investment decision, as in practice?

This project-level measure is different but interrelated with the programme-level decision of the optimal project mix. The programme mix decision will be taken up in section D.4.

D.3.1 Project benefits within a committed programme

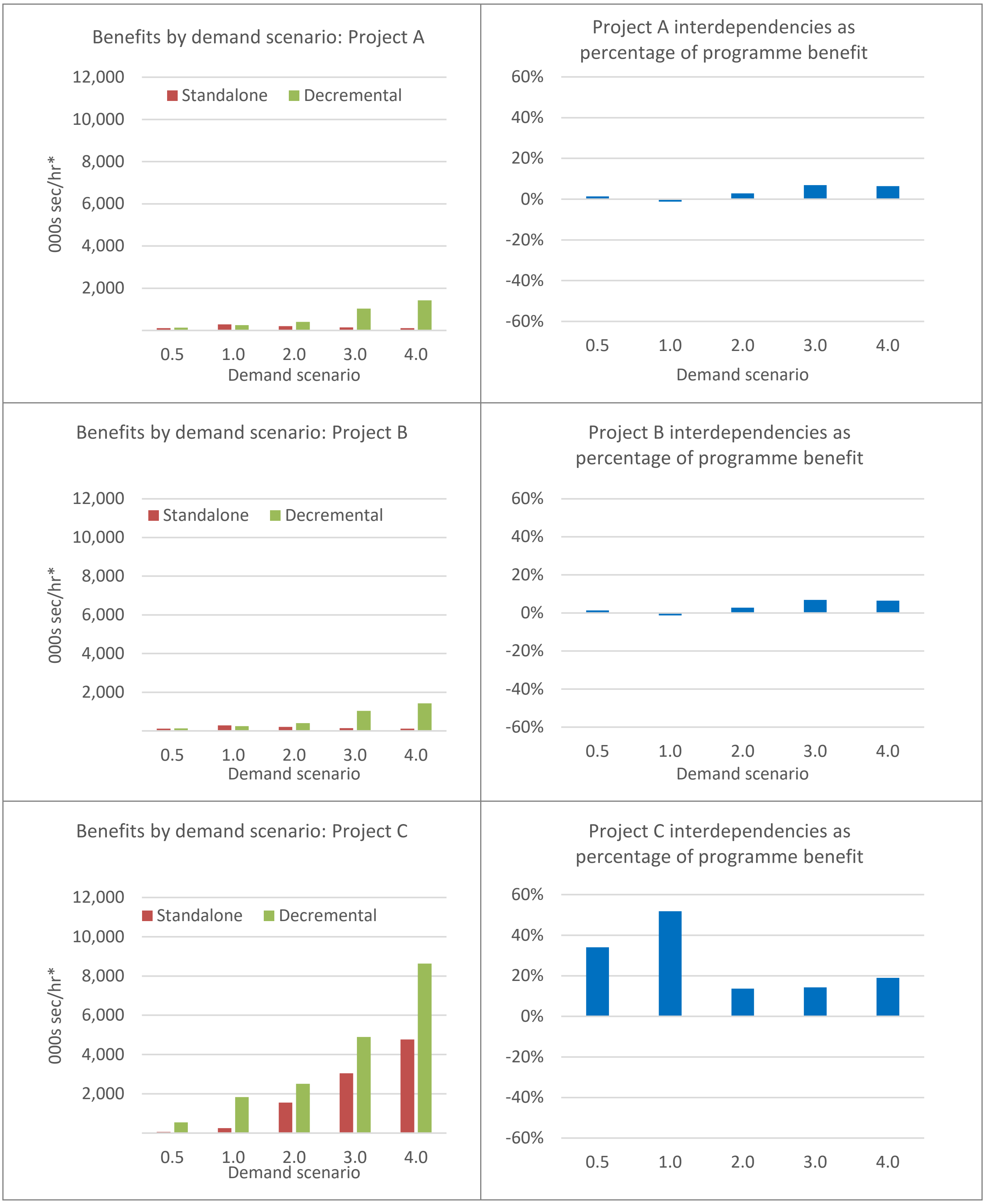
The standalone and decremental benefits for each project are graphed in Figure D.4, along with the percentage of the total programme benefits that arise from the interdependency component of each project's decremental benefit. The standalone benefits are also shown in Table D.4, as are the total programme benefits under each demand scenario. Each project's decremental benefits are shown in Table D.15. Recall the decremental effect is the reduction in programme benefits that would occur if one project were to be removed.

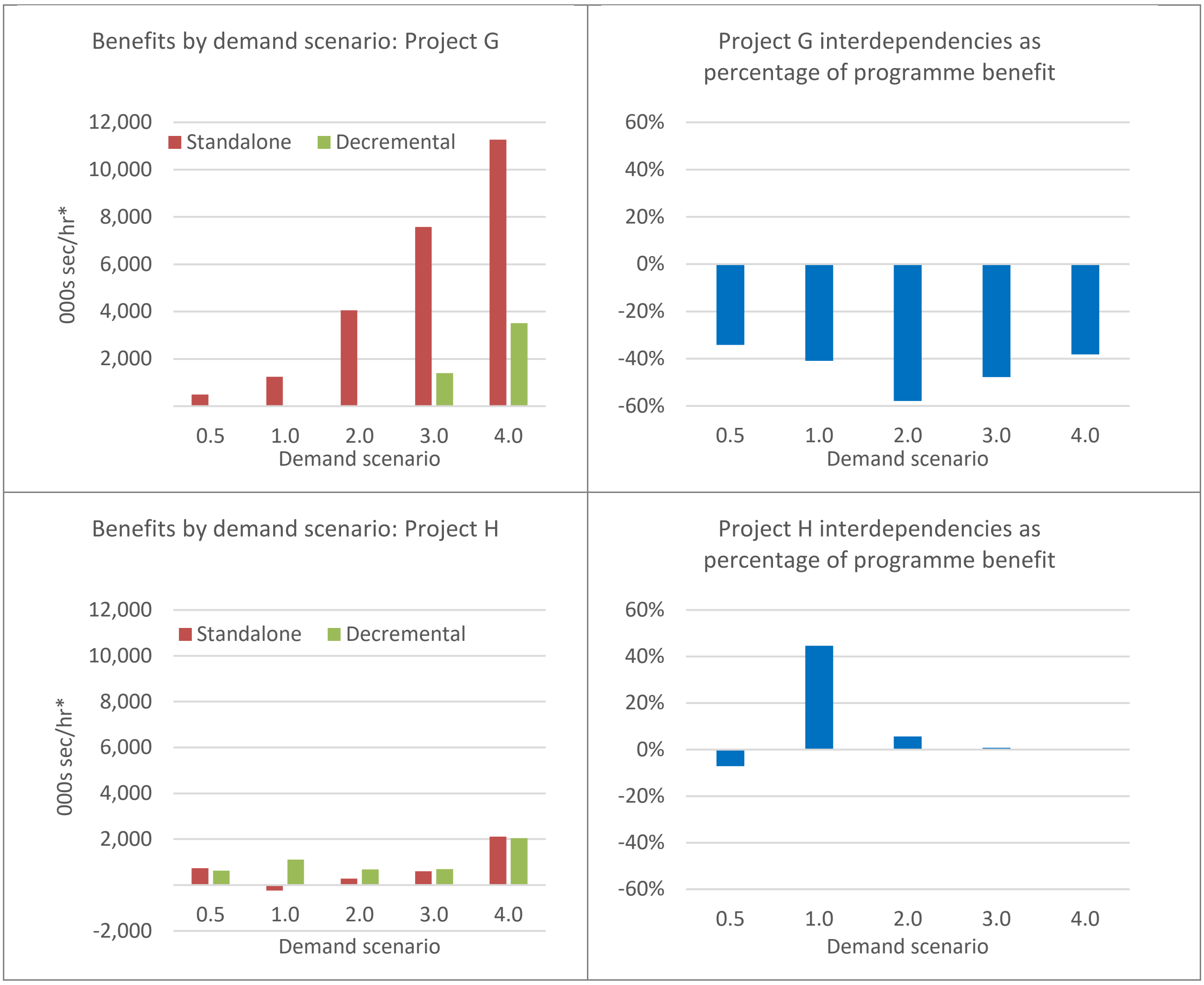
Table D.15 Decremental benefits (seconds of travel time savings per representative hour) for projects within Programme ABCGH, by demand scenario

Demand scenario	Project A	Project B	Project C	Project G	Project H
0.5	135,115	135,115	550,089	0	632,551
1.0	247,338	247,338	1,830,995	0	1,113,719
2.0	404,536	404,536	2,511,098	0	677,500
3.0	1,037,819	1,038,099	4,892,131	1,402,911	702,323
4.0	1,422,998	1,423,029	8,635,123	3,509,709	2,040,890

For example, Project A has a standalone benefit of 208,996 seconds of travel time savings per representative hour (sec/hr) and a decremental benefit of 404,536 sec/hr under Demand Scenario 2.0. The decremental measure is picking up the standalone benefit plus the interdependency benefits created by Project A coexisting with Projects B, C, G, and H. The interdependency benefits connected with Project A amount to 3% of the total programme benefits of 20,324,215 sec/hr. As to be expected with projects that largely complement other projects, the decremental benefits for Projects A, B and C exceed the standalone benefit. Project C is the source of the largest positive interdependency benefits. Also as expected, the standalone benefit exceeds the decremental benefit for the competing Project G, with interdependencies associated with G amounting to around 30–50% of programme benefits. Project H is competing at some demand levels and complementary at others.

Figure D.4 **Standalone and decremental benefits of projects, plus project interdependencies net of standalone effects**



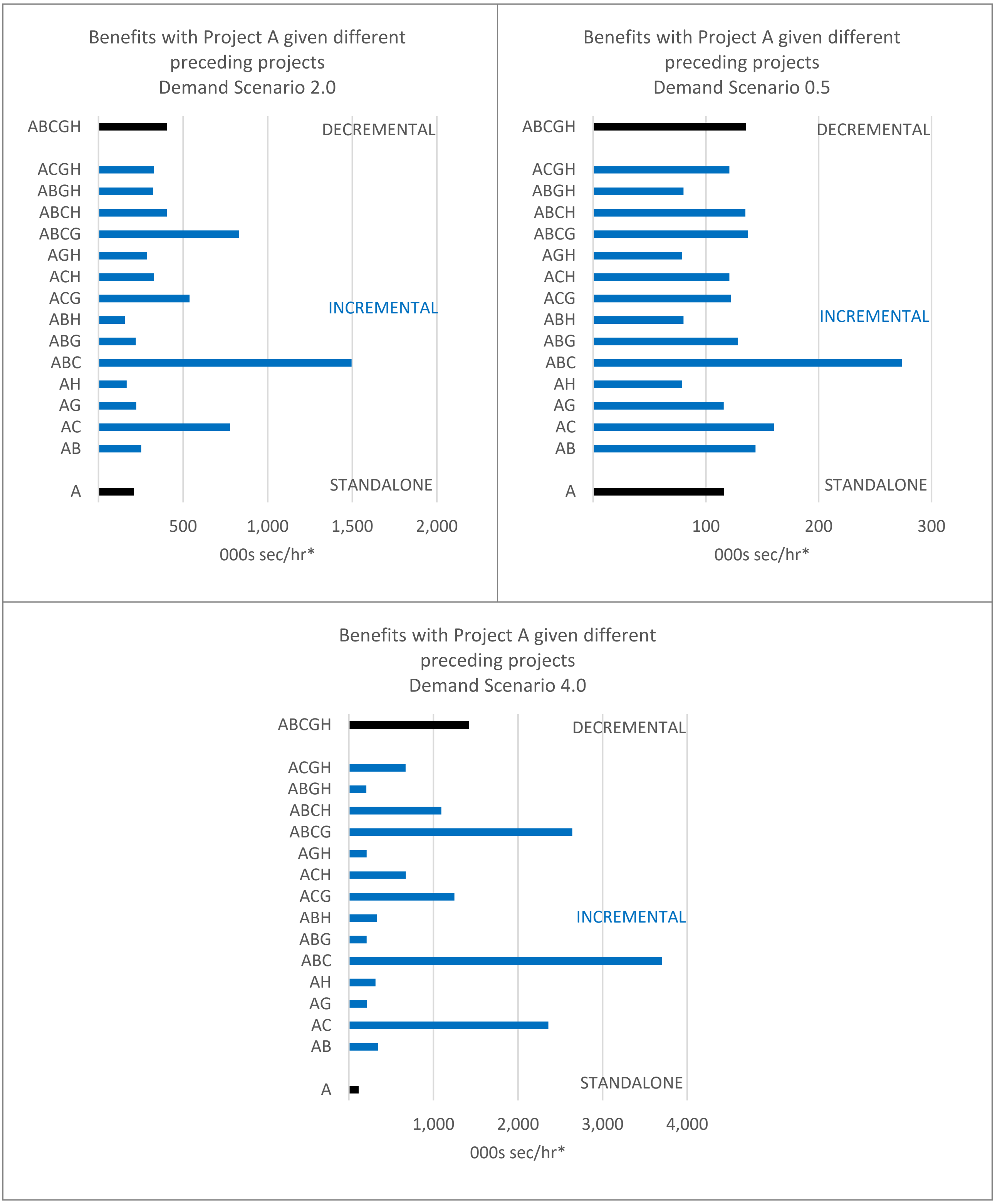


* 000s sec/hr = thousands of seconds of travel time savings per representative hour

The third measure of project benefit – the incremental benefit – differs depending on which projects are considered to precede the one being appraised (or at least have commitment). The order could be dictated by a rule such as rank projects by BCR or by construction priorities. At this stage we have no such rules for these projects, and in the sketch network we assume that they occur simultaneously with the project being appraised. An additional important property of the incremental benefits is that they are very useful to identify the projects or project combinations for which project interdependencies are most relevant (see Figure D.3).

As an example, we can see in Figure D.5 for Project A the various measures of benefit under Demand Scenario 2.0, plus the extreme Demand Scenarios 0.5 and 4.0. The first noticeable difference is the interdependency effects associated with Project A are relatively small in the no congestion situation (top right graph) but high (and variable) given congestion and re-routeing (bottom graph). However, this is not always the case – for example, Project C (not shown here) has strong interdependencies even at low congestion levels (due to re-routeing).

Figure D.5 Conditional benefits for Project A

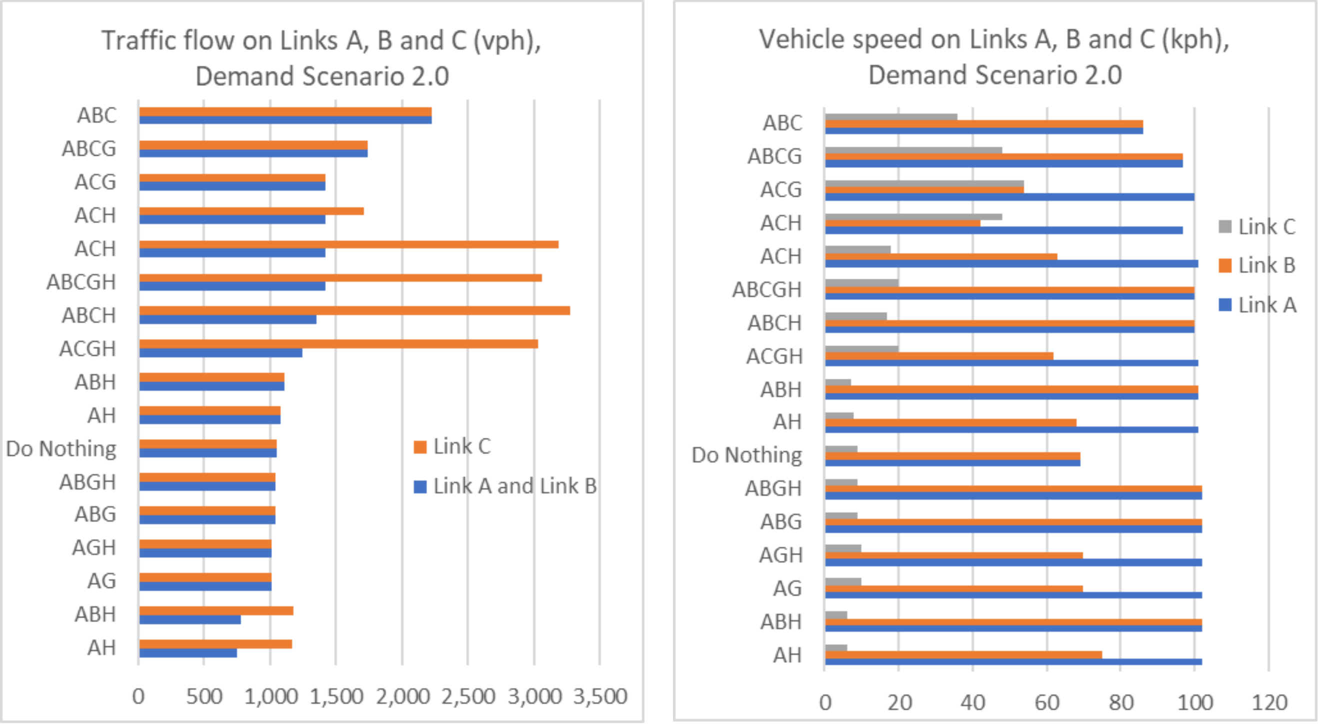


* 000s sec/hr = thousands of seconds of travel time savings per representative hour

Looking closer at Demand Scenario 2.0, the previously reported standalone (208,996 sec/hr) and decremental (404,538 sec/hr) benefit measures are shown. The incremental benefit measure depends on what projects are considered to precede Project A and ranges from 156,406 sec/hr (if A follows BH) to

1,495,781 sec/hr (if A follows BC). This is quite a substantial range. Even the pairwise incremental benefit measures are quite different. As can be seen, Project A's interdependencies are heavily dependent on whether Project C occurs (in a positive manner), but are eroded if Project H occurs. In fact, Project H can reduce Project A's benefit below the standalone benefit. What is happening in the network is that significant re-routeing occurs onto Links A, B and C (from the Y to Z movement) if Projects G and H are not constructed. This 're-routeing' benefit is then 'lost' when Projects G and H are constructed. In fact, for 6 project combinations with Project A, the traffic flows on the project are below those in the Do Nothing/Base scenario (see the lower part of Figure D.6, where the blue bar gives the traffic flow on Links A and B). We can also see from the same figure that in the main, Project A remains uncongested in the different scenarios (the blue bar in most project combinations is close to 100 kph), and it is network-related impacts on Links C and G – particularly the interaction with Project C and Project H – that determine the different network speeds (and thereby the different origin–destination journey times). Links C and G can be very congested – with link speeds below 10 kph in the Do Nothing/Base – and can be lowered further if Project H is implemented.

Figure D.6 Traffic flows and speed on Links A, B and C under Demand Scenario 2.0



The following notes reiterate and expand on key points arising from this section.

First, decremental and incremental benefit measures are key indicators of the level of project interdependencies that arise from a project.

- They help in identifying the key interactions of other projects with the project being appraised.
- The decremental benefit is of most interest when the programme is established and appraising whether the project adds value to that programme.

Second, graphical presentation of the benefits is easier to understand and build an understanding from than tabular presentation.

Third, to build up the full set of incremental benefits as presented in these graphs, it is required to model all project combinations (in this case 32 – with 5 different projects) and all demand scenarios of relevance.

D.3.2 Project benefits when other projects are uncertain

Often there is uncertainty as to whether other projects within the programme will be undertaken, especially when projects are phased and/or projects are undertaken by different parties. Uncertainty is also likely to exist when the interdependent projects do not sit within a programme.

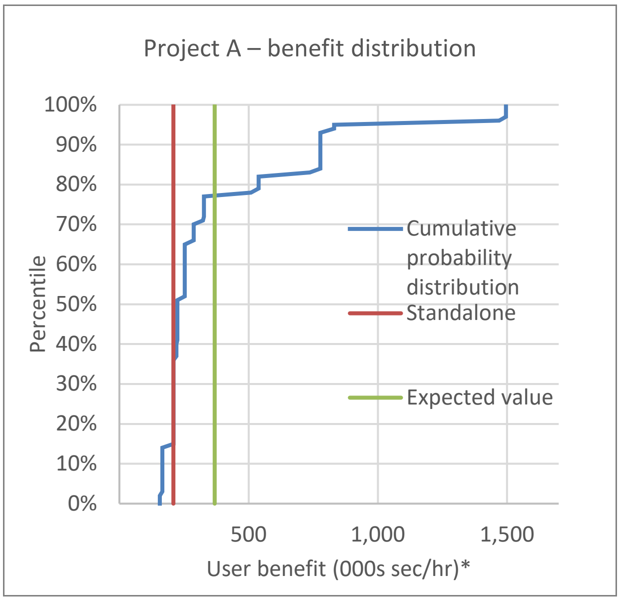
Uncertainty about other projects does not change the standalone benefit measure, but it does mean the incremental and decremental benefits are more complicated to measure.

Extending the Project A example from the previous sub-section, we can see from the earlier Figure D.5 how sensitive Project A's benefits are to project interdependencies. The interdependency benefits can be as large as 6 times the benefit of the standalone benefits. These maximum-level interdependency benefits are associated with the construction of Project C, and Project C's operation in an uncongested state. If C is not implemented or Project H is implemented (which congests Project C), then the interdependency benefits from Project A are much reduced. Clearly the likelihood of Projects C and H going ahead are quite material to the expected value of Project A.

One way to address uncertainty is to use the expected value when the probability of projects being undertaken is known. We will return at the end of this sub-section to the case when probabilities are unknown. The expected value when all projects are certain is the average incremental benefit to expect across all the permutations of ways that the five projects could be ordered. The probability-weighted average provides the expected value when each or any project has a probability between 0 and 1 of proceeding.

Consider, then, that each other project was to proceed with a known probability of, say, 0.3. The expected incremental value of Project A can be calculated by applying the standard probability-weighted formula to the values shown in Figure D.5, giving as answer in Demand Scenario 2.0 of 368,742 sec/hr. That is, even a small probability of other projects occurring can mean that the marginal benefit of Project A exceeds the standalone benefit (which remains 208,996 sec/hr). A full distribution of benefit outcomes – for Project A, Demand Scenario 2.0, and a 0.3 probability of other project delivery – is shown in Figure D.7. Here it can be seen that the median value is close to the standalone value for Project A, but that the expected value is close to the 75th centile of the distribution. That is, the expected value will only be achieved or exceeded on 25% of occasions. This information is clearly of interest to decision-makers, as it identifies the risky nature of the interdependency benefits. It stems from the sensitivity of Project A to the construction of Project C and potential competition with Project H.

Figure D.7 **Cumulative probability distribution of Project A's incremental benefit under Demand Scenario 2.0 if the probability of each other project being undertaken is 0.3**



* 000s sec/hr = thousands of seconds of travel time savings per representative hour

Whilst the chosen probability of 0.3 for the other projects was arbitrary, it is of interest to see how the distribution of incremental values changes with project probabilities. Key scenarios are discussed below and are summarised in Table D.16.

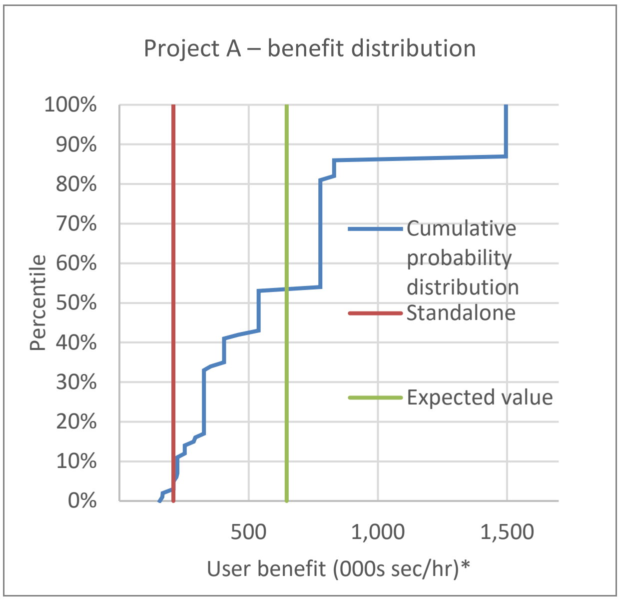
Table D.16 **Summary of expected Project A incremental benefit for other project probabilities (p)**

p(C)	p(G)	p(H)	p(Other)	Expected value (sec/hr)*
1.00	1.00	1.00	1.00	404,536
0.30	0.30	0.30	0.30	368,742
0.85	0.30	0.30	0.30	647,338
0.85	0.30	0.09	0.21	762,162

* seconds of travel time savings per representative hour

Consider next a scenario where Project C has a high degree of stakeholder commitment behind it – that is, whilst it is not firmly committed, it has been studied extensively, with engineering studies conducted, and it features on long-term programmes of regional development (eg, 10-year plans). In this case we may think that Project C will have a high likelihood of going ahead and attribute it, say, 0.85 probability (up from 0.3). The expected value of Project A's incremental benefit increases to 647,338 sec/hr and the probability distribution changes dramatically. The median value is now over 500,000 sec/hr and the expected value would occur or be exceeded on 45% of occasions.

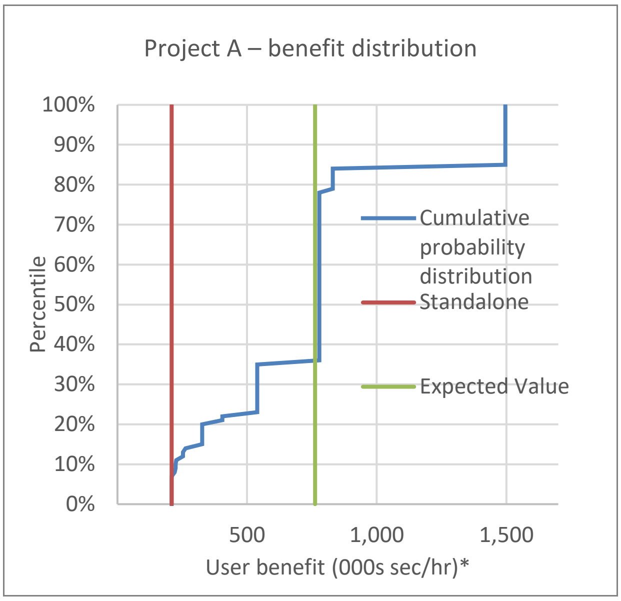
Figure D.8 **Cumulative probability distribution of Project A's incremental benefit under Demand Scenario 2.0 if the probability of each other project being undertaken is 0.3, aside from Project C, which is 0.85**



* 000s sec/hr = thousands of seconds of travel time savings per representative hour

We now extend this analysis further and consider that Projects G and H are mutually exclusive – that is, if one occurs then the other will not. There is a probability of 0.3, say, that either G or H will go ahead, but within that we place a probability that H will go ahead of 0.7 and G a probability of 0.3. This could reflect, for example, that Project H is easier to implement as it is a bypass and there are less physical constraints. The expected benefit has now increased to 762,162 sec/hr, which is more than three times the standalone benefits, with the median benefit of 777,920 sec/hr slightly higher. Figure D.9 illustrates the probability distribution. The expected value is now expected to be exceeded on 65% of occasions. Not only is the expected value higher than in the scenario depicted in Figure D.7, but the risk of ending up with lower value is much lower. This scenario therefore presents a completely different risk profile to the decision-maker, where project interdependencies are concerned. A risk-averse decision-maker may therefore be more likely to factor the opportunity to derive positive project interdependencies into their decision than in the previous examples. There still, of course, remains a substantial difference between the standalone value of Project A and the expected value of Project A, including its interdependencies, showing the value of project interdependencies to Project A. From an analytical perspective, there of course remains the substantial challenge of identifying probabilities for these scenarios.

Figure D.9 Cumulative probability distribution of Project A's incremental benefit under Demand Scenario 2.0 if Project C has a probability of 0.85 and Project G and H are mutually exclusive



* 000s sec/hr = thousands of seconds of travel time savings per representative hour

The following notes bring together and expand key points from this section.

- Expected incremental values provide a tool to measure expected project benefits when high variability in project interdependencies are combined with risk around commitment to a full programme.
- Complementary interdependency benefits do not seem to be orders of magnitude different – if you just look at a set of complementary schemes with no re-routeing.
- The re-routeing effects can generate massive project interdependencies, but then in combination with competing schemes the re-routeing effects can be so severe as to wipe them out.
- The expected incremental benefits can fall below standalone benefit when competing projects are present.
- Probability distributions are a useful way to combine many items of data and identify chances of achieving maximum benefits – our examples show how the chance of exceeding the expected value can vary quite dramatically.
- But there are two major problems with this approach:
  - First, these probabilities do not yet exist – research is needed to identify them – for example, how likely are projects to proceed if they are within a plan, or worked up but not yet approved, or only at concept level?
  - Second, a probability that another project proceeds is accompanied by a probability that it will not proceed. If under this 'not proceed' scenario the expected incremental NPV of the initial project will be negative, then decision-makers need to accept that this *will* happen sometimes (eg, 3 out of 20 times if the probability of proceeding is 0.85, or 14 out of 20 times if only 0.3). In other words, the distribution of outcomes, and in particular the probability of negative-NPV situations, will be very important to a risk-averse decision.
- These are reasons to be cautious when applying probability-weighted incremental benefits within a project CBA, including uncertainty about probabilities and the tolerance of occasional low outcomes, but the calculation does provide insight into risk and will naturally lead to consideration of risk mitigation,

including possibly seeking ways to put more value in the initial project so that it passes a BCR threshold on both a standalone basis and an expected incremental basis. Also, the information may lead to preference of the initial project over an alternative with a similar standalone BCR but which does not share the additional expected incremental interdependency benefits.

- It should also be kept in mind that ignoring the expected incremental interdependency benefits will eventually lead to a sub-optimal mix of projects and that alternative ways, such as discrete scenario analysis and expert judgement, to consider expected interdependency are also fraught with problems, especially when the permutations become large and complex, which this research project has shown can happen quickly.
- When looking at the expected value of a project from the project level, interdependency benefits may enhance or reduce the benefits vis-à-vis the standalone benefits. However, these interdependency benefits are contingent on other projects happening. As these are uncertain, it is likely that these projects will also be progressing through the governmental decision-making process. They too will have a claim on the interdependency benefits.
    - It might be better to focus efforts on quality assurance and determining the risks of whether project benefits might be eroded by building competing schemes – rather than looking for extra benefits due to programmatic complementary interdependencies (ie, if one thinks that 30% extra benefits is not worth the work – some may disagree). The difficulty is that ‘programmes’ – such as upgrades to route corridors, upgrades to single modes, etc – are often not set up without competing schemes so stakeholders are ‘institutionalised’ not to look for the competing schemes.
- Decision-makers require an appetite for risk (ie, willingness to accept low-value projects some of the time) to make investments that rely heavily on interdependencies with projects that are only probable, an appetite that is less likely to occur when projects are of a costly, one-off nature.

D.3.3 Project benefit when demand changes over time and costs are known

The previous analysis was undertaken within a static framework. That is, shifts occur along the demand curve as travel cost changed, but the demand curve itself does not shift. We now turn to a dynamic framework with a series of temporal demand curves, as would be expected to happen over a multi-year period such as the 40- or 60-year horizon of a Waka Kotahi CBA. Each model run was for a static scenario.

This change does not fundamentally alter the conclusions reached above but does provide the interim step required to undertake a CBA.

Once again, we are faced with having to make arbitrary decisions to apply to the sketch model. Given that the type of projects likely to be of relevance to this research project are in congested and fast-growing areas, we show results below for a demand curve that started at Demand Scenario 1.0, a point where the initial supply curve was steep, and with subsequent growth at 2% per annum – this has been termed the Core Growth Scenario. Demand curves between each modelled demand scenario were calculated by linear extrapolation. It is worth recalling that the demand growth is at a fixed cost on each demand curve whereas the costs and volumes actually occurring (in the model) result from movements along each demand curve to find the travel cost and volume that intersects with the project scenario supply curves (which also differ by section). Thus, the actual travel growth occurring in total and on each road section can be very different to the 2% underlying assumption.

Standard MBCM values were applied to calculate the present value of the 32 project permutations. Summary statistics are shown in the left side of Figure D.10 (a variation of Figure D.4) showing the standalone and decremental benefits, plus the percentage of the total programme benefits that are attributable to interdependencies associated with each project. Not surprisingly, the results again show A, B, and C as complementary, with C having the largest interdependency effect (being part of project combinations that provide interdependencies that amount to 16% of the total programme benefits), and G as competing. H has little interdependency benefits and small standalone benefits as well.

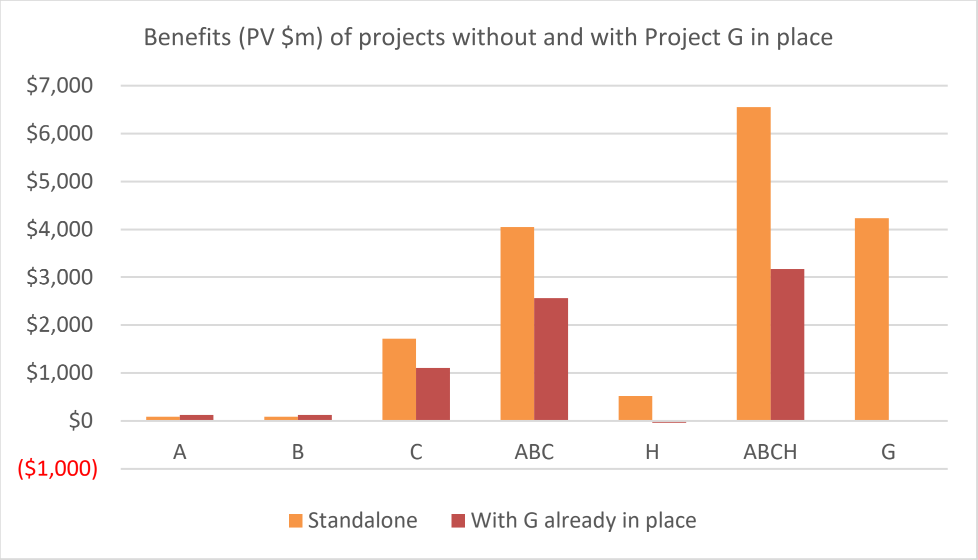
While the starting demand and growth rates are arbitrary here, in an analysis of real projects and networks it is likely that these graphs will be an important summary of the benefit analysis.

Figure D.10 Standalone and decremental benefits of projects ($m and BCR), project interdependencies net of standalone benefits as percentage of programme benefits, and range of incremental BCRs

Note: PI = project interdependency; lhs = left-hand side; rhs = right-hand side

An illustration of how incremental benefit measures differed is further shown in Figure D.11, where the standalone benefit for each project is compared to the incremental benefit of each other project in the presence of Project G.

Figure D.11 Standalone benefits and incremental benefits with Project G, for Core Growth Scenario



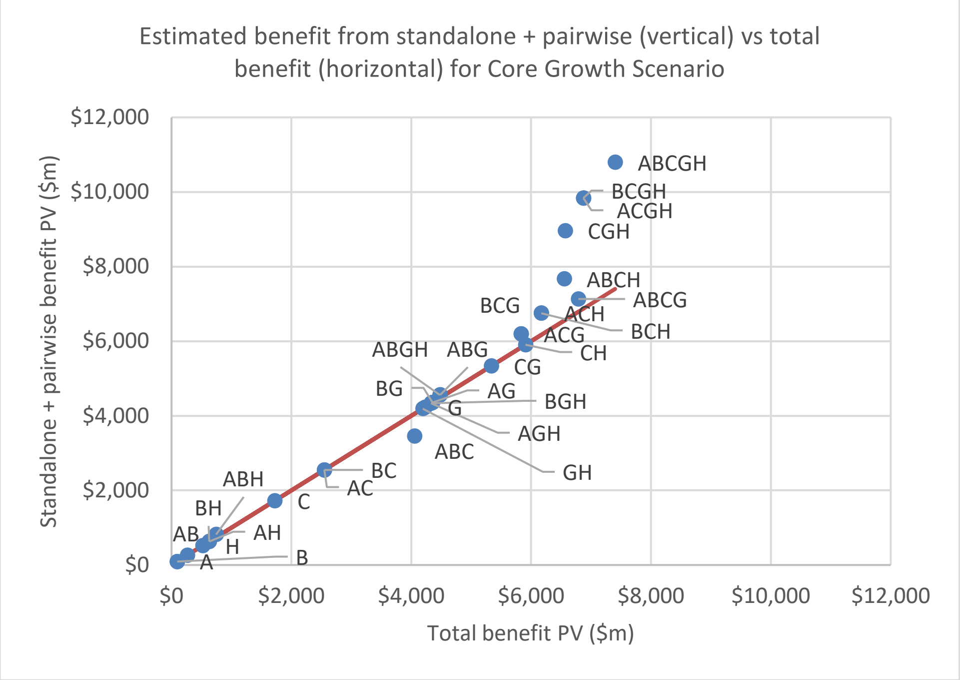
The next step in the benefit analysis is to compare benefits with costs. This requires cost assumptions for each project. Clearly this is arbitrary for the sketch model, but we are typically interested in projects that have a low standalone BCR that are judged to have interdependencies. On this basis, the costs were set for each project assuming a BCR of 1.0 as at the Core Growth Scenario above, this being a starting point where the Base Case supply curve was very steep (see Figure D.2), with the exception of Project G, which was given a BCR of 2.5 at this point, primarily to bring the cost into line with Project C and also to force Project G into at least one of the optimal portfolios (see next section).

Applying these assumptions to the Core Growth Scenario demand profile over 60 years leads to the range of BCRs in Figure D.10. The standalone BCRs are as assumed. The decremental BCRs confirm the value to the programme of A, B and C – in particular, C's BCR increasing from 1.0 to 1.7 in recognition of the interdependency benefits it delivers. Conversely, the decremental BCR for Project G declines to 0.5 from the 2.5 standalone BCR, consistent in this case with the negative interdependency benefits it delivers. The BCR for Project H is similar whether measured by the standalone or decremental method.

The incremental BCRs show a wide range, which serves as a warning if choosing to use only one incremental BCR. The effects were largest for the lower cost Projects A, B and H, which benefitted from interdependencies with Project C, further pointing to Project C as an enabler project.

A further graph to reinforce an earlier point is given below. Figure D.12 considers the situation when only partial modelling information is available and instead the benefit of a mix of projects is calculated as the standalone plus pairwise benefits – that is, the higher-order benefits are assumed to be zero. The vertical axis shows the estimate thus derived while the horizontal axis shows the total benefit for the project mix, known in this case because a full permutation of model runs was made. Clearly relying on single and pairwise estimates when calculating the benefit of a mix of projects can be inaccurate. In the sketch model, this inaccuracy was largest when congestion and re-routeing were combined, as in programmes that contained Projects C, G and H at moderate demand levels (and was also the case at high demand).

Figure D.12 Combined project benefit estimated using standalone and pairwise benefits only versus actual



D.4 Optimal programme

The above section focused on a measure of benefit for an individual project. This naturally leads to thinking in terms of whether all projects within the programme are actually required. This section considers selection of the optimal project mix, again using the projects modelled under Scenario All and the assumptions built up under the Core Growth Scenario to illustrate the issues.

Two methods were used to find the optimal portfolio:

a. Maximise the portfolio NPV subject to the portfolio cost being within budget and to the decremental BCR for each project component being above 1.0.

b. Maximise the portfolio NPV where the chosen project combination has to be within budget and perform as well or better than the marginal project in the government investment programme (across all government sectors).[53]

Mostly the two methods reached the same optimal portfolio, but not always. The difference between the methods is likely due to the manner in which the constraints on the NPV maximisation are applied, but this will be considered in more detail within a later phase of this research project. It should be further noted that the optimal portfolio in both methods differs when the BCR threshold is raised. The results for optimisation method (a) are reported below, including the mix of projects that make up each optimal programme and the costs and benefits associated with each optimal mix (Table D.17 and Figure D.13). The project mix derived from optimisation method (b) is shown in Table D.18.

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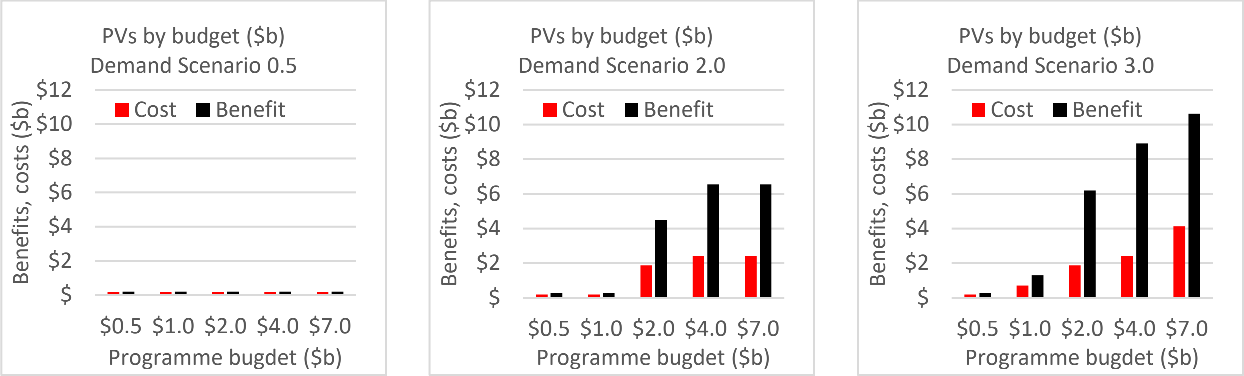
[53] This is implemented by taking the set of project combinations that lie within the budget and then using the incremental BCR methodology set out in the MBCM.

Table D.17 Optimal programmes by starting-year demand scenario and budget ($m), with decremental BCR threshold of 1 and benefits fully calculated

Budget ($m)	Demand scenario		
	0.5	2.0	3.0
$500	AB	AB	AB
$1,000	AB	AB	ABH
$2,000	AB	ABG	ABG
$4,000	AB	ABCH	ABCH
$7,000	AB	ABCH	ABCGH

Figure D.13 Optimal programme total costs and benefits ($b), by starting-year demand scenario and budget



Keeping in mind that many assumptions have led to this point for the sketch model, the optimal portfolio selection does bring out several points worthy of note.

- A small budget severely constrains options and may render the need for a large number of model permutations unnecessary.
- That said, demand will typically increase in many of the situations of interest and even at (relatively) low budgets ($1 billion) the optimal mix can change over time – in this case once the network moves from a starting point of Demand Scenario 2.0 to Demand Scenario 3.0, taking around 36 years at 2% per annum, it would be optimal to add Project H to the programme, with shorter intervals at higher levels of demand.
- Furthermore, with more budget, also likely over time, even more value-add was possible with this sketch network by including Projects C and H if the starting Demand Scenario was 2.0 and with even more budget eventually Project G as well. The final programme shown above has a BCR of 2.6, such is the level of interdependency present.
- An interesting dynamic is that a mid-level budget ($2 billion) would bring Project G into the portfolio instead of Projects C and H. As stated above, this situation is contrived but it is included to illustrate that the portfolio mix is dependent on costs and budget, as well as benefits, and that the optimal mix can and will differ given different contexts. This would point towards programme-level analysis to ensure that optimal packages are designed for the long term – in this case we would not wish to construct Project G to then have to remove it to obtain the optimal project mix at a later point in time.

In sum, Project C was assumed to be costly but enabled large benefits, more so when Projects A, B and/or H are also undertaken. Projects A and B on their own were unlikely to be undertaken, but considered together they added value and were of significant value in the presence of C. Project G appeared to offer value, but this was often diminished when considered alongside other projects and was not optimal long term (assuming more demand and more budget). Project H was generally of marginal value only.

Of particular interest to this research project is: Could these (contrived) optimal portfolios be derived without the full set of model runs, 160 in this case?

Table D.18 shows the optimal programme should all interdependency benefits higher than pairwise be assumed to be zero, thereby reducing the number of model runs in this case to 16. The results at a glance are similar to Table D.17, with the few additional projects highlighted. However, a lack of understanding of higher-order interdependencies in this case would have led to early adoption of Project H (at an assumed cost of $0.5 billion), which was in fact of marginal value, generally having a fully informed decremental BCR near 1. Similarly, incomplete information would have led to Project G (cost $1.7 billion) being included at congestion levels that were too low to justify the immediate investment. In other words, over-investment in projects that undermine other projects would have occurred if benefit assessment was constrained to standalone and pairwise measurement only.

Table D.18 Optimal programmes by starting-year demand scenario and budget ($m), with decremental BCR threshold of 1 and benefits estimated with standalone and pairwise benefits only – differences to Table D.17 highlighted

Budget ($m)	Demand scenario		
	0.5	2.0	3.0
$500	AB	AB	AB
$1,000	ABH	ABH	ABH
$2,000	ABG	ABG	ABG
$4,000	ABCH	ABCH	ABCH
$7,000	ABCGH	ABCGH	ABCGH

Otherwise, Projects A and B would be unlikely to proceed if considered alone, but a pairwise assessment with each other or C would likely tip the scales to go. Interestingly, Project AB has a BCR of 1.4 and may not have relied on having incremental BCRs with Project C of 16 to provide the go-ahead, but decision-makers would likely be more inclined towards Project AB knowing there was a high but not certain prospect of C. This would more likely be the case if decision-makers were also aware that, given strong growth, C would eventually add significant value.

D.5 Other benefits

We turn now to benefits other than time or travel cost savings. We would expect interdependencies via agglomeration and those that are closely related to changes in VKT to differ from those of time savings. For agglomeration, this is due to the non-linear nature of the access to economic mass function, and the fact that function is dependent on accessibility between zones and employment in a zone, whilst time savings are dependent on accessibility between zones and zonal travel demands. For impacts heavily correlated with VKT (such as noise, safety and carbon) they will vary from time savings due to re-routeing effects – a bypass will increase VKT (and carbon) but give rise to time savings.

D.5.1 Agglomeration interdependencies

We have therefore calculated agglomeration interdependencies for each of the project and demand scenarios in the sketch network – this gives rise to 130 different scenarios. The scale of the agglomeration benefits varies by scenario – both network and demand scenarios. The key points that arise from this analysis are as follows.

Agglomeration interdependencies are context dependent. They depend on accessibility changes (changes in travel time) and also the size of the zones. If zone sizes differ between scenarios, the agglomeration interdependencies also differ. For example, 1,000 employed in each zone gives a different interdependency outcome from one where employment is concentrated in Zone Y.

There is a similarity between direction and size (as a percentage of standalone benefits) of agglomeration interdependencies and time saving interdependencies, but also significant differences. We note this because:

- We see a strong correlation between time saving benefit interdependencies and agglomeration interdependencies (once extreme outliers are excluded). That is, if time saving interdependencies are positive, then agglomeration interdependencies are also likely to be positive. Correlation coefficients are between 0.8 and 0.9 (with outliers excluded).
- This correlation, however, disguises significant variation.
  - For a significant number of scenarios, the timing saving and agglomeration interdependencies can be of the opposite sign (26 out of 130).
  - The percentage increase in benefits arising from interdependencies appears to be generally higher for agglomeration benefits than for time savings. Numerically, the agglomeration interdependencies are 60% larger (*ceteris paribus*) than the time saving interdependencies with all zones having an equal employment level.[54] With employment concentrated in Zone Y,[55] this reduces to 20% on average (excluding outliers).

The similarities between the time saving interdependencies and the agglomeration interdependencies stem from the common link in interzonal accessibility, whilst their differences stem from the fact that time savings are also dependent on changes in demand (primarily induced and re-routeing traffic), whilst agglomeration interdependencies are also dependent on employment levels in each zone.

The graphs in Figure D.14 below show the interrelationship between time saving interdependency benefits and agglomeration interdependency benefits for the sketch model. Due to the outlier nature of some changes (eg, Project H in Demand Scenario 1.0, which arises due to Braess’s paradox), the left-hand graph excludes all interdependency benefits greater than 100% of the standalone benefits whilst the right-hand graph includes all outliers.

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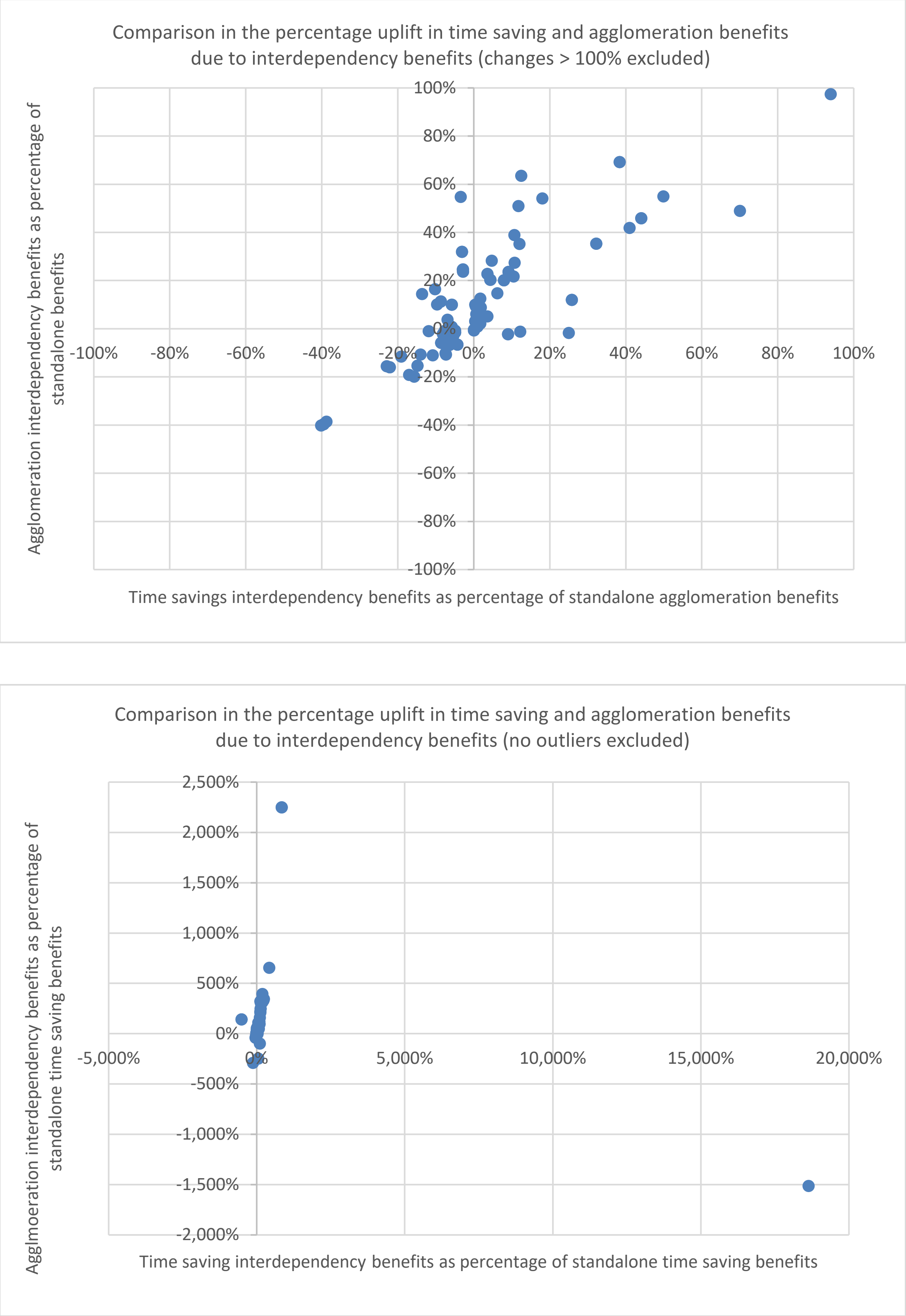
[54] Zones X, Y and Z each have 1,000 workers.

[55] Zone X has 300 workers, Zone Y has 2,000 workers, and Zone Z has 700 workers.

Figure D.14 Agglomeration interdependency benefits versus time saving interdependency benefits for sketch model runs



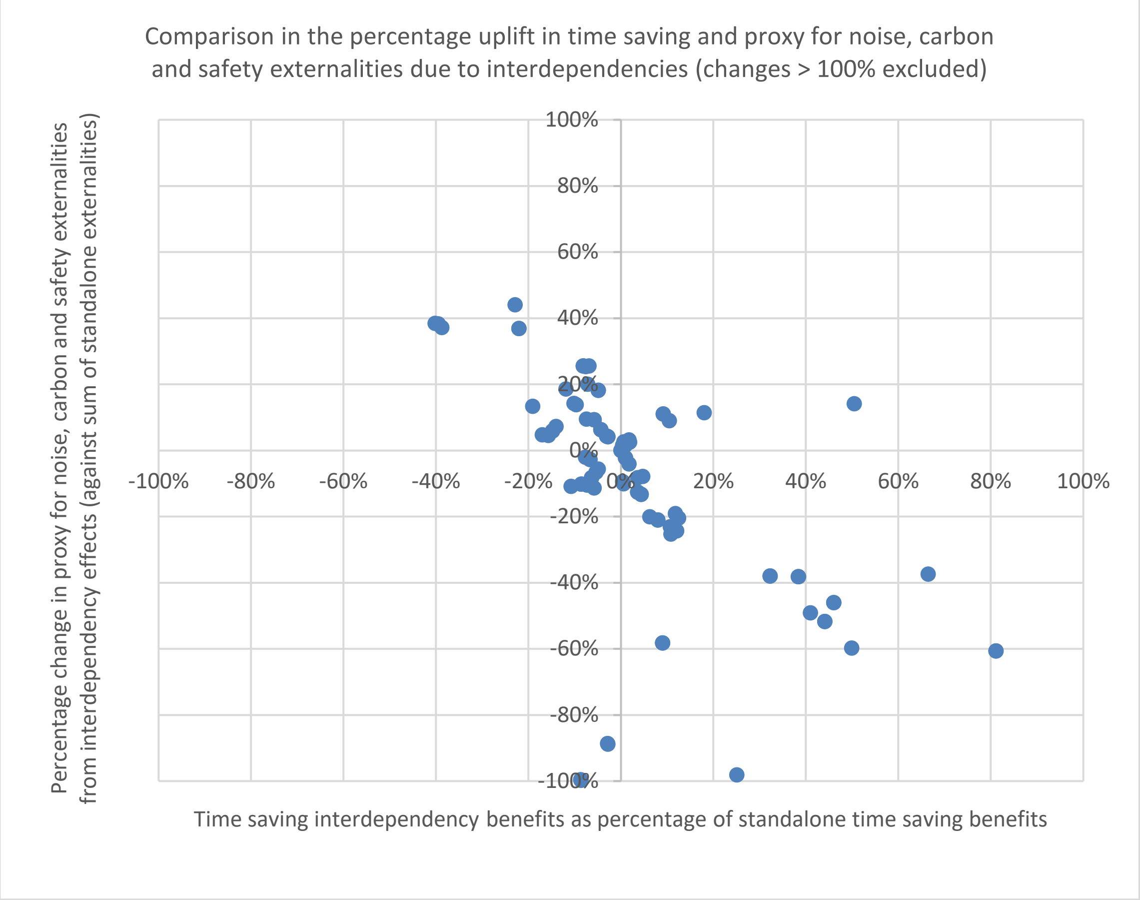
D.5.2 Safety, noise and carbon interdependencies

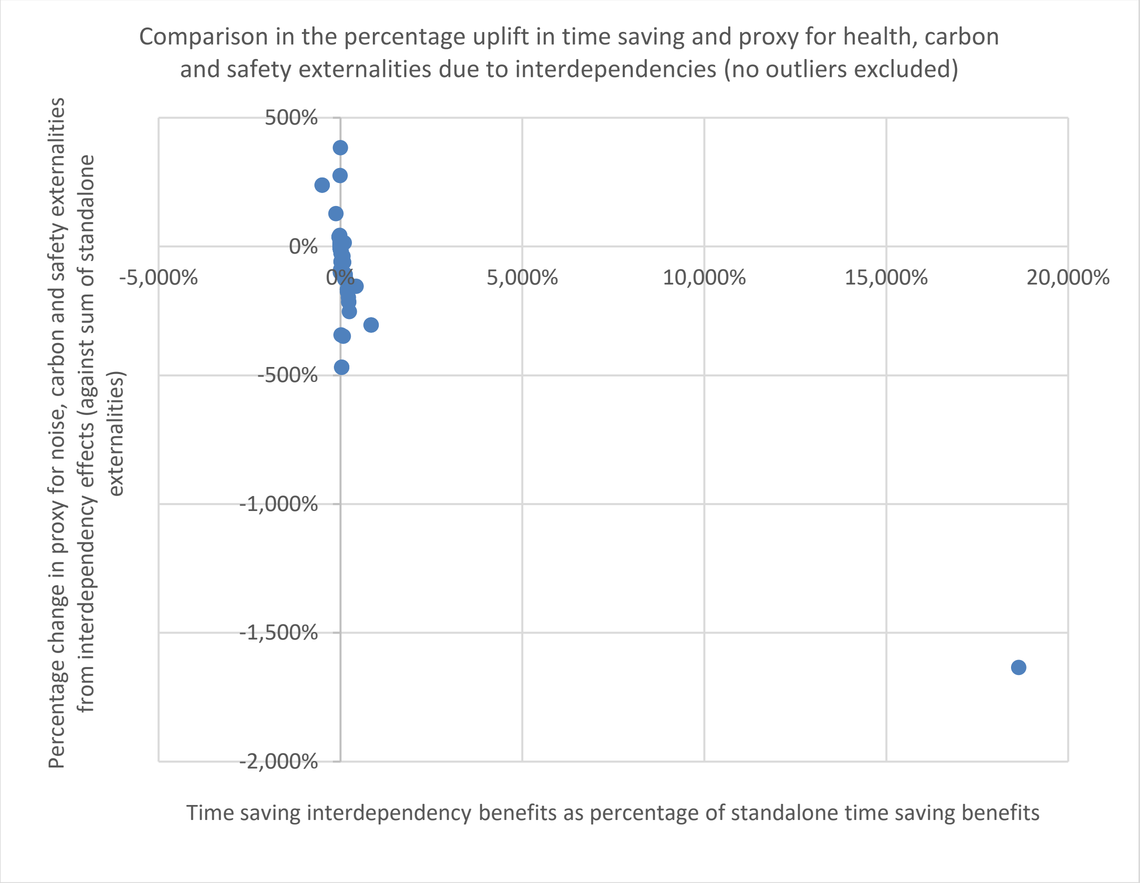
VKT were used as a proxy for safety, noise and carbon interdependencies. A similar analysis was undertaken in how the interdependency benefits varied in relation to time saving interdependencies. Similar graphics are presented in Figure D.15 below. Two things are to note:

- The graph slopes in an opposite direction. That is, larger time savings are typically associated with more negative impacts on noise, safety and carbon. This arises because lower travel costs induce more traffic. The greater the time saving, the larger the level of induced traffic and the larger these negative impacts.
- The level of correlation is also much lower, with a much larger spread. The correlation coefficient is correspondingly much lower at 0.55 (for the whole dataset).

Once again, we see projects that are complementary in time savings competing in noise, safety and environmental externalities and vice versa. We find in our data that this comprises just under a quarter of our data. It can also vary within projects. As we are using VKT as a proxy for these external costs, the variation between time saving interdependencies and these benefits stems from the non-linear nature of the demand function giving rise to induced traffic, and strong re-routeing effects as traffic from Z switches routes depending on congestion levels and projects implemented.

Figure D.15 VKT-related interdependency benefits versus time saving interdependency benefits for sketch model runs





D.5.3 Conclusion

The key policy conclusion from this sub-section is that if agglomeration, noise, carbon and safety benefits are relevant to the appraisal, then the interdependency analysis needs to explicitly consider these benefit categories. Scaling time saving interdependency benefits up or down will potentially lead to biases.

References for Appendix D

Quality Transport Planning (QTP), & Sinclair Knight Merz (SKM). (2010). *Christchurch Assignment and Simulation Traffic (CAST) model. Technical note 1: Speed-Flow relationships* [Unpublished document].

Steinberg, R., & Zangwill, W. I. (1983). The prevalence of Braess' paradox. *Transportation Science*, *17*(3), 301–318.

Venables, A. J. (1999). Road transport improvements and network congestion. *Journal of Transport Economics and Policy*, *33*(3), 319–328.

Appendix E: Checklist to apply before analysing project interdependency

An important early step in analysing project interdependency is to identify those projects, both inside and outside of a programme, which will potentially affect the benefits to be realised from the candidate projects being analysed. This applies to transport projects that might increase or decrease the benefits of the candidate project(s), but competing projects can be easy to overlook, so a checklist approach to identification is recommended as a means to ensure good coverage.

E.1 Questions to ask

Do the sources below indicate:

1. which projects sitting within current long-term plans (10-year or 30-year) are likely to *increase* the benefit of the project being assessed (ie, complementary projects)
2. which projects sitting within current long-term plans (10-year or 30-year) are likely to *decrease* the benefit of the project being assessed (ie, competing projects)?

To be clear, interdependent projects may be other projects for the same transport mode, other projects using another single mode and other projects that are multi-modal. Also, projects may sit within or outside a programme that contains the project being assessed.

Potential sources include:

- the interdependency table that should (may) be within the strategic case for the projects of interest
- regional and national land transport plans
- nearby transport projects being actively considered that are not yet in land transport plans
- similar projects from other parts of the country[56] or world
- sketch modelling that may have been undertaken.

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[56] which could be shown in a set of examples accumulated over time by Waka Kotahi

Appendix F: Alternative case study model phasing

The case study explored different phasing of model runs and also considered whether the phasing, and the presentation of results, was sensitive to a stronger 3-way interdependency then was shown in the case study. Details on this part of the case study analysis are provided in this appendix.

F.1 Case study model phasing using the pairwise rule

The case study involved five groupings of projects – Groups A, P and U – within the Major Cycle Routes (MCR) programme and X and R sitting outside the programme. Potentially this creates 32 permutations (ie, scenarios). Applying the pairwise rule would require the modelling of 16 of these scenarios for each demand period, leaving 16 scenarios not modelled and implicitly assuming that all remaining interdependency terms equalled zero. This later assumption can be tested by running a scenario for all projects and then testing whether the benefits from all projects are indeed approximated by the sum of the standalone and pairwise effects. Depending on whether this decremental test was undertaken, the reduction in scenario modelling would be 15–16 scenarios (times the number of demand periods). The breakdown of scenarios to model and not model is shown in Table F.1 for groupings of 5 and 4 projects.

The amount of modelling with 4-stage models of 16 standalone and pairwise scenarios was considered beyond the resources of this research project. The pragmatic solution was to first test whether the external road projects (R) showed any material interdependency with the cycle projects by testing whether the initial incremental benefit of R differed materially from the decremental test of R. The interdependency of R with the cycle projects was low, so the numbers of standalone and pairwise scenarios were reduced to 4 and 6. These were then modelled, effectively reducing the programme to analysis of the cycle projects only.

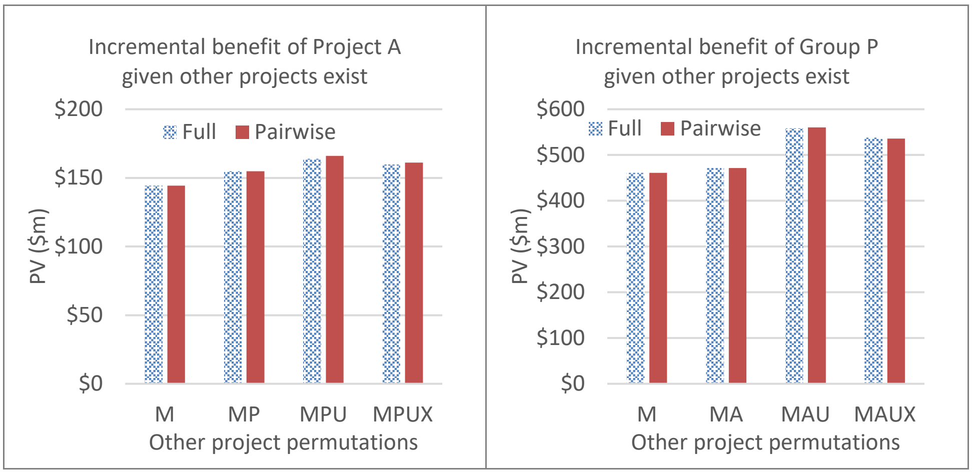
Table F.1 Number of scenarios to model with pairwise rule

	5 projects		4 projects		5 projects with initial test of R project	
1. Do Minimum	1		1		1	
2. Initial standalone and decremental test	Not applicable		Not applicable		3 (note, this is not a strict pairwise test)	
If initial test shows R interdependency to be…					Not weak	Weak
3. Standalone benefits	5		4		4	4
4. Pairwise interdependency benefits	10		6		10	6
5. If decremental test also applied	0	1	0	1	Applied in (2)	Applied in (2)
Total scenarios modelled	16	17	11	12	18	14
Scenarios not modelled	16	15	5	4	14	18

If the pairwise rule had been applied in this case study, without the decremental test, then the results would have approximated closely the results from the full analysis above. In other words, the extent of interdependence beyond pairwise was relatively small. That will not always be the case. It holds in this case because sensitivity by cyclists to distance means re-routeing between parallel cycle routes is limited and the cycle routes are not themselves modelled as congestible. More generally, when interdependence is higher, there is assurance in testing the magnitude of the remaining interdependence beyond pairwise with a full programme decremental test. In this case, the difference between the modelled results of APUX and the estimate derived from effects modelled for Groups A, P, U, X, AP, AU, AX, PU, PX and UX was $4.6 million or 0.5% of the fully modelled programme benefit, confirming the low level of higher-order interdependence and justifying the assumption that interdependence was zero beyond pairwise. As said, this test may not always justify the assumption, plus care must be taken if any potentially offsetting interdependence was suspected.

Looking closer at the results for each project group, the estimates derived using the pairwise rule for incremental benefits for A and P were similar to those derived from the full modelling set (full results are shown in Figure F.1 as blue columns while the pairwise-derived approximations are shown in red).

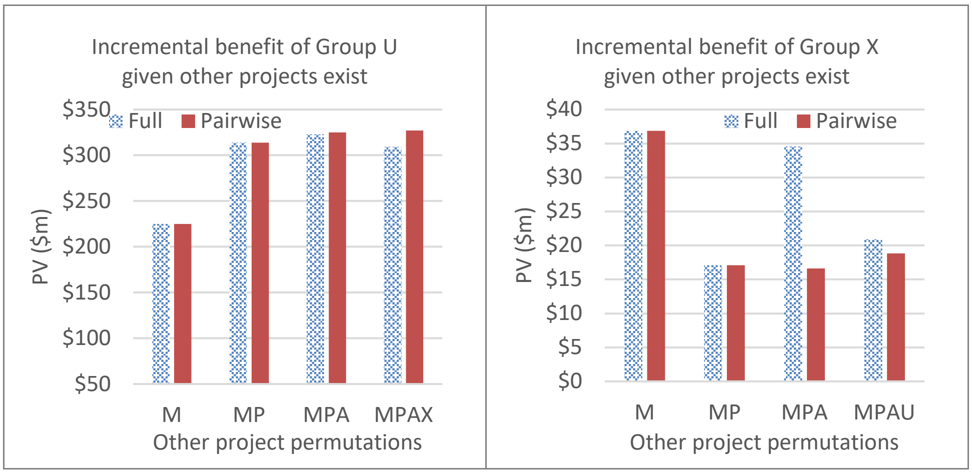
Figure F.1 Present value of benefits ($m) for Project A and Group P derived using the pairwise rule



Likewise, the estimates for incremental benefits for U were similar to those derived from the full modelling set (left of Figure F.2). The decremental BCR was overstated with the pairwise rule, but the difference was small.

The pairwise rule would have led to the understatement of the MPA scenario if appraising Project X (right of Figure F.2). However, while these benefits are relatively large compared to the benefits of X, these interdependency effects are relatively small compared to the benefits of A and hence were immaterial to any decision about A (our primary focus).

Figure F.2 Present value of benefits ($m) for Groups U and X derived using the pairwise rule



Brought together as incremental BCRs, the standalone and ‘Very likely’ BCRs are fully provided by the pairwise rule, and the estimated ‘Extended Programme Decremental’ benefit was marginally higher at 5.8 (Table F.2) instead of 5.7.

Not surprising in view of the slight difference in benefit estimates, the optimal project mix remains the same, as in Table 5.7, when benefits are estimated using the pairwise rule in this case.

Table F.2 Benefit of Project A to report, derived using the pairwise rule

Benefit title*	PV of benefits ($m) – full modelling	PV of benefits ($m) – pairwise	BCR – pairwise
Standalone benefit	$144	$144	5.2
‘Very likely’ benefit	$155	$155	5.6
Decremental benefit	$160	$161	5.8
PV of costs	$28	$28	

F.2 Case study model phasing using the selective tests

Applying forethought as to which scenarios were required to measure the benefit of Project A gave rise to the following sequence of testing (Table F.3).

Table F.3 Selective phasing of scenarios to be modelled

Run	Scenarios	Comment	Decision to make
1	M	The standard DoMin	M used to denote DoMin network.
2	MA	Gives **standalone** for A (BCR_{stand}) [ie, MA–M]	Test standalone. If standalone is high, then you may only need to check whether competing projects exist.
3 4 5	MR MPXUA MPXUAR	Gives 2 incrementals for R [MR–M] and [MPXUAR–MPXUA]	Test need for R. If the two incrementals are similar then no interdependency exists with road project. Therefore drop R from further runs (or leave with DoMin).
6	MPXU	Gives **adjusted decremental** for A (BCR_{decrem}) [MPXUA–MPXU]	Test extent of interdependency with A. Assume R dropped (in above step). ‘Adjusted decremental’ signifies X is appended to programme. The Decremental minus Standalone benefit measures the total interdependency effect; if small then no need for further runs unless more precision required.
7 8	MPA MP	Gives **incremental** for A (BCR_{likely}) [MPA–MP]	Test if more/less benefit with probable projects. This gives a more accurate incremental than the standalone. Decremental minus Incremental benefit measures the interdependency due to UX; if large then you may wish to drill down further.
9 10	MPGA MPG	Gives interdependency effect of A and G (if required) [MPGA–MP] gives GA And [MPG–MP] gives G and hence GA-A-G	Sub-project G, say, chosen from **sketch model** and judgement that it is the most likely sub-project within UX that is interdependent. It may be that G=X. If unexplained UX effect still large then repeat for H, I, J… as necessary.
11 12	MU MX	Complete **standalone** for other project groups (if required) [MP–M], [MU–M], [MX–M]	

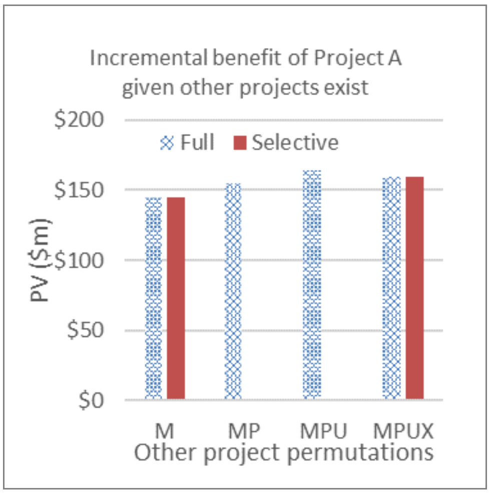
The results as they would have emerged via the phased modelling are now discussed.

After 6 scenarios (Figure F.3):

- We find whether the external road projects (R) were independent with the cycle projects – they were not material (except for minor effects and keeping in mind interdependency could still occur for specific cycle sections within the project groups).
- We find whether A shows interdependency with the other cycle projects – it did, showing a slight net complementary effect, but at this stage it is unknown which projects are causing this effect and also if any are competing.
- We find the net benefit of the other cycle projects – in this case P, X and U – have a combined benefit of $800 million, but we do not know the breakdown of benefits by P, X and U.

This may be sufficient information, in which case no further modelling is required.

Figure F.3 Present value of benefits ($m) for Project A using the selective rule – after 6 scenarios

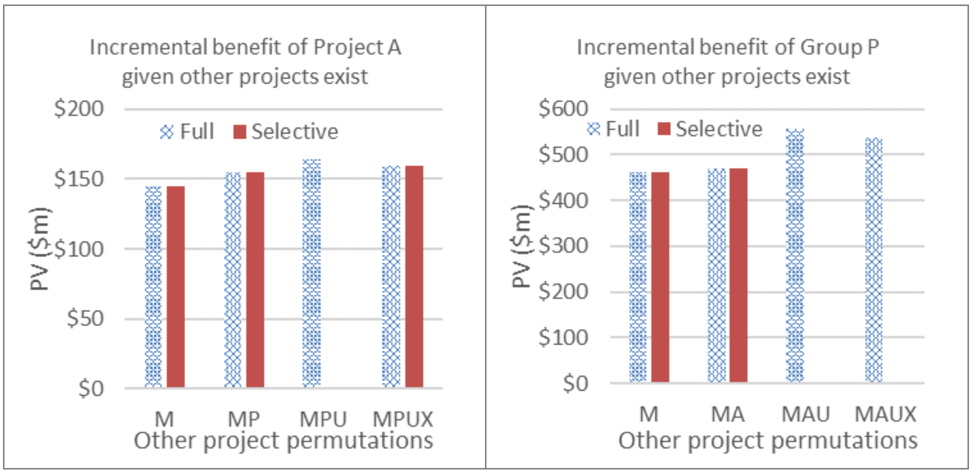


After 8 scenarios (Figure F.4):

- We deconstruct the interdependency effect of A into that due to Group P and that due to the other cycle projects – in this case we find P and A are complementary and combined X and U are also complementary with A, but there still exists the possibility that X may be competing with A (offset by complementary effects of U).
- We now know the standalone effect of P – which was $471 million, leaving $329 million extra benefit when X and U are added to the full cycle programme.
- We still do not know the breakdown of benefits by X and U (and the interdependencies).

This may be sufficient information, in which case no further modelling is required.

Figure F.4 Present value of benefits ($m) for Project A and Group P using the selective rule – after 8 scenarios

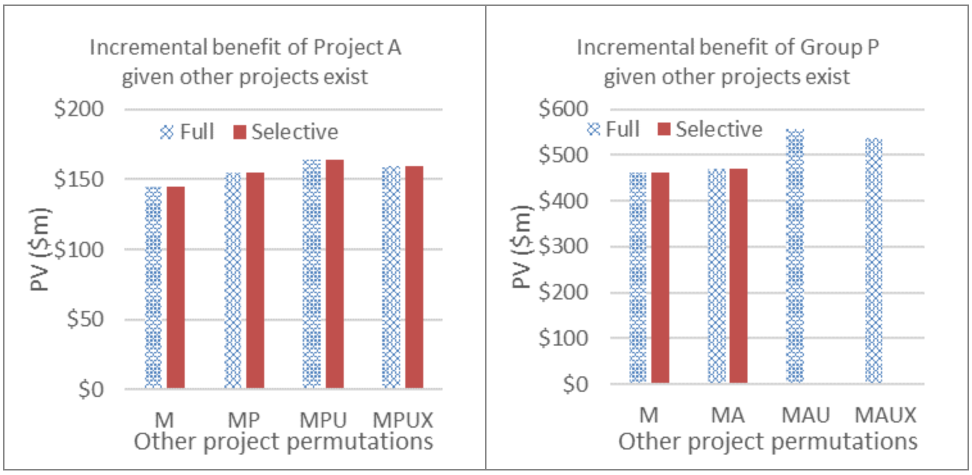


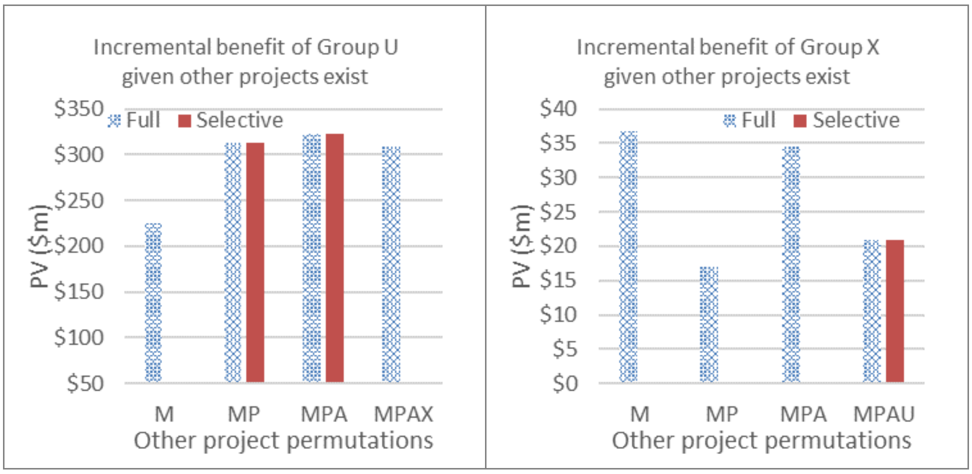
After 10 scenarios (Figure F.5):

- We now have the full set of benefit measures for Project A, including the deconstruction of the interdependency effect of A with X and U – it turns out that X, expected to be competing, is complementary to A and so also is U.
- We know no more about P.
- We now know that U provides $309 million of the full cycle programme benefit – we also know from above that P provides $491 million as a standalone benefit but the decremental benefit of P may be more or less when X is added to P, A and U.
- We do know that the benefit of X is $35 million with P and A in place, but the decremental benefit of X may be more or less when U is added to P, A and X.

This may be sufficient information, in which case no further modelling is required.

Figure F.5 Present value of benefits ($m) for Project A and Groups P, U and X using the selective rule – after 10 scenarios



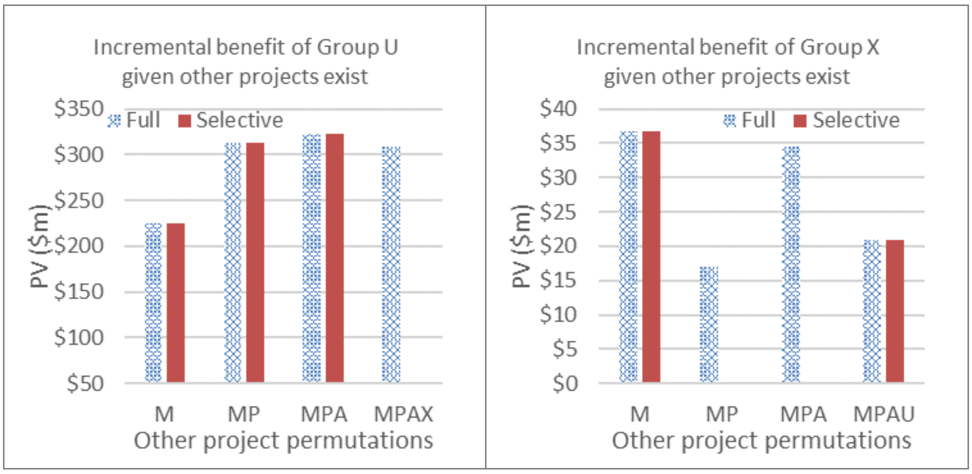


After 12 scenarios (Figure F.6):

- We know no more about A and P.
- We now have the standalone benefits for U and X.
- We know that the benefit of X is $35 million with P and A in place but the decremental benefit of X may be more or less when U is added to P, A and X.

The extent of further modelling is likely to vary considerably by situation. In many cases, no further modelling would be required. One further run (MAXU) would reveal the decremental benefit of P, if that was of importance. More likely, interest would turn to U and the use of value engineering to the projects and sub-projects that make up this group.

Figure F.6 Present value of benefits ($m) for Groups U and X using the selective rule – after 12 scenarios



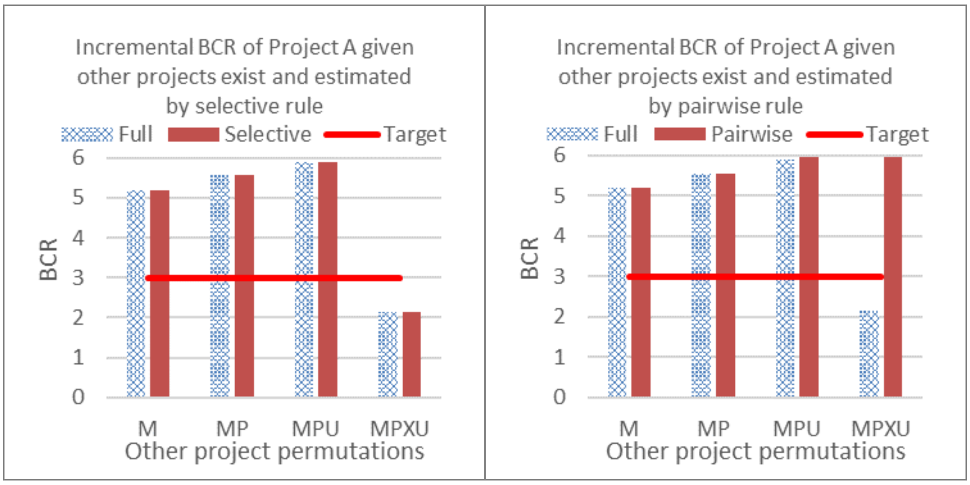
F.3 What if A and X compete only when U exists?

Of interest was to explore how the above results might differ if a stronger 3-way interdependency had been present in the case study.

The results of the full set of scenario modelling were taken and $100 million present value of benefits was added to scenarios where UX exists without A. This is equivalent to assuming the mix of cyclists on the ‘competing’ A and X routes changed from around 85:15 A:X to 35:65 when U exists, a substantial amount of re-routeing. The present value cost of X was increased by $30 million to be similar to A.

The hypothetical BCR results for Project A are shown in Figure F.7 below. The competing effect of A and X in the presence of U shows as a low programme decremental benefit for A, the benefit in effect having been re-routed to X. If the modelling has followed the 'selective approach', and putting aside the initial R projects, then the correct BCRs for A would have been delivered after 8 scenarios, and the existence of a strong competing interdependency would have been evident after 4 scenarios. If instead the modelling followed the 'pairwise rule' of 11 standalone and pairwise scenarios, then the interdependency effect would have been missed (which shows as last orange column in the right-hand graph not dropping to the level of the blue column). This shows the importance of a programme decremental test if competing effects are suspected, either applied to the administrative programme or to an extended programme.

Figure F.7 BCR for Project A assuming AUX interdependency using the selective (left) and pairwise rules (right)

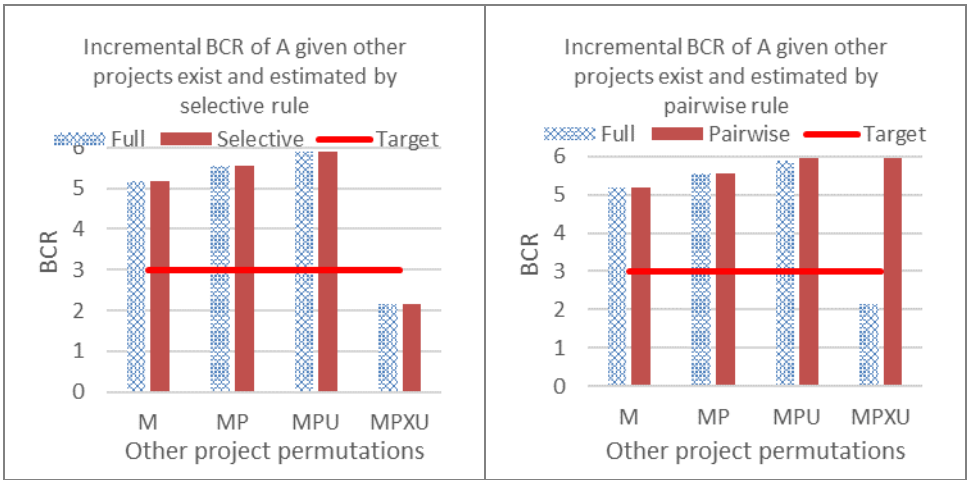


F.4 What if A and X compete only when P exists?

The situation above was varied slightly by changing the $100 million benefit addition to scenarios with PX without A. This has the same switching effect between A and X but now only when P is present.

Again, the BCR results for Project A are shown in Figure F.8 below. Not surprisingly, the two graphs are the same as above and again the pairwise rule overstates the last decremental benefit.

Figure F.8 BCR for Project A assuming PAX interdependency using the selective (left) and pairwise rules (right)



However, the BCRs reported are sensitive to how the scenarios are phased, an important result when it comes to considering how multiple BCRs are to be reported.

The above graphs apply a variation of the format first presented in Figure 4.2, with the BCRs shown from left to right against scenarios with decreasing probability. It would also be possible to show the competing effect of some unknown projects that are added to the DoMin to form the decremental test by using the right-hand format of Figure 4.4. This would deconstruct the effect of the unknown group (here extended to be XU) into that due to the competing group of projects (which is X here).