Sustainability and Adaptable/Flexible Infrastructure

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Publication Date:
2018

DOI:
https://doi.org/10.26190/unsworks/3436

Sustainability and Adaptable/Flexible Infrastructure

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A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

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April 2018

THE UNIVERSITY OF NEW SOUTH WALES
Thesis/Dissertation Sheet

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Abbreviation for degree as given in the University calendar: **PhD**

School: **Civil and Environmental Engineering** Faculty: **Engineering**

Title: **Sustainability and Adaptable/Flexible Infrastructure**

Abstract

Infrastructure is basically intended for long-term operation and can be worth a large percentage of peoples' and governments' wealth. Future changes with large inherent uncertainties attached may cause infrastructure to face unanticipated circumstances in terms of demographic or technological changes or climate change. This may lead to inefficient or obsolete infrastructure, creating the need for adaptation. Infrastructure adaptation causing enormous expenditure, resource consumption and possible disruption to services represents a significant sustainability issue.

Given that infrastructure can be adapted to change some way into the future, but with different extents of effort, expenditure and sustainability impacts, developers are caught in a dilemma as to whether to design infrastructure for adaptability. Adaptability can be incorporated ab initio in infrastructure design with the view that adaptation may (but not necessarily) take place in the future. Adaptation is thus a key issue with existing infrastructure, as well as the design and construction of new infrastructure.

The literature widely acknowledges infrastructure adaptability to enhance sustainability, but falls short in valuing the sustainability. The literature on infrastructure adaptability is also criticised as a result of some perceived confusion due to numerous interpretations and categorisations. Hence, this thesis i) adopts a holistic approach, giving infrastructure adaptability and flexibility a genuine, universal interpretation and clarifying its relationship with the concept of sustainability valuation; ii) quantitatively evaluates the sustainability of adaptable infrastructure using an existing, easy-to-use Real Options Analysis (ROA) combined with a Life Cycle Assessment (LCA) approach for social and environmental analyses; iii) presents a new approach that advances the sustainability valuation of adaptable infrastructure; this approach extends ROA to the sustainability context using Social/Environmental Costing (SEC). Different case examples from the Australian context are utilised to illustrate the approaches proposed in the thesis.

The thesis gives a conceptual benchmark and improves the understanding of infrastructure adaptability. In addition, it provides rational, easy-to-use methods for establishing the viability of adaptable infrastructure from a sustainability viewpoint. The thesis will thus be of interest to both academics and practitioners involved in the construction industry and contemplating prolonging the useful life of infrastructure through adaptation over time.

ORIGINALITY STATEMENT

‘I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.’

Signed ……………………………………………..............

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Acknowledgement

Firstly, I would like to express my sincere gratitude to my supervisor Professor Carmichael for his encouragement and support, for instilling confidence in me to grow as a researcher, and for his patience and immense knowledge. His valuable feedback and direction helped me in all the time of my PhD study, and his advice on my career has been priceless. I would also like to express my appreciation to my co-supervisor Dr Akbarnezhad for his consultation and support during the time of my study.

I would also like to thank my review panel members, Professor Waller, Professor Turner, Dr Davis, and Dr Shen for their constructive comments and suggestions in my research progress review meetings.

My sincere thanks also goes to Professor Cox, Dr Vali Pour Goudarzi and all other academics or industry representatives who provided me with their helpful suggestions on engineering aspects of the case studies and constructability of the ideas. Without their precious advice the current societal impact of the research would be unlikely to achieve.

I would also like to thank all of the caring fellow officemates, friends and staff in the School of Civil and Environmental Engineering who provided a friendly working environment and supported me to strive towards my goals.

Finally, a special thanks to my family. I would like to express my deep appreciation to my beloved wife Morvarid for her understanding, spiritual support and self-devotion throughout my study and my life in general, which made completion of this study possible. Words cannot express how grateful I am to my mother and father for all of the sacrifices they have made to raise me. The upbringing they gave me and their prayer for me have sustained me thus far.

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List of acronyms

A	A form adaptation – designed-in adaptability
AV	Adaptability Value
CBD	Central Business District
DCF	Discounted Cash Flow analysis
EPA	Environmental Protection Agency
GDP	Gross Domestic Product
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
MADM	Multi-Attribute Decision-Making
NA	NA form adaptation – Non-designed-in Adaptability
NPV	Net Present Value
PW	Present Worth
ROA	Real Options Analysis
SAW	Simple Additive Weighting
SEC	Social/Environmental Costing
SETAC	Environmental Toxicology and Chemistry
SLCA	Social Life Cycle Assessment
SRTs	Sustainability Reporting Tools
TOSIS	Technique for Order Preference by Similarity to Ideal Solution
UNSW	University of New South Wales

Abstract

Infrastructure is basically intended for long-term operation and can be worth a large percentage of peoples' and governments' wealth. Future changes with large inherent uncertainties attached may cause infrastructure to face unanticipated circumstances in terms of demographic or technological changes resulting in changed needs and wants, or climate change manifested by increased temperatures, altered rainfall patterns or extreme weather events and sea level rise. This may lead to inefficient or obsolete infrastructure, creating the need for adaptation to ensure the continuing relevance of the existing infrastructure providing desired services to society. Infrastructure adaptation causing enormous expenditure, resource consumption and possible disruption to services represents a significant sustainability issue.

Given that infrastructure can be adapted to change some way into the future, but with different extents of effort, expenditure and sustainability impacts, developers are caught in a dilemma as to whether to design infrastructure for adaptability or flexibility. As an alternative to conventional design, some adaptability features can be incorporated *ab initio* in infrastructure design with the view that adaptation may (but not necessarily) take place in the future, depending on future circumstances. Adaptation is thus a key issue with existing infrastructure, as well as the design and construction of new infrastructure.

The literature acknowledges infrastructure adaptability to enhance sustainability, but falls short in valuing the sustainability and even the financial performance of adaptable infrastructure. The literature on infrastructure adaptability is also criticised as a result of some perceived confusion due to numerous, and sometimes divergent, interpretations and categorisations. Hence, this thesis i) adopts a holistic approach, giving infrastructure adaptability and flexibility a genuine, universal interpretation and clarifying its relationship with the concept of sustainability valuation; ii) quantitatively evaluates the sustainability of adaptable infrastructure using an existing, easy-to-use Real Options Analysis (ROA) combined with a Life Cycle Assessment (LCA) approach for social and environmental analyses; this approach is

suitable for a comparative study between designed-in and non-designed-in adaptable infrastructure; iii) presents a new approach that advances the sustainability valuation of adaptable infrastructure; this approach extends ROA to the sustainability context using Social/Environmental Costing (SEC). Different case examples from the Australian context are utilised to illustrate the approaches proposed in the thesis.

The thesis gives a conceptual benchmark and improves the understanding of infrastructure adaptability such that practical solutions for adaptation can be sought more effectively. In addition, it provides rational, easy-to-use methods for establishing the viability of adaptable infrastructure from a sustainability viewpoint. The methods are also compatible with those commonly used in practice, suitable for engineering applications and capable of accounting for investors' preferences. The thesis will thus be of interest to both academics and practitioners involved in the construction industry and contemplating prolonging the useful life of infrastructure through adaptation over time.

Chapter 1: Introduction

1.1 Problem statement

'The 21st century challenge is living with whatever human-induced long-term change' (Trewin 2003, p. 39). Numerous examples of infrastructure that has failed to perform properly under major changes of demographics and climate exist. The consequence has mostly been to adapt infrastructure to these changes, since infrastructure is basically intended for long-term operation. The adaptation of infrastructure with massive investments, resource consumption and environmental impact, together with possible disruption to substantial services provided for the society, represents a significant sustainability issue.

In a look-ahead approach, designers face significant changes with inherent uncertainties attached (Hallegatte et al., 2011; Conrad and Raucher, 2013). In terms of climate change, infrastructure in coastal areas, such as coastal defences, buildings and nearby roads may be adversely impacted by sea level rise, or stormwater drainage systems may become obsolete as a result of changes in rainfall pattern. Roads, transportation facilities and housing infrastructure may also be insufficient owing to changes in demographics; namely, total population, age profile, household type and users' wants. These changes with great uncertainties may require more frequent replacement of infrastructure (Carmichael, 2014).

This has created the need for infrastructure flexibility/adaptability as the ability—giving the option, the right but not the obligation—to accommodate changes (Gosling et al., 2013, after Faludi, 1977 and Olsson, 2006) and respond to the uncertainty as the nature of change is unknown at the time of design (Gerwin, 1993). As such, decisions will be based on continually updated information rather than solely on the accuracy of predictions (Conrad and Raucher, 2013). Given that infrastructure can be adapted to change some way in future but with different extents of effort, expenditure and sustainability impacts, developers are caught in a dilemma as to whether to design infrastructure for flexibility or adaptability. This implies the notions of fortuitous (non-designed-in) adaptation versus designed-in adaptation (Carmichael, 2014). Adaptable infrastructure often requires extra upfront cost/effort, leading to investors/developers' reluctance to invest in building adaptability in design, and hence potential sustainability issues in future. Thus, the significance of investigating the viability of infrastructure adaptability from the sustainability viewpoint is evident.

Despite the fact that infrastructure adaptability is acknowledged to enhance sustainability through extended useful life (Moffatt and Russell, 2001; Wilkinson et al., 2009; Taneja et al., 2012; Langston et al., 2013), there is still lack of effort to place a quantitative value on the sustainability of adaptable infrastructure. Some studied adaptability qualitatively (Gann and Barlow, 1996; Attfield, 1999; Heath, 2001; Slaughter, 2001; Schneider and Till, 2005; Till and Schneider, 2005; Schmidt et al., 2010; Gosling et al., 2013), and some others used inadequate approaches, which either do not take uncertainty into account or pay less attention to social and environmental aspects, or utilised numerical methods that are difficult to exploit in practice (Moffatt and Russell, 2001; de Neufville and Scholtes, 2011; Fawcett et al., 2014).

1.2 Aim and scope

The research aim is to establish the viability of adaptable infrastructure, from the sustainability viewpoint.

From an extensive literature review, a number of gaps are identified; namely i) incoherence and clutter exists in the literature, mainly due to numerous and sometimes divergent categorisations and interpretations of infrastructure adaptability, ii) most publications have not put a quantitative value on sustainability, or even the financial performance of adaptable infrastructure, and iii) there is lack of a method giving a single measure for decision-making on building in adaptability. ROA is used to evaluate the financial viability of investing in adaptable infrastructure, but takes no account of social and environmental aspects; there is a need for incorporation of sustainability in options analysis and the valuation of adaptable infrastructure. The thesis is intended to solve the research problem and fill these gaps in the literature. Hence, the research aim is addressed through the following steps:

- Clarifying the literature and improving the understanding of infrastructure flexibility/adaptability using a holistic approach
- Quantitatively comparing infrastructure designed with flexibility/adaptability in mind with infrastructure not so designed (conventional thinking), from the sustainability viewpoint
- Giving a single measure for the sustainability valuation of adaptable infrastructure through extending current ROA to the sustainability context

The research questions and hypotheses are defined accordingly, on the basis of the steps outlined above, as given in Table 1.1.

Research question	**Research hypothesis**
Are various methods/types of infrastructure adaptability semantically different/the same?	All methods/types of infrastructure adaptability are semantically the same.
Is building in adaptability viable from the sustainability viewpoint?	Building in adaptability is viable from the sustainability viewpoint.
To what extent is building in adaptability viable from the sustainability viewpoint?	Incorporating sustainability in analysis greatly improves the viability of adaptable infrastructure.

Table 1.1. Research questions and hypotheses.

Infrastructure here refers to the basic physical assets, such as buildings, roads, dams, ports, facilities and equipment and so on required for the operation of a society. The research is focused on infrastructure design as the ability to manipulate physical architecture. Accordingly, the infrastructure adaptability/flexibility in engineering design, but not managerial decisions, is emphasised. The study also puts particular emphasis on climate and demographic changes and the associated impacts on infrastructure, but not other possible major changes.

1.3 Research methodology

This section describes how the research is carried out for each of the steps introduced earlier.

Clarify the literature

The thesis utilises control systems thinking (Carmichael, 2015) to establish a universal framework to renew and promote the understanding of infrastructure adaptability or flexibility, either designed-in or fortuitous. A case example involving rock seawall adaptability in an Australian coastal protection context is given to demonstrate the applicability of the approach presented.

Quantitative (comparative) analysis

Two forms of adaptation (denoted A and NA) are considered and compared:

> A. Where adaptability features have been designed and built in *ab initio*, with the view that adaptation may (but not necessarily) take place in the future depending on future circumstances.
>
> NA. Where the infrastructure has been designed and built without adaptability features in mind, but where future adaptation may still be fortuitously possible, albeit with greater effort.

The study is undertaken in three steps: design, estimation and analysis, for three different situations; namely, housing infrastructure, buildings subjected to changing needs and seawalls impacted by rising sea levels.

Design. Creative design is involved in how adaptability might be incorporated in order to produce the best outcome. Any design is checked against common practice and industry representatives' opinions to come up with realistic solutions. The analysis makes certain design assumptions, but readers may be able to develop better design concepts. Accordingly, the methodology, rather than the absolute design and associated numbers, is emphasised in the thesis.

Estimation. Financial costing estimates follow commonly used cost guides based on quantity take-offs from drawings, either hypothetical or as-built, together with quotations from various builders, engineers, tradespeople and industry representatives (see Appendix G for advisers' details). Social and environmental issues estimates follow commonly used databases for lifecycle inventories as well as construction crew calculations, based on the quantity take-offs.

Analysis. Financial valuing of adaptability is addressed through an ROA method suitable for engineering applications (Carmichael et al., 2011), while the social and environmental matters are evaluated along Life Cycle Assessment (LCA) lines. A sensitivity analysis also indicates how changes in analysis input values affect the financial viability of building in adaptability.

Extend ROA—a single sustainability measure

The thesis presents an upgraded ROA, by integration with Social/Environmental Costing (SEC), to address the sustainability valuation of infrastructure adaptability. The approach takes the economic burden of sustainability issues into account and leads to a single measure for the sustainability of adaptable infrastructure. The options analysis, as used for financial valuing, is utilised; however, the uncertainty of the sustainability intangibles is treated differently, accounting for a range of possible estimates with associated reliabilities. The given approach is demonstrated on rock seawall adaptability—the identical case example adopted shows the relationships between the approaches presented and the consistency in the thesis.

1.4 Significance of the study

The research makes certain contributions within each step, creating scientific and/or societal impacts.

The thesis establishes a universal framework with inclusive interpretations that improves the understanding of infrastructure adaptability or flexibility. This approach provides academics with a clear picture of the concept and a sound basis for future research. This improved understanding will also lead to informed decision-making by managers or industry practitioners on infrastructure adaptation.

The study also presents a new approach (ROA in conjunction with LCA) and demonstrates its application to the sustainability valuation of adaptable infrastructure. As such, this not only advances current knowledge, but also provides industry practitioners with an easy-to-use method for comparing alternatives and decision-making on building in adaptability on the basis of financial viability and/or sustainability performance. Through the approach given, it is possible to gauge the viability of including specific adaptability in any design and construction.

The thesis further progresses knowledge through presenting an upgraded ROA (integrated with SEC) that is capable of explicitly indicating the sustainability enhancement due to incorporating infrastructure adaptability. The approach gives a compatible extension to ROA as it takes the economic burden of sustainability issues into account and leads to a single measure (in dollars) for the sustainability of adaptable infrastructure, which is suitable for comparison and decision-making purposes. People involved in the construction industry, as well as investors and corporates with social or environmental liabilities, will thus benefit from this approach. They will be able to calculate whether, and to what extent, incorporating specific adaptability in any design is viable in terms of sustainability. The methods presented in the thesis can be applied to other situations and locations.

Overall, this research will benefit academics and those in the construction industry through the introduction of new concepts and methods that facilitate establishing the viability of adaptable infrastructure from a sustainability viewpoint.

1.5 Overview of the thesis

The thesis outline is as follows. Chapter 2 firstly provides a literature review on major changes, the definitions and classifications of infrastructure flexibility/adaptability, the link between adaptability and sustainability, associated valuation techniques and attempts to value the sustainability of adaptable infrastructure. The chapter concludes with the identification of gaps in the literature. Chapter 3 provides the methods and theories utilised in subsequent chapters.

Chapter 4 adopts a systems approach to infrastructure adaptability, reaching a set of inclusive interpretations. Infrastructure design is examined systematically, with system variables identified, to introduce adaptability as closed-loop control. Some suggestions on the adaptability of different infrastructure items are expressed using systems definitions based on the identified variables. The notions of designed-in adaptability and real options are also interpreted using the adopted systems approach. The expressions given are finally demonstrated in a case example.

The next three chapters demonstrate the approach (ROA combined with LCA) proposed for the sustainability valuation of adaptability in three different types of infrastructure in the Australian context; each chapter examines adaptability in a piece of infrastructure. Chapter 5 studies seawall adaptability under rising sea levels, with particular attention to rock seawall upgrades. Chapter 6 examines usage adaptability in housing infrastructure subjected to changing needs; a case example involving a single-storey house expandable to a two-storey house is presented. Chapter 7 studies the adaptability of open plan buildings under changing wants or demands; an educational building refurbishment is considered as a case example. Suggestions on adaptability are given according to possible future changes. A conclusion is drawn on the viability of building in adaptability for each type of infrastructure on the basis of the sustainability analysis outputs.

Chapter 8 presents an approach to extend ROA to the sustainability context by integrating it with SEC. This approach is demonstrated on a case example, giving a single sustainability value for adaptability, followed by arguments on the contribution of the inclusion of sustainability issues to the viability of adaptability. In this chapter, social and environmental intangible uncertainty is dealt with innovatively by using different pricing methods with associated reliabilities. An argument is then developed regarding the effect of the inclusion of social/environmental costs in the adaptability value.

Chapter 9 summarises the research findings and draws, but does not generalise, a conclusion on the viability of adaptable infrastructure from a sustainability viewpoint. The thesis puts an emphasis on valuation based on the approaches presented. The methods used, but not necessarily the assumptions on designs and associated numbers, will be applicable to other situations and locations.

Chapter 2: Background

2.1 The challenge of change

A great challenge to infrastructure development in the current century is dealing with significant changes. Much has been written on the challenges of dealing with climatic changes (Trewin, 2003; Dobes, 2008; Commonwealth of Australia, 2015). Demographic changes also represent a significant challenge to planning (Smith, 2003; Commonwealth of Australia, 2015). Technological changes, with their unknown nature, complicate the situation (Commonwealth of Australia, 1980). All changes have uncertainty attached to them, and all may threaten the performance of infrastructure as long-lived assets (Carmichael, 2015).

Climate change, as a result of exorbitant greenhouse gas emissions, is being revealed in sea level and temperature rises and change in the occurrence and magnitude of extreme weather events and rainfall patterns across different regions. For instance, Australia's climate is predicted to experience a highly uncertain changing trend over the coming decades (CSIRO–BoM, 2007, 2015; NCCOE, 2012b; IPCC, 2013), manifested by:

- Continuing increases in mean daily temperatures, with more frequent and hotter hot days, less frequent and warmer cold extremes, and reduced frost.
- Decreases in average rainfall, but an increase in the intensity and/or frequency of extreme rainfall events (wettest day in 1 year and 20 years), drought proportion increments, less frequent moderate and severe droughts, and more frequent and longer extreme drought.
- A considerable mean sea level rise; which is also considered the most contributory factor to extreme sea level changes.

Demographic changes originate from variations in the fertility rate, life expectancy and net migration (Smith, 2003; ABS, 2013b; Johnstone et al., 2013; Commonwealth of Australia, 2015). At a local scale, these factors are associated with urbanisation and suburban sprawl. The uncertainty associated with such changes impacts demand prediction (needs and wants), development planning and infrastructure usage. Changed demographics generally appear in altered population sizes and/or the structure–age distribution (Commonwealth of Australia, 2015). In Australia, the total population is projected to grow by about 65±20% until 2055 (ABS, 2013b), while the ratio of working age population to the elderly population will fall by nearly 39±3% (ABS, 2013a). The flow-on will be changing demands, wants and uses of infrastructure.

Technological changes occur as progressive changes aiming to promote efficiency. The ever-changing technologies with their great uncertainties lead to changes in patterns of use; as a result, services provided by infrastructure and industry require upgrading (Commonwealth of Australia, 1980; Yates, 1988).

Overall, the uncertainty about the timing and intensity of these changes may result in unanticipated circumstances (Conrad and Raucher, 2013) and lead to infrastructure becoming inadequate and obsolete (Carmichael, 2014). Some examples follow:

- Climate change. Rising sea levels may cause underperformance of seawalls, ports and nearshore water drainage systems (Headland et al., 2011; NCCOE, 2012a). Extreme rainfall events may lead to flooding of buildings and transport infrastructure in low-lying areas (Dobes, 2010; Headland et al., 2011) or overloading of water drains and dams. Declining mean precipitation may lead to water supply and rainwater retention systems becoming inadequate. Comment on the sensitivity of various infrastructure types to climate change can be found in AS (2013, pp. 43–48).
- Demographic change. Increasing demands may result in insufficient capacity in buildings and healthcare infrastructure (Moffatt and Russell, 2001; Till and Schneider, 2005; de Neufville et al., 2008; Guma, 2008), energy and water

supply systems (Huang et al., 2010; Basupi and Kapelan, 2015) and transport infrastructure such as roads/railways, seaports and airports (Ohama, 2008; Taneja et al., 2012). Changed wants may lead to inefficiency or incompatibility, and so to abandoned buildings (Arge, 2005; Till and Schneider, 2005), including healthcare centres (Lee, 2007) or seaport terminals (Taneja et al., 2012).

- Technological change. The introduction of new polymeric materials may abolish the use of conventional materials and change fender fabrication methods in bridges or seaports. The tendency towards off-site construction may add to the demand and cause existing prefabrication plants to become inadequate (Commonwealth of Australia, 1980; Yates, 1988). Smart railways or modern means of transportation may lead to existing facilities becoming obsolete (Lovell et al., 2010). Innovative, renewable sources of energy may further reduce the need for coal-based energy supply infrastructure (Yates, 1988).

Given that infrastructure is intended for long-term use, adaptations may be required to prolong its useful life. For example, this might include heightening a seawall, widening a roadway or the conversion of a school to a healthcare centre for an ageing population or the development of facilities for renewable energy supply. Change has created renewed interest in the notion of infrastructure adaptability, and the use of real options thinking to value this adaptability.

2.2 Terminology: Infrastructure adaptability/flexibility

The literature uses the terms adaptability and flexibility in different ways, and sometimes interchangeably. In lay terms, adaptability refers to being able to change or be changed easily in order to deal with new situations.

Fricke and Schulz (2005) refer to flexibility and adaptability as the two aspects of designing for changeability, while McConnell (2007) considers that '*flexibility* *requires an outside agent as an effector for change while an adaptable system can change from an internal effector'* (McConnell, 2007, p. 47). In a similar way, Ross et al. (2008) and Spiller et al. (2015) use flexibility to mean changes made through an external intervention by a change agent, while adaptability is the capability of a design to change itself and continue to function.

Some writers use both flexibility and adaptability to mean the ability to accommodate changes (Gann and Barlow, 1996; Slaughter, 2001; Greden, 2005; Straub and Špacková, 2017) where knowledge of the change is unclear at the time of design and construction (Gosling et al., 2013, after Grewin, 1993 and Upton, 1994). Wang and de Neufville (2005) define flexibility in projects as the ability to change the technical design.

For the purposes of this thesis, the sense of the terms flexibility and adaptability is taken to be the same, referring to the capability to change the infrastructure design in line with future circumstances. It should be noted that the terms flexibility and adaptability, as used in the literature and this thesis, differ from 'robustness' where infrastructure is over-designed such that resisting to enough wide range of external changes without any future change to the infrastructure (de Neufville and Scholtes, 2011; Ryan et al., 2013). Such adaptability is seen, for example, in a phased design of a seawall where some elements are initially oversized to enable raising seawalls at a later time if required. The flexibility or adaptability as used in this thesis involves any type of future changes in structure, scale or functionality (Saleh et al., 2003; Fricke and Schulz, 2005; Ross et al., 2008) and any possible flexible solutions, namely modular design, phased design/development, design for indeterminacy or design for disassembly as suggested in the literature (Till and Schneider, 2005; Fricke and Schulz, 2005; de Neufville and Scholtes, 2011; Hatcher et a., 2011; Spiller et al., 2015).

Adaptability and flexibility can give timelessness and continuing relevance to infrastructure (Slaughter, 2001). The ever-changing natural, social and technological environments impact the longevity of structures, creating the need to extend their useful lives (Slaughter, 2001; Zhao and Tseng, 2003; Wilkinson et al., 2009). The following review covers the existing categories and attitudes towards infrastructure adaptability—namely built-in (A form) or not built-in (NA form) adaptability—the relationship between infrastructure adaptability and sustainability and the associated valuation approaches.

2.3 Managerial vs. engineering adaptability

The literature views methods of incorporating infrastructure adaptability or flexibility in different ways. Wang and de Neufville (2005) look at flexibility in two categories of ‘on project’ and ‘in project’. Similarly, Taneja et al. (2012) talk of ‘managerial’ and ‘physical’ flexibilities, and Gosling et al. (2013) introduce ‘process flexibility’ and ‘design flexibility’. In general, the former concerns managers’ abilities or options to plan (i.e., delay, phase, expand, contract or abandon) an infrastructure investment (Geltner, 2007; Masunaga, 2007; Zhang, 2010); this relates to managerial decisions with a larger-scale outlook on a project. The latter is associated with the ability or options (e.g., to expand or switch) embedded in engineering design at a smaller-scale outlook to respond to uncertain changes. Managerial approaches might cover a wide range of concepts namely design (Sit and Taylor, 1998; van der Brugge and van Raak, 2007; Conrad and Raucher, 2013). The engineering design or adaptability can be viewed as an integral part – a part of the whole – or a means of delivering managerial adaptability (de Neufville, 2003; Woodward et al., 2011). This thesis incorporates both categories of adaptability, while emphasises engineering design for adaptability.

Some studies introducing real managerial options (with no attention to design) as a means to deliver infrastructure adaptability exist (Barman and Nash, 2007; Cardin, 2007; Lister, 2007; Taneja et al., 2012). Barman and Nash (2007) and Cardin (2007) suggest the application of managerial options (e.g., to phase, delay or abandon) to real estate development under uncertain market conditions. They argue that such real options, unlike financial options, ‘*represent the option holder’s ability to directly* *influence the value of the underlying asset'* (Barman and Nash, 2007, p. 16). Mayer and Kazakidis (2007) suggest incorporating flexibility in mine planning under changing demands; namely, through either a full development, giving the option to expand production, or a gradual development, providing the option to shut down. Taneja et al. (2012) talk of managerial flexibility to phase, defer or abandon investments in port infrastructure. Headland et al. (2011) acknowledge adaptability and so-called 'adaptive management' in coastal defences through staged development to respond to rising sea levels. Conrad and Raucher (2013) also suggest utilising adaptive management in water systems infrastructure under a changing climate, '*as an iterative process for improving management actions through monitoring changes*; such a strategy is believed to *explicitly recognise uncertainty and utilise flexible decision-making to promote resilient systems'* (Conrad and Raucher, 2013, p. 3).

Although such managerial flexibility is beneficial as it provides options, it largely imitates financial options flexibility with little attention to the fact that real (civil engineering) assets are physical. The ability to 'design' the physical architecture is the main advantageous distinction between real and financial assets. This is the reason some emphasise incorporating engineering adaptability in design to deliver real options (de Neufville, 2003; Arge, 2005; Fricke and Schulz, 2005; Engel and Browning, 2008; Carmichael, 2014). de Neufville (2003) suggests that '*thinking in terms of real options leads designers to build flexibility into a system design… giving the capability to change the design'* (de Neufville, 2003, p. 2). He proposes that flexible systems design is proactive in dealing with uncertain changes, as opposed to the conventional reactive approach. Arge (2005) discusses the concept of adaptability as what merely relates to the physical design of buildings. Wang and de Neufville (2005) introduce flexibility in projects as being created by changing the technical design of a system. Engel and Browning (2008) suggest the application of options theory in engineering design, introducing architectural options to deliver adaptability. Carmichael (2014) mentions incorporating flexibility in infrastructure design with '*possibilities of utilising in-built or deliberate flexibility… acting as a hedge against future uncertainties'* (Carmichael, 2014, pp. 8–12); however, he adds that some infrastructure may otherwise end up having fortuitous flexibility with later reconsideration in design.

Given the importance of design in delivering infrastructure adaptability, here the term adaptability refers to the capability of changing physical engineering design in line with change in future circumstances. As such, adaptation options lie under designed-in A form where adaptability is deliberately incorporated in initial design or non-designed-in (fortuitous) NA form where infrastructure is adapted with no forethought. Most infrastructure, and literature on adaptation, appears to fall under the NA form. For example, Medellín-Azuara et al. (2008) suggest additional water reuse or greater conjunctive operation of ground and surface waters as adaptation options where climate warming threatens California's water supply system. Guma (2008) talks of unplanned additions to building space where existing space cannot accommodate demands. Headland et al. (2011) and Burcharth et al. (2014) study fortuitous adaptations for coastal defences such as heightening or building a berm next to the existing structure when sea levels change. In terms of A form, the likely changes are already accounted for in adaptation options. Auld et al. (2006) emphasise developing adaptation options such that incorporated in design for prompt implementation. They suggest developing methods for incorporating changes into climatic design and engineering practice of new infrastructure, while taking advantage of adaptation learning and reactive solutions such as retrofit or relocate for existing infrastructure. Engel and Browning (2008) suggest utilising modularity in buildings with the view to accommodate future changes in uses. Ohama (2008) suggests initial addition to substructure required for possible extension of airports' runway in future. This A form is the focus of this thesis. The NA form is not addressed in detail in the thesis, but rather, is used as a comparison with the A form.

2.4 Infrastructure adaptability: Other classifications

The existing studies mainly adopted a limited attitude towards engineering systems adaptability and emphasised specific features, leading to a plethora of categorisations

(Moffatt and Russell, 2001; Arge, 2005; Fricke and Schulz, 2005; Till and Schneider, 2005; Wang and de Neufville, 2005, Lee, 2007). Fricke and Schulz (2005) suggest systems changeability comprising two different aspects of flexibility and adaptability, which differ in terms of the source of change, which is either external or internal. Similarly, when examining changeability and associated subcategories, Ross (2006) talks of other system properties, or 'ilities', such as scalability (ability to change in size or scope) and modifiability (ability of changing the system's attribute set). x also talk of upgradability, where external changes are imposed on a system to prolong its useful life.

Moffatt and Russell (2001) break down a building's adaptability into a number of approaches; namely, flexibility in space planning, convertibility in use and expandability or shrinkability in space volume. In a similar way, Arge (2005) looks at adaptability in terms of three concepts of generality (ability of multifunctional use), flexibility (ability to rearrange elements) and elasticity (ability to extend or partition the building) to meet changing needs. Till and Schneider (2005) classify the methods of housing flexibility into use and technology, each being subdivided into soft tactics, allowing certain indeterminacy and hard tactics, concerning elements with more specifically determined uses. Schmidt et al. (2010) introduce a number of qualities as 'ables'—namely, available, flexible, refitable, moveable, extendable or scalable and recyclable or reusable—in order to characterise the physical capacity of adaptable buildings. However, they acknowledge that there is '*a mixture of correlating definitions in the literature leaving no clear way of easily deciphering the semantically tangled strategies* [of adaptable design]' (Schmidt et al., 2010, p. 237).

Mayer and Kazakidis (2007), after Singh and Skibniewski (1991), classify manufacturing and mining flexibility into different types according to the ability to change the operation processes, mix processes, route along different paths, production volume, expand the system size and machine efficiency. de Neufville et al. (2008) categorise flexibilities into operational, tactical and strategic in order of effectiveness and exercise pace. Taneja et al. (2012) define three categories of flexibility; namely, 'just-in-case', where a margin is built in the design for more robustness, 'just-for-now or *ad hoc*', applicable to non-adaptive systems, and 'just-in-time', being exercised on demand; the latter is believed to contain real options.

Such different and sometimes divergent attitudes have spread through the many other attempts made to interpret adaptability for various types of infrastructure, such as transport (McConnell, 2007; Ohama, 2008), buildings/real estate (Slaughter, 2001; Greden et al., 2005; Schmidt et al., 2010), water management systems (Huang et al., 2010; Basupi and Kapelan, 2015; Marques et al., 2015) and coastal defences (Townend and Burgess, 2004; Woodward et al., 2011; Flocard and Blacka, 2012). Accordingly, this has resulted in incoherence in the literature which confuses readers. Hence, there is a lack of a holistic approach that can clarify the quiddity of infrastructure adaptability, before working out its value in terms of sustainability.

2.5 Terminology: Sustainability

The concept of sustainability started to develop in 1960s due to growing awareness and concern about environment. The idea of EcoDevelopment, as a precursor of the concept of sustainable development, was first introduced at the United Nations conference on environment in 1972 as 'an approach to development aimed at harmonising social and economic objectives with ecologically sound management' (Hill and Bowen, 1997 after Gardner, 1989). Sustainable development was then the focus of many studies and political endeavours that resulted in further development of the concept.

Probably the most well-known definition of sustainable development was offered by the Norwegian Prime Minister and Chair of the World Commission on Environment and Development (WCED), Gro Harlem Brundtland, in 1987 as 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. According to Sage (1998), sustainability refers to the fulfilment of human needs through simultaneous socio-economic and technological progress and conservation of the Earth's natural systems. Also, UK's Sustainable

Development Association defines sustainability as ‘a dynamic process which enables humans to realise their potentials and improve the quality of their life in ways that simultaneously protect and enhance the Earth’s life-support systems’ (Parkin, 2000).

The existing definitions basically introduce sustainability as a way of maintaining a balance between ‘development’ and ‘conservation’; or in the other words, managing the relationship between ‘meeting human needs’ and ‘protecting the environment’ to yield the greatest benefit for present and future generations (Hill and Bowen, 1997; Plessis, 2007). To this end, the needs must be met such that critical environmental limits are not exceeded (Plessis, 2007). Also from the definitions, three main pillars of sustainability are recognised as financial, social and environmental, and a balance must be sought between these for a sustainable development (Ofori, 1998; Pires et al., 2017). Accordingly, this thesis emphasises all the three aspects. Since this thesis is focused on infrastructure projects and construction discipline, the concept of construction sustainability with associated financial, social and environmental issues are investigated.

2.5.1 Sustainability in construction

The term ‘sustainable construction’ is generally used to express the responsibility and contribution of construction industry to sustainable development (Hill and Bowen, 1997; Chen and Chambers, 1999; Zainul Abidin, 2010), and pertains to areas of environmental protection, social welfare and economic prosperity (Zainul Abidin, 2010]. Kibert (1994) introduces sustainable construction as ‘the creation and responsible management of a healthy built environment based on resource efficient and ecological principles’. In a similar way, CIB (1999) defines sustainable construction as ‘the reduction in the use of natural resources and the conservation of the life support function of the environment by construction processes, buildings and the built environment under the premise that the quality of life is maintained’. According to Huovila and Richter (1997), it aims at minimising the use of energy and emissions that are harmful for environment and health. The Architecture and Building Research Institute (2003) also suggests that sustainable construction relates to ‘a design geared towards human health and comfort, pursuing coexistence with the global environment, and fostering the sustainability of the people’s living environment. Buildings should consume relatively few natural resources and manufacture relatively little waste’. As such, the criteria of sustainability performance in construction are perceived to include human health and comfort, emissions, waste production, and use of resources i.e. water and energy which already recognised as indicators for evaluating adaptive capacity (Moffatt and Russell, 2001; Spiller, 2016). Associated with construction, there might be other social criteria such as neighbourhood disturbance through traffic disruption and noise or dust pollution (Chen et al., 2008; Shen and Zhang, 2011), safety incidents (Rajendran and Gambatese, 2009) and worker employment (Alansar et al., 2008; Chen et al., 2010). This thesis studies such criteria along with project profitability, covering three basic aspects of sustainability. Particular criteria may be considered to be relevant and emphasised in a specific comparative study.

Basically, construction can be viewed at activity level or project level; the former specifically looks at a construction activity in a particular phase of project, while the latter relates to the entire project life cycle comprising conceptual planning, design, construction, operation and end-of-life (Plessis, 2007). This thesis uses an integrated approach to construction such that a life cycle approach to infrastructure projects is adopted, while some specific phases and associated activities might be focused for comparative studies purposes. Accordingly, the relevant sustainability criteria will be assessed for specific phases or activities of projects.

2.6 Adaptability and sustainability

Many suggest adaptability as a strategy greatly contributing to addressing sustainability in an environment of uncertainty (Larsson, 1999; Moffatt and Russell, 2001; Smit and Pilifosova, 2001; Till and Schneider, 2005; Wilkinson et al., 2009; Taneja et al., 2012; Conejos et al., 2013; Gosling et al., 2013; Langston et al., 2013). Adaptability can avoid inefficient or wasted infrastructure by providing options to respond to uncertain future changes (Scholtes, 2007; de Neufville et al., 2008; Taneja et al., 2012; Conrad and Raucher, 2013; Carmichael, 2014).

Gosling et al. (2013) introduce adaptable buildings as a means to realise the sustainable construction agenda. Conejos et al. (2013) suggest that incorporating adaptability criteria in designing future buildings will contribute to create low-carbon built environments. Schneider and Till (2005) argue that flexibility leads to economic, social and environmental viability in housing design. They add that *'sense tells us flexibility is more beneficial in the long term because obsolescence of housing stock is limited, but there is little quantitative data to substantiate this argument'* (Schneider and Till 2005, p. 162). Moffatt and Russel (2001), after Larsson (1999), suggest that buildings' adaptability can considerably reduce resource consumption, air emissions and demolition solid waste, while acknowledging the need to investigate the relationship between adaptability and environmental loadings.

Adaptability is translated into a closed-loop control (Carmichael 2015), which is further discussed in Chapter 4. Further, sustainability in construction implies a transition from conventional linear to closed-loop processes resembling the cyclical patterns in natural ecosystems (Miyatake, 1996; Fiksel, 2006). Hence, an improved sustainability performance is anticipated through adaptability. Fiksel (2006) argues that sustainable development in the changing global environment depends on having adaptability. Adaptability contributes to sustainability as maintains infrastructure in operation and avoids inefficient infrastructure by responding to the changing environment (Taneja et al., 2012; Conrad and Raucher, 2013; Carmichael, 2014; Williams et al., 2017). However, many scholars believe that quantitative sustainability assessment is still required for justification (Gann and Barlow, 1996; Moffatt and Russell, 2001; Slaughter, 2001; Schneider and Till, 2005; Gosling et al., 2013).

To sum up, the literature recognises infrastructure adaptability as contributing to sustainability enhancement (Moffatt and Russell, 2001; Wilkinson et al., 2009; Taneja et al., 2012; Langston et al., 2013). However, there is still a lack of quantitative research to support this opinion (Gann and Barlow, 1996; Moffatt and Russell, 2001; Slaughter, 2001; Schneider and Till, 2005; Gosling et al., 2013); this is so particularly in terms of social and environmental aspects. The need for justification using suitable quantitative examination is further understood where investigating built-in adaptability, usually resulting in extra upfront costs and/or social and environmental impacts.

In the following, the review covers commonly used techniques for valuing adaptability and sustainability, and whether sustainability valuation of adaptable infrastructure has been attempted.

2.7 Adaptability valuation: ROA techniques

Valuation refers to quantitative assessment where adaptability value or performance is calculated and expressed numerically. Valuation techniques can generally be categorised as either deterministic or probabilistic, with the latter taking uncertainty into account. The application of conventional deterministic valuation for adaptability valuation is criticised. For example, deterministic Net Present Value (NPV) which is the difference between the present value of cash inflows and cash outflows over a period of time, as used to analyse the profitability of a project, will no longer be suitable (de Neufville et al. 2006; Carmichael et al. 2011). This is because the deterministic approach neglects uncertainty and the ability to make a choice (Trigeorgis, 1996; Amram and Kulatilaka, 1999; Copeland and Antikarov, 2001; Barton and Lawryshyn, 2011), and commonly uses a risk-adjusted discount rate, ignoring long-term impacts and benefits over the lifespan of the infrastructure (Carmichael and Balatbat, 2009; Kodukula and Papudesu, 2006; Raar, 2011).

Given that adaptability provides infrastructure with an option, a right, but not an obligation, to adapt to changed circumstances, Real Options Analysis (ROA) is required for valuation (Copeland and Antikarov, 2001; de Neufville, 2003; Carmichael et al., 2011). ROA techniques can generally be divided into financial-based, referring to those relying on financial options theory, where the concept of real options originates from, and engineering-based, which attempt easier, rational methods suitable for engineering applications (Masunaga, 2009).

Financial-based ROA

Commonly used financial-based ROA methods involve solving partial differential equations such as the Black-Scholes, binomial lattices, and simulations (Copeland and Antikarov, 2001; Kodukula and Papudesu, 2006). Although the Black-Scholes is easy to compute, unlike some other partial differential equations, it is problematic in regard to its derivation and meaning, determination of input values and inability to deal with multiple sources of uncertainty (Kodukula and Papudesu, 2006; Carmichael, 2014).

Simulations involve generating a large number of paths the underlying asset value may follow over the option life within the boundaries specified by volatility; this method has limitations when used for the options with sophisticated conditions (Kodukula and Papudesu, 2006). Binomial lattices account well for contingent decisions, and are even capable of evaluating fairly complex options with specific path dependencies and interdependencies (Wang and de Neufville, 2004) (see for example, Zhao and Tseng, 2003; Kontogianni et al., 2014 for lattice applications). However, lattices are computationally complex (Kodukula and Papudesu, 2006) and, similar to simulations and the Black-Scholes, are not attractive for practitioners (Carmichael and Balatbat, 2009).

The application of financial options-based methods for real options valuation is generally criticised. These methods are suitable for the valuation of market underlyings, but are not directly applicable to real assets and have shortcomings when used this way (Damodaran, 1999; Copeland and Antikarov, 2001; Howell et al., 2001; Wang and de Neufville, 2005; Kodukula and Papudesa, 2006; Mattar and Cheah, 2006; Lewis et al., 2008; Carmichael et al., 2011; de Neufville and Scholtes, 2011) due to:

- The arbitrage principle, where the asset is freely traded, is a key assumption in financial options, but difficult to interpret for real assets.
- The difficulty of determining the volatility that is inapplicable in a real options and project sense, not dealing with fluctuating underlying assets value.
- Real options on large time-scales deal with delayed option exercise and investment calculations on the basis of discrete time discounting, which is not the case for financial options.

Engineering-based ROA

There has been little tendency towards ROA application among practitioners (van Putten and MacMillan, 2004; Hartmann and Hassan, 2006; Block, 2007). This is because of the above-mentioned issues concerning the financial-based methods (Hull, 1997; Damodaran, 2008), the acceptance of deterministic Discounted Cash Flow (DCF) analysis, and the lack of understanding of ROA, such that it is perceived as a substitute, but not a supplement, to conventional methods and/or as a method that takes excessive risk (Kodukula and Papudesu, 2006, Block, 2007; Carmichael, 2014). In addition, many of the valuation models are inconsistent with the methods used in practice (Barton and Lawryshyn, 2011). As a result, attempts have been made to develop easy-to-use ROA methods using spreadsheet calculations that are suitable for engineering applications.

Many acknowledge the need for addressing the technical issues associated with financial-based methods and suggest use of traditional DCF calculations in ROA (Luehrman, 1998; van Putten and MacMillan, 2004; Trigeorgis, 2005; de Neufville et al., 2006, Carmichael and Balatbat, 2009; Barton and Lawryshyn, 2011; Raar, 2011); having said that, ROA is complementary to, rather than a substitute for, the conventional appraisal methods (van Putten and MacMillan, 2004; Kodukula and Papudesu, 2006).

de Neufville et al. (2006) suggest a computer-based spreadsheet model for estimating real options value in engineering systems using Monte Carlo simulation. The model captures uncertainty by simulating numerous possible scenarios and performs deterministic DCF analysis for each scenario; it then gives the real options value as the difference between the average NPV of flexible and non-flexible strategies for all scenarios. Comments on the application of this method are given in the literature for a number of infrastructure projects (see for example, Greden et al., 2005; Cardin et al., 2008, 2013).

The method is directed at real options, and enables incorporating flexibilities (via the 'IF' function in the spreadsheet) and uncertainty of analysis input. However, the method has still some deficiencies, since it:

- Considers the downside potential of investment, while the option is only exercised when the NPV of a flexible strategy is greater than that of the base case, implying the upside potential (Howell et al., 2001).
- Needs defining a probability distribution for each analysis input, is numerical, and provides little insight into calculations (Wang and de Neufville, 2005; Carmichael 2014); these make it difficult for engineers to use the model.

Carmichael and Balatbat (2009) suggest the application of probabilistic DCF analysis using a second order moment approach to estimate real options value. This approach only requires characterising cash flows and the associated present worth in terms of their moments, which can readily be obtained using three-point estimates as is done in PERT (see for example, Carmichael, 2006, 2011; Carmichael and Balatbat, 2008a, 2008b). Real option is valued using a fitted, typically normal, distribution of total present worth, looking at only the upside potential of investment.

The given approach thus addresses all the issues related to the above mentioned financial or engineering-based real options methods and brings advantages, namely the possibility of incorporating multiple exercise with uncertain price, allowing for differing discount rates and variances between cash flows (Carmichael et al., 2011). The method's simplicity and reliability, as well as its consistency with DCF analysis, commonly used in practice (Block, 2007; Damodaran, 2008), makes it appealing to engineers and hence properly bridges between ROA and engineering applications. This thesis adopts and extends the given approach, as discussed later.

2.8 Sustainability assessment techniques

With assessment of sustainability comprising financial, social and environmental criteria, a multi-objective situation arises, which is generally dealt with in three ways (Carmichael, 2013b, p. 267):

1. *Develop an independent best solution for each objective in isolation, and then trade off the multiple solutions obtained.* There is a belief that giving a single measure for sustainability is inconsistent with the high levels of diversity in needs, circumstances and perceptions; thus, a qualitative way of concluding the sustainability achievement might be preferred (Schmidt and Sullivan, 2002).
2. *Isolate one of the objectives as a sole objective and convert the other objectives to constraints.* Choice of the sole objective and constraint levels is subjective. This approach is also inconsistent with concept of sustainability seeking a comprehensive, balanced achievement in all aspects (Hill and Bowen, 1997).
3. *Assemble all the objectives into a composite single objective.* Rendering a single value might be desirable in some situations for the purposes of comparison and decision-making. There are some techniques for combining social, environmental and financial measures and reaching an overall sustainability measure, which are reviewed below.

The choice of assessment technique depends on the sustainability issues type. Social and environmental issues can be grouped into measurables and non-measurables (Dompere, 1995). Measurables involve those that can be measured directly and expressed quantitatively, while non-measurables relate to inherently subjective issues that are unable to be directly measured in numbers. Measurables are commonly evaluated through Life Cycle Assessment (LCA) tools (ISO, 2006; Hsu, 2010;

Lehmann et al., 2013; Surbeck and Hilger, 2014); non-measurables are typically expressed using linguistic terms due to their subjectivity (Siew et al., 2016). However, there are techniques for turning non-measurable expressions into numbers for the purpose of either giving a more sensible measure or combining them with other criteria.

The fuzzy-based approach

A way of dealing with non-measurables is to link linguistic expressions and defined scales with fuzzy set membership (Tan et al., 2011). To this end, a fuzzy number (characterised by a function) is allocated to each expression. Fuzzy ratings of sustainability issues are weighted using fuzzy weightings and summed to create an overall fuzzy rating, which is then normalised and switched to a linguistic term (see Siew et al., 2016 for further details and example).

This approach offers advantages in terms of dealing with subjectivity, as it turns subjective expressions into numbers and goes beyond giving a deterministic measure (Tan et al., 2011; Siew et al., 2016). However, it is appropriate only for addressing combinations of non-measurables; thus there is an issue regarding the integration of its outcome with measurables, while general criticisms over the definitions of scales and allocation of fuzzy numbers to ratings and weightings still exist.

The MADM technique

Assessment techniques adopted in multi-attribute decision-making (MADM) methods, such as TOPSIS or SAW (see for example, Zanakis et al., 1998; Tzeng and Huang, 2011), require that the values of sustainability issues are normalised and then weighted to calculate alternatives fitness. For instance, this may be defined as the summation of scores or the distance from an ideal solution. The assessment method used in sustainability reporting tools is a particular example of this technique, with an already normalised and weighted scoring model (Rogmans and Ghunaim, 2016).

The MADM technique is capable of combining measurables and non-measurables, expressed by linguistic terms or equivalent deterministic measures. This method divides the possible range of outcomes into a number of scales and then assigns a score to each scale; for example, a Likert scale of 1–5 assigned to a range of ‘very low’ to ‘very high’. Definition of scales, allocation of scores and weightings are the main issues a consensus is difficult to reach on; hence any result can always be criticised (Carmichael, 2013b; Siew et al., 2013).

The SEC method

Social/Environmental Costing (SEC) is another way to combine different criteria and deliver a single sustainability measure; this is done through monetising social and environmental impacts or liabilities on the basis of the ‘polluter pays principle’ (Steen, 2005; de Beer and Friend, 2006). According to the Environmental Protection Agency (EPA, 1995) *‘social and environmental costs involve those costs that have a direct financial impact on a company (internal costs), and costs to individuals, society and the environment for which the company is not accountable (external costs)’* (EPA, 1995, p. 34).

SEC attempts to extend market boundaries and calculations to non-market objects by the expression of social and environmental externalities in monetary terms (Dompere, 1995; Mirasgedis et al., 2000; Lohmann, 2009, after O’Neill, 2007), renewing the conventional appraisal of total economic value and directing further attention to social and environmental issues (Dascalu et al., 2010). Some examples include the use of carbon credits traded in the carbon market to convert emissions to dollars (Stern, 2007; Lohmann, 2009), or the suggestion to integrate pollution into market calculations (Coase, 1960) through, for example, trading pollution rights.

Costing certain sustainability issues might be challenging, and even if this was not so, there is still a lack of agreement on the choice of suitable indexation and monetisation methods (Dompere, 1995; Bein, 1997; de Beer and Friend, 2006). Generally speaking, every method has its own advantages and disadvantages, and ‘*valorises some point of view and silences another’* (Lohmann, 2009, p. 529, after Bowker and Star, 2005). Given that the benefits of incorporating adaptability are unlikely to be realised by investors, SEC is able to closely connect the concept of adaptability to investment profitability by representing a sustainability measure that is to be paid by investors (Dascalu et al., 2010).

2.9 Sustainability valuation of adaptable infrastructure

While there is reasonable agreement in the literature on the need to move towards adaptability, most publications have not put any sustainability value on adaptability (Gann and Barlow, 1996; Heath, 2001; Moffatt and Russell, 2001; Wilkinson et al., 2009), apart from a few using inadequate methods (Moffatt and Russell, 2001; Fawcett et al., 2014).

Moffatt and Russell (2001) suggest the application of LCA tools to quantify the contribution of adaptability to sustainability. Given that LCA has shortcomings when used for adaptability valuation, such as reliance on single-point estimates and ignoring uncertainty, Fawcett et al. (2014) have adopted a probabilistic approach to evaluate the costs and environmental impacts of flexible infrastructure using Monte Carlo simulation. However, this approach has limitations in terms of its numerical basis giving little insight into the calculations and the need to determine probability distributions for the analysis inputs (Wang and de Neufville, 2005; Carmichael, 2014). Moreover, interpreting the environmental results and undertaking sensitivity analyses is complex (Fawcett et al., 2014). Overall, the lack of a proper approach for the sustainability assessment of adaptability, capable of addressing the above issues, is evident.

2.10 Summary

From the literature review, three main gaps are identified, as summarised below.

First gap

Despite the fact that the incorporation of adaptability into infrastructure and its financial valuation has been widely attempted in the literature, the incoherence in the literature remains due to confusion over managerial options and the lack of a comprehensive point of view on adaptability. This confusion can be perceived in two aspects. First, some studies have intended to deliver infrastructure adaptability while paying less attention to 'design'; while the major advantage distinguishing real (civil engineering) assets from financial assets is their ability to change physical architecture (Barman and Nash, 2007; Cardin, 2007; Lister, 2007; Headland et al., 2011; Taneja et al., 2012). Second, there are many categorisations and short-sighted interpretations of infrastructure adaptability and flexibility (Moffatt and Russell, 2001; Fricke and Schulz, 2005; Till and Schneider, 2005; Wang and de Neufville, 2005; Lee, 2007), some of which are divergent; this has resulted in clutter in the literature. Clearly, a holistic approach that can clarify the quiddity of infrastructure adaptability and flexibility is lacking.

Second gap

Although many acknowledge infrastructure adaptability as enhancing sustainability through extended useful life (Larsson, 1999; Slaughter, 2001; Smit and Pilifosova, 2001; Till and Schneider, 2005; Scholtes, 2007; de Neufville et al., 2008; Taneja et al., 2012; Conrad and Raucher, 2013; Langston et al., 2013; Conejos et al., 2013; Gosling et al., 2013; Carmichael, 2014), most publications have not put a quantitative value on the sustainability performance of adaptable infrastructure (Gann and Barlow, 1996; Attfield, 1999; Moffatt and Russell, 2001; Slaughter, 2001; Till and Schneider, 2005; Schneider and Till, 2005; Schmidt et al., 2010; Gosling et al., 2013); this is particularly the case with respect to the social and environmental aspects of adaptable infrastructure. Thus, there is a need for a suitable approach that examines the current intellectual justifications for the viability of adaptable infrastructure.

Third gap

ROA is used in the literature to evaluate the financial viability of investing in adaptable infrastructure under uncertain conditions (Copeland and Antikarov, 2001; Carmichael et al., 2011). ROA currently takes no account of social and environmental aspects, while adaptability requires an integrated valuation of all sustainability aspects (Moffatt and Russell, 2001; Wilkinson et al., 2009; Taneja et al., 2012; Langston et al., 2013). Moreover, the potential benefits, in terms of social and environmental aspects, of building in adaptability have been neglected by investors. Hence, efforts should be made to incorporate sustainability into adaptability valuation and ROA by taking intangible uncertainties into account and giving a single measure for comparison and decision-making.

Chapter 3: Theory

This chapter clarifies the methods, approaches and associated terminology which are being employed in the following chapters. These are existing methods already established in the literature, but have been adapted in some way for specific applications in this thesis. Each method is referred to associated chapter/s where further detail and applications are discussed.

3.1 The systems approach

A systems approach implies utilising systems thinking or theory as multidisciplinary concepts having received much attention in the literature. 'Systems thinking' means looking at '*a system as a collection of parts that interact with each other to function as a whole'* (Lewis, 1998, p. 90). Systems thinking provides a methodology and modelling tools for understanding complexity through recognising the structure of a system and the relationships between its components (van Gigch, 1974; Maani and Cavana, 2000). Bertalanffy (1950) introduces the concept of system theory as '*formal correspondence of general principles, irrespective of the kind of relations or forces between the components'* (Bertalanffy, 1950, p. 28). Systems thinking can help managing and improving situations of real world complexity more effectively (Reynolds and Holwell, 2010). Adams et al. (2014) define systems theory as a unified group of propositions providing a skeletal structure for the explanation, and increased understanding, of the behaviour of real-world systems. According to Bawden (1998) and Chapman (2004), '*the core aspects of systems thinking are gaining a bigger picture [being holistic] and appreciating other people's perspectives [being more pluralist]'* (Chapman, 2004, p.14). As such, systems thinking avoids working based on a single unquestioning perspective and allows for understanding relationships between variables (Reynolds and Holwell, 2010).

Systems approaches seek resolution - improving the situation - rather than solution - solving the problem (Reynolds and Holwell, 2010). There are many approaches used for different situations to deal with complexities and improve understanding (Jackson, 2000). For the purpose of this thesis, the term ‘systems approach’ is used as a universal approach examining the infrastructure system as a whole and deepening the understanding of the concepts of adaptability or flexibility. The aims of adopting such an approach, given in Chapter 4 of this thesis, can be listed as given in Hammond (2002) as: 1) to foremost reveal the isomorphy of the concept from various fields and help transferring from one field to another, 2) to minimise the duplication of theoretical effort in different fields, 3) to encourage the development of theoretical models, and 4) to promote the unity of science through improving communications among specialists. The adopted systems approach, methodology and modelling are given in detail in Chapter 4.

3.2 Options analysis

The financial value of adaptable infrastructure may be established through Real Options Analysis (ROA). The method used in this thesis for valuing flexibility/adaptability is one developed in Carmichael and Balatbat (2008a) that uses probabilistic Discounted Cash Flow (DCF) analysis with second order moment approach. This method allows for incorporating uncertainty, and differing discount rates and variances between cash flows (Carmichael et al., 2011). Appendix A gives a general formulation of the method; here a formulation specific to the comparative analyses in Chapters 5, 6 and 7 is presented.

The financial analysis examines (A) the extra cost of designing in adaptability and the subsequent adaptation cost, compared with (NA), the more usual situation of not designing in adaptability and its greater adaptation cost. There is a trade-off between extra cost now and extra cost in the future. The time, T, at which adaptation might occur is allowed to vary to show the relationship between time of adapting and adaptability value.

The option analysis follows Carmichael et al. (2011) and Carmichael (2014). Only costs at T are considered in the option analysis. The expected values, E[ ], and variances, Var[ ], of all costs for both A and NA at T are estimated. There are a number of ways by which this can be done. Here, optimistic (a), most likely (b) and pessimistic (c) values are estimated, as is done in the planning technique PERT. This leads to an expected value or mean = (a + 4b + c)/6 and variance = $[(c-a)/6]^2$ (see for example, Carmichael 2006; Carmichael and Balatbat 2008a.) Because estimates for A and NA are based on similar assumptions, it is anticipated that there will be very strong correlations between the estimates for A and NA.

To ascertain the value of adaptability compared with conventional practice, the difference between NA and A is examined. Let X_T be the net cost at time T. That is,

$$X_T = NA_T - A_T \tag{3.1}$$

where A_T and NA_T are the costs, at T, of A and NA respectively. Then,

$$E[X_T] = E[NA_T] - E[A_T] \tag{3.2}$$

$$\mathrm{Var}[X_T] = \left(\sqrt{\mathrm{Var}[NA_T]} - \sqrt{\mathrm{Var}[A_T]}\right)^2 \tag{3.3}$$

These are discounted to give the present worth, PW, of the difference.

$$E[PW] = \frac{E[X_T]}{(1+r)^T} \tag{3.4}$$

$$\mathrm{Var}[PW]\, X \frac{\mathrm{Var}[X_T]}{(1\,\Gamma\, r)^{2T}} \tag{3.5}$$

where r is the interest rate. Calculation of the adaptability value follows, Adaptability value = ΦM (3.6)

where $\Phi = P[PW] > 0$ and is termed the investment feasibility (Carmichael and Balatbat, 2008a), P is probability, and M is the mean of the present worth upside measured from PW = 0. To calculate Φ and M, and knowing E[PW] and Var[PW], any distribution can be fitted to PW, but it is anticipated that most people would use a normal distribution (Hillier, 1963; Tung, 1992).

This adaptability value is then compared with the cost of building in adaptability at time 0. Financial viability is established for adaptability when the adaptability value exceeds this initial cost.

3.3 LCA

Environmental and social intangibles can be grouped into measurables and non-measurables. Measurables involve factors that can directly be measured and expressed quantitatively, while non-measurables relate to issues with inherent subjectivity that are unable to be directly measured in numbers. This thesis focuses on quantification of measurables, which are commonly evaluated through Life Cycle Assessment (LCA) tools (ISO, 2006; Hsu, 2010; Lehmann et al., 2013; Surbeck and Hilger, 2014).

LCA can be used to evaluate the environmental impacts of activities and materials over a building's or infrastructure item's life cycle (manufacture, transportation, construction, operation and deconstruction) (ISO, 2006; Hsu, 2010). LCA might take one of the two approaches outlined below or a hybrid of these (Sharrard, 2007; Jazayeri et al., 2008):

- *Process LCA:* the impacts are quantified based on the resources used in the building's life cycle. This approach is considered to be more accurate, but time-consuming and the required data may be difficult to obtain (Bilec, 2007; Moon et al., 2014).

- *Input-Output (I-O) LCA:* data in the I-O tables, derived from macroeconomic studies of monetary flows, are used to estimate impacts. A coefficient in an I-O table represents the amount of input required to produce one unit of output (Horvath, 1997; Joshi, 1998). This approach takes less time, but is less accurate than process LCA (Bilec, 2007; Moon et al., 2014).

Social Life Cycle Assessment (SLCA), utilising the concept of LCA, may also be applied to value social impacts (UNEP/SETAC, 2009; Lehmann et al., 2013; Surbeck and Hilger, 2014). However, social issues are largely non-measurable. Only those issues that can be dealt with using SLCA are considered in this thesis.

Non-measurables are typically expressed using linguistic terms; fuzzy set ideas might also be attempted (Tan et al., 2011; Hudec and Vujošević, 2012; Siew et al., 2016). The scoring of sustainability reporting tools (SRTs) (for example, BREEAM, 2015; LEED, 2015; GBCA, 2016), however, is not believed to be sufficiently targeted to be useful here (Siew et al., 2013). SRTs mainly emphasise environmental criteria and pay less attention to financial and social aspects; SRTs evaluate sustainability impacts at one time, but not over a building or infrastructure life cycle; they can also be criticised for subjectivity or ambiguity in definition of scales and allocation of scores.

In Chapters 5, 6 and 7, the process LCA approach is adopted; environmental and social issues are kept as intangibles. '*LCA is a relative approach, which is structured around a functional unit* being studied… [It identifies the] *environmental* [or social] *burden between life cycle stages or individual processes'* (ISO, 2006, p. 7). Generally, LCA phases comprise (ISO, 2006): 1) goal and scope definition, where the breadth, depth and detail of the study are determined, characterising the system boundary, life cycle stages, unit processes and flows, 2) Life Cycle Inventory analysis (LCI), in which the relevant inputs and outputs of a product system are quantified through data collection and calculation, 3) Life Cycle Impact Assessment (LCIA), which evaluates the significance of impacts through associating inventory data with selected impact categories, and 4) interpretation, in which the findings from the analysis are presented, the limitations explained and recommendations provided.

The thesis performs a comparative study; the quantification of inventories thus suffices. LCI eliminates the need for weightings and associated subjectivity (Carmichael, 2013b; Siew et al., 2013). LCI is still capable of evaluating sustainability issues over the infrastructure life cycle (ISO, 2006); it is also more straightforward; thus is believed to be suitable for quantification of sustainability of adaptable infrastructure which is in its infancy. Hence, for the purpose of this thesis, the assessment is carried out as an LCI study, such that sustainability impacts are considered as inventory flows and tracked over the specified unit processes at specified times (ISO, 2006) (Figure 3.1). Accordingly, the sustainability impacts, particularly the permanent ones, are not emphasised in this thesis. The social and environmental inventories are compared between the NA and A forms of adaptation.

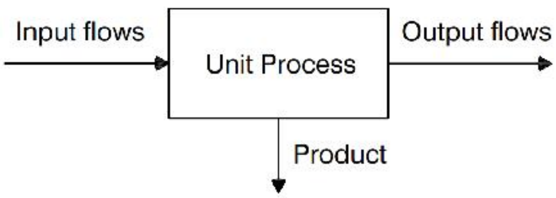

Figure 3.1. Example of a unit process within a product system (ISO, 2006).

As for the financial aspects, the sustainability analysis looks at the social and environmental impacts at times t = 0 and T, assuming impacts subsequent to T to be the same for both A and NA forms. Operational impacts between t = 0 and t = T are also assumed to be the same. Should these assumptions not be so in particular cases, the differences could readily be included in the analysis.

The sustainability assessment of adaptable infrastructure is finally enhanced in Chapter 8 through integrating ROA with Social/Environmental Costing (SEC), using LCA outcomes.

Summary on viability assessment approach/criteria. Basically, infrastructure adaptation is acknowledged as a viable solution in the literature since avoids wasted infrastructure and huge loss of money and resources through prolonging infrastructure service life (Moffatt and Russell, 2001; Engel and Browning, 2008; Short et al., 2010). But this thesis compares designed-in adaptation against fortuitous adaptation, where infrastructure is adapted in both cases; hence the infrastructure lifespan is excluded from criteria for viability.

As mentioned earlier in Chapter 1, the methodology, rather than the design and associated numbers or outcomes on viability, is emphasised in the thesis. The presented analysis approach produces outcomes based on which decision makers with different priorities can decide on viability of designing for adaptability. There are appraisal measures for financial viability of investments including payback period, internal rate of return, benefit to cost ratio and present worth (Carmichael, 2014). Net present value has been used in the literature as a criterion for financial viability of adaptability (Headland et al., 2011; Linquiti and Vonortas, 2012; Cardin et al., 2013). Adaptability Value (AV) which is obtained from Present Worth (PW) distribution, as discussed in section 3.2, is used in this thesis. Adaptability is financially viable if AV exceeds the initial cost of building in adaptability. Social and environmental viability is established if sustainability performance criteria be favourably improved through incorporating adaptability; for example, higher worker employment or lower emissions.

When adaptable design is a dominant solution performing better with regard to all criteria, viability is quite simply established. Otherwise, decision on viability will depend on priorities and weightages given to different criteria by decision makers. The study of possible weightings is out of the scope of this thesis. However, Chapter 8 attempts to eliminate the need for weighting the criteria and give a single measure for viability assessment of infrastructure adaptability.

Chapter 4: Infrastructure Adaptability/Flexibility – A Systems Approach

4.1 Introduction

The inevitable changes in natural, social and technological environments affect infrastructure performance and longevity (Slaughter, 2001; Zhao and Tseng, 2003; Wilkinson et al., 2009). Adaptability can extend the useful life of infrastructure, ensuring continued relevence (Slaughter, 2001; Short et al., 2010).

Australia's population is anticipated to grow in size and change in composition and distribution in the majority of states and territories, leading to changed needs (Commonwealth of Australia, 2015). '*The 21st century challenge of living with whatever human-induced long-term change is superimposed on the continuing natural variability [of climate]'* (Trewin, 2003, p. 39). There is considerable uncertainty regarding the timing and intensity of such changes (IPCC, 2013; Commonwealth of Australia, 2015). These uncertain changes may bring about unanticipated circumstances surrounding infrastructure in future; namely, natural changes may impose loadings other than that planned for (Dobes, 2008), and technological or social changes may have negative implications for existing services in areas such as health, education and housing (Trewin, 2003). As a result, infrastructure may become inadequate or obsolete (Conrad and Raucher, 2013; Carmichael, 2014).

Climate change, with its associated effects on sea levels, air temperatures and rainfall patterns, may cause current coastal protection, flood defences, drainage and water supply systems to become inadequate. Demographic changes in terms of population size and/or structure, resulting in changed demands and wants, may lead to insufficient or obsolete buildings, water supply systems or transport infrastructure. Technological changes manifested in the use of new materials, equipment and methods lead to change in required services and infrastructure obsolescence. For example, introduction of smart roadways/railways or modern means of transportation may abolish use of existing transport facilities (Lovell et al., 2010); or innovative sources of energy may make existing facilities obsolete (Yates, 1988).

As a result of external change, infrastructure intended for long-term operation may require adaptation in order to extend its useful life. This has created renewed interest in infrastructure adaptability or flexibility. Here, the terms adaptability and flexibility are taken to be the same, referring to the capability to change in line with changed future circumstances (Gann and Barlow, 1996; Slaughter, 2001; Schneider and Till, 2005; Greden, 2005; Wang and de Neufville, 2005; Gosling et al., 2013, after Grewin, 1993 and Upton, 1994).

As discussed earlier in Chapter 2, there is confusion in the literature regarding two aspects; first, many deal with infrastructure adaptability and flexibility, as has been done with stock options, by emphasising managerial adaptability with no regard to technical design (Barman and Nash, 2007; Cardin, 2007; Lister, 2007; Headland et al., 2011; Taneja et al., 2012). Although this attitude may be beneficial in terms of responding to uncertainties, it underestimates infrastructure's capability for incorporating adaptability through a change in design or physical architecture. In other words, design is a major advantage distinguishing infrastructure, as real (physical) assets, from financial assets and this requires further emphasis when delivering real options. Second, the literature on infrastructure adaptability and flexibility has yet to settle on an agreed research framework and categorisation (Moffatt and Russell, 2001; Fricke and Schulz, 2005; Till and Schneider, 2005; Wang and de Neufville, 2005; Lee, 2007). This points to the need for a holistic approach to infrastructure adaptability and flexibility.

As a contribution towards a general framework, the chapter adopts a systems approach for adaptable design. There are many approaches available for dealing with complexities and improving understanding (Jackson, 2000; Reynolds and Holwell, 2010); the approach presented here is based on the work by Carmichael (2013b, 2015). The chapter first looks at infrastructure design, with system variables identified, to introduce adaptability as closed-loop control. It then clarifies suggestions on adaptable infrastructure and associated options, using the given systems definitions, and suggests adaptability valuation. Finally, a case example involving rock seawall adaptability in the Australian coastal protection context illustrates the approach. The outcome is intended for people seeking a systematic approach to decision-making on infrastructure adaptability.

4.2 Infrastructure systems design

Engineers typically design infrastructure for forces exerted by the surrounding environment, with possible changes in the future. They know how infrastructure functions, and so design the infrastructure item's engineering characteristics such that it responds to these forces and gives the desired performance. For example, hydraulics engineers aiming to design a canal for projected rainfall/runoff rely on their hydraulics engineering knowledge and choose the canal section dimensions for minimum overflow.

The process engineers go through during infrastructure design can be examined systematically. To this end, the underlying system variables are defined and identified for a number of infrastructure items in the following sections.

4.2.1 System variables

Considering infrastructure as a system, the variables characterising infrastructure may be grouped as inputs, states and outputs (Carmichael, 2013a) (Figure 4.1):

- Inputs are categorised into: influenceable inputs (referred to here as controls), comprising design variables such as infrastructure capacity; and non-influenceable inputs (emanating externally to the system) including those resulting from climate and demographic factors. Constants may also be present, although they are not considered here.

- States and outputs both characterise the system's performance, behaviour or response; for example, the level of traffic congestion or runoff or overflow water. The states are non-measurable and non-observable and reflect the system's internal behaviour, while the outputs are measurable, observable and represent the system's external behaviour (Carmichael, 2013b, 2015). For elementary engineering models, the state and the output may turn out to be the same.

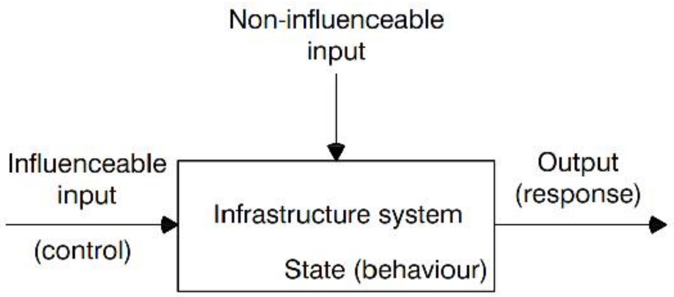

Figure 4.1. Representation of infrastructure system and underlying variables (Carmichael, 2013b).

Possible controls, states and outputs for certain types of infrastructure subjected to non-influenceable inputs of climate and demographic changes are given in Tables 4.1a and 4.1b (see Appendix B for more examples).

Control	State	Output
Coastal defences – sea level rise		
Crest level	Freeboard	Water overtopped
Seaward slope	Wave overtopping; armour stability	Water overtopped; armour displacement
Transport – sea level rise and/or extreme rainfall change		
Distance receded from coastal/low-lying areas	Risk of flooding	Overflow water
Quay wall height	Freeboard	Water overtopped
Transport – air temperature rise		
Vehicles' air conditioning capacity	Occupants' level of comfort	Indoor temperature
Buildings/real estate – air temperature rise		
Heat barriers capacity	Occupants' level of comfort	Indoor temperature
House bushfire protection	Risk of fire	Property damage
Buildings/real estate – extreme rainfall change or sea level rise		
Lower floor elevation	Freeboard; risk of flooding	Water seepage
Urban development – rainfall change		
Settlement location	Risk of flooding	Flooded area
Water management systems – sea level rise or rainfall change		
Stormwater drain/canal capacity	Head difference; water flow rate	Undrained water
Water management systems – rainfall change		
Rainwater retention capacity	Water supply; runoff	Service pressure; flooded area
Dam wall height	Flood risk	Overflow water; downstream damage

Table 4.1a. Examples of variables of infrastructure system under changing climate.

Control	State	Output
Buildings – change in user population		
Number of storeys; building footprint	Over occupation	Per capita space
Buildings – change in user wants or population		
Space layout	Space usage efficiency	Active space area
Space use	Usage fitness	Occupancy rate
Transport – change in user population		
Number of road lanes; Bridge's deck width; Quay length	Traffic congestion	Travel time
Transport – change in user wants or population		
Port layout	Space usage efficiency	Active space area
Water resources systems – change in user population		
Capacity of water reservoirs/distribution network	Service pressure	Disruption to operation
Dam hydropower station capacity	Voltage level	Disruption to operation

Table 4.1b. Examples of variables of infrastructure systems under changing demographics.

Infrastructure design fits within synthesis configuration as design variables (controls) are decided upon for a given performance (state or output) (see for example, Carmichael 2013a, 2013b). Possible forms of the three components of synthesis, namely objective functions, constraints and a model of the system are briefly discussed in the following.

4.2.2 Objective functions

Synthesis leads to non-unique results for the system controls; thus, objectives are required to be able to compare alternative solutions (Carmichael, 2013a, 2013b). Objective functions can be defined based on whatever value a designer is concerned about. With infrastructure design, this might be the infrastructure technical performance, represented by state or output. Other possible objectives might be design and construction costs, or associated social or environmental impacts. Extremisation of these objectives is intended to reach a unique design solution; however, there are different approaches to deal with multiple conflicting objectives (see for example, Carmichael 2013b).

$$\max J_1 = \text{technical performance} \tag{4.1a}$$

$$\min J_2 = \text{costs, social or environmental impacts} \tag{4.1b}$$

4.2.3 Constraints

Constraints limit the possible solutions to admissible ones. They are typically expressed in the form of equalities and/or inequalities, and may originate from budget, timeframe, political, environmental, legal or technical matters, depending on different circumstances (Carmichael, 2013b). The best design, or control value, must not only extremise the objective function but also satisfy the constraints. With infrastructure design, constraints might include budget or environmental limitations on the construction of a dam, time constraints on road/railway construction, political limitations on the choice of a settlement location, legal restrictions on building height, or technical limitations to availability of a specific material or armour size for coastal protection.

4.2.4 Model of the system

'A model is often a constitutive equation that characterises the system and enables the effect of alternative controls on the system to be predicted' (Carmichael, 2013b, p. 122). The infrastructure system model can be obtained using formulae in design standards, or otherwise by fixed principles or system identification. Any specific infrastructure item requires individual consideration to establish the model equations. Some examples include stress-strain or load-deflection equations for structural design, or traffic volume-capacity equations for road design.

4.3 Infrastructure adaptability: The closed-loop control

The projected forces the infrastructure is designed for may not be realised due to the uncertain nature of the environment. As a result, the infrastructure may underperform and become inadequate or obsolete. Engineers will accordingly have to redesign the infrastructure. This implies the need for incorporating adaptability (Carmichael, 2015). For example, hydraulics engineers would have to redesign a canal that has failed under changed rainfall patterns, creating the need to incorporate adaptability.

Infrastructure adaptability can be translated into systems terms. The unexpected changes in projected forces, referred to as disturbance, prevents the planned-for infrastructure performance (state or output) from being established (Carmichael, 2013b). In control systems theory, '*this creates a need to go beyond usual open loop control, to create closed-loop (feedback) control … In closed-loop control, unlike open loop control, there is a circular transmission of information'* (Carmichael, 2015, pp. 1–2). The actual infrastructure performance is monitored and compared with the planned-for performance, giving the difference or error. Based on the error, a feedback or corrective action; that is, a change in the design variables (controls) is decided upon. Infrastructure adaptability is shown in Figure 4.2 as closed-loop control.

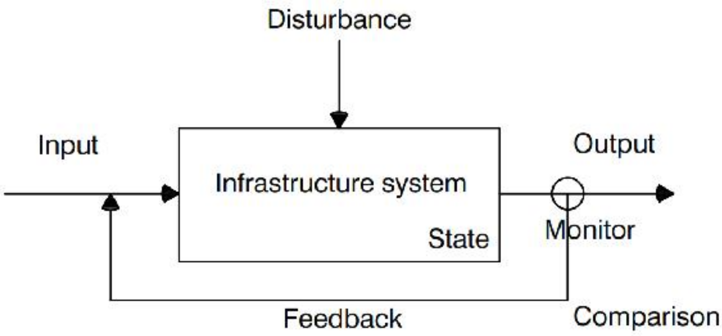

Figure 4.2. Representation of infrastructure adaptability as closed-loop control (Carmichael, 2013b, 2015).

The usual three components of closed-loop control formulation; namely, the system model, objective function and constraints (Carmichael, 2013b) are applicable to infrastructure adaptability, and are discussed in the following sections.

4.3.1 System model

The information obtained from the infrastructure performance monitoring and subsequent adaptations is inherently discrete. Hence, the infrastructure system model is preferably formulated in the form of a first-order difference equation, as a standard state equation with discrete time (Carmichael, 2013b, 2015):

$$x(k+1) = F[x(k), u(k), k] \qquad k = 0, 1, 2, \ldots, N-1 \tag{4.2a}$$

where k is a counter of time or period; x(k) is the infrastructure performance (state) at k; u(k) is the control (here is the change in infrastructure design variables) at k; and F is a non-linear function. The equation above implies that the state, at k+1, depends only on the immediately previous state and control at k.

Where system identification is involved, there would be an additional equation, called the response, output or observation equation (Carmichael, 2013b, 2015):

$$z(k) = h[x(k), u(k), k] \qquad k = 0, 1, 2, \ldots, N \qquad (4.2b)$$

where z represents the infrastructure performance (output); and h is a function of the arguments shown.

In the above equations: determination of boundary conditions is required; namely, the initial conditions, x(0) and u(0), and possibly the terminal conditions, x(N) and u(N)… ‘*Parameters or constants and inputs from the external environment are not explicitly stated, even though they may be present… A disturbance term may be included in acknowledging uncertainty*’ (Carmichael, 2015, p. 11).

4.3.2 Objective function

As closed-loop control, the aim of infrastructure adaptation is to nullify the effects of disturbance (manifested in changed non-influenceable inputs) on the infrastructure performance. The objective function is accordingly the infrastructure performance error; that is, the difference (var) between planned-for performance, x, and actual performance, xA, being minimised repeatedly over time (Carmichael, 2015).

$$\min J_3 = x(k) - xA(k) = \mathrm{var}\,(k) \qquad k = 1, 2, \ldots, N \qquad (4.3a)$$

There might also be other objectives on the basis of decision-makers’ value systems, such as the costs of design and construction, or the associated social or environmental impacts, being minimised throughout the infrastructure lifetime:

$$\min J_4 = \sum_{k=0}^{N} \text{(costs, social/environmental impacts)}; \; k = 0, 1, \ldots, N \qquad (4.3b)$$

4.3.3 Constraints

Constraints of various forms, including equalities and inequalities, may be present. Non-negativity constraints are generally included, but explicit characterisation of these constraints requires separate consideration of each specific infrastructure item.

With infrastructure adaptation, similar to the earlier explanation for infrastructure design, the constraints might be in terms of budget or environmental limitations on a dam wall height increase, time limitations on a road/railway retreat from low-lying areas, political limitations to settlement relocation, legal restrictions on raising building height, and constructability issues or technical limitations on the availability of a seawall armour size, for example.

4.3.4 Infrastructure adaptability and sustainability

Infrastructure adaptability has been shown as a closed-loop control. Similarly, sustainability in construction implies a transition from conventional linear to closed-loop processes (Figure 4.3) resembling the cyclical patterns in natural ecosystems (Miyatake, 1996; Fiksel, 2006). Hence, an improved sustainability performance is perceived through incorporating adaptability. Indeed, adaptability is anticipated to enhance sustainability as it helps infrastructure remain in operation and lengthen its life cycle, and avoids inefficient or wasted infrastructure by responding to the changing environment (Taneja et al., 2012; Conrad and Raucher, 2013; Carmichael, 2014; Williams et al., 2017).

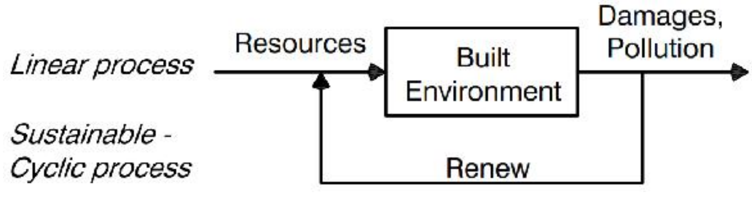

Figure 4.3. Processes of built environment development (adapted from Miyatake, 1996).

The literature recognises infrastructure adaptability as a strategy greatly contributing to sustainability enhancement (Larsson, 1999; Moffatt and Russell, 2001; Smit and Pilifosova, 2001; Till and Schneider, 2005; Wilkinson et al., 2009; Taneja et al., 2012; Conejos et al., 2013; Gosling et al., 2013; Langston et al., 2013). Fiksel (2006) argues that a sustainable development in the changing global environment depends on having adaptability. Schneider and Till (2005) argue that *'sense tells us flexibility is more beneficial in the long term because obsolescence is limited, but there is little quantitative data to substantiate this argument'* (Schneider and Till, 2005, p. 162). The idea requires quantitative assessments for justification (Gann and Barlow, 1996; Moffatt and Russell, 2001; Slaughter, 2001; Schneider and Till, 2005; Gosling et al., 2013), particularly when comparing different adaptability approaches, such as built-in and non-built-in, that all result in extended useful life.

4.4 Suggestions on adaptable infrastructure: A universal interpretation

Many suggestions have been proposed in the literature for incorporating adaptability in infrastructure. Having recognised infrastructure adaptability as part of closed-loop control thinking, these suggestions can be characterised by the influenced controls, u, which are the adjustments in design variables. Tables 4.2a and 4.2b illustrate some suggestions on adaptable infrastructure under changing climate and demographics using the influenced controls corresponding to the design variables identified earlier (see Appendix C for the sources of these suggestions and more examples). The tables also give the terms used to imply the ability or option exercised through each adaptability suggestion.

Control, u	Ability or option to	Source
Coastal defences – sea level rise		
Additional height (crest level)	upgrade; extend	Woodward et al. (2011), Burcharth et al. (2014)
Reduction in slope	upgrade	Townend and Burgess, (2004), Burcharth et al. (2014)
Transport – sea level rise and or extreme rainfall change		
Increase in distance from coastal/ low-lying areas	relocate	Dobes (2008)
Increase in height of quay wall	extend; rise	Taneja et al. (2012)
Transport – temperature rise		
Addition to vehicles' air conditioning capacity (i.e., space, support, AC units)	upgrade	Dobes (2008, 2010)
Buildings/real estate – temperature rise		
Additional heat barrier capacity (i.e., space, supports, barriers such as shade blinds, trees)	expand; upgrade	Shashua-Bar and Hoffman (2004), Dobes (2008)
Addition to houses' bushfire protection (i.e., space, preliminaries, fire shelters)	install; upgrade	Dobes (2010)
Buildings/real estate – extreme rainfall change or sea level rise		
Increase in floor elevation	rise; upgrade	Dobes (2010), Headland et al. (2011)
Urban development – rainfall change		
Relocation of settlement	relocate	Schuetze and Chelleri (2011)
Water management systems – sea level rise or rainfall change		
Addition to stormwater drainage capacity (i.e., system elevation, section size, pumps)	install; upgrade	Headland et al. (2011), Gersonius et al. (2013)
Water management systems – rainfall change		
Addition to rainwater retention capacity	expand	van Stokkom et al. (2005), Schuetze and Chelleri (2011)
Addition to dam flood protection (i.e., structure strength, spillway/crest level)	upgrade; expand	Gersonius et al. (2013)

Table 4.2a. Adaptable infrastructure – controls and associated options: changing climate.

Control, u	Ability or option to	Source
Buildings – change in user population		
Additional storeys	expand/shrink	Moffatt and Russell (2001), de Neufville et al. (2006), Guma (2008)
Additional footprint (i.e., land, erections)	extend; expand	Lee (2007), Ressler (2014)
Buildings – change in user wants or population		
Change in space layout (i.e., interior wall locations)	expand/shrink; move	Moffatt and Russell (2001), Slaughter (2001), Arge (2005), Greden (2005)
Change in space use	convert; switch; sublet/shrink	Gann and Barlow (1996), Kendall (1999), Moffatt and Russell (2001), Till and Schneider (2005)
Transport – change in user population		
Additional number of road lanes (i.e., land, substructure, pavement)	extend	de Neufville (2003)
Additional width of bridge's deck (i.e., capacity of piles, footings, abutments)	expand	Gesner and Jardim (1998), Bennett et al. (2009)
Additional length of quay (i.e., piers, deck)	extend	Taneja et al. (2012)
Transport – change in user wants or population		
Change in port marine layout	scale up/down	Taneja et al. (2012)
Water resources systems – change in user population		
Addition to distribution network capacity (i.e., reservoirs, control tanks, pipes)	expand	Huang et al. (2010), Basupi and Kapelan (2015), Marques et al. (2015)
Addition to dam hydropower station capacity (i.e., space, footing, turbine)	expand; upgrade	Wang and de Neufville (2006)

Table 4.2b. Adaptable infrastructure – controls and associated options: changing demographics.

As can clearly be seen from these tables, any type of infrastructure flexibility/adaptability (e.g., expandability/shrinkability, upgradability, scalability, movability, convertibility, flexibility in plan/layout) and the options exercised (e.g., option to expand/grow, extend, shrink/contract, convert/switch), lie under a single universal concept implying the 'ability or option to influence the controls'. In other words, these are the controls over which a decision-maker has the ability or option, the right (but not the obligation), to influence and adapt infrastructure.

4.4.1. Designed-in adaptable infrastructure

Given that infrastructure may inevitably be adapted to the uncertain changing environment to prolong its lifetime, designers face the dilemma of whether to design infrastructure for adaptability or not. This implies the notions of designed-in adaptability versus non-designed-in or fortuitous adaptability (Carmichael, 2015, 2016).

The term designed-in adaptability is here used in the real options sense, where a deliberate decision is made and '*the asset is designed ab initio with the view that infrastructure adaptation will likely (but not necessarily) take place in the future*; on the contrary, with non-designed-in adaptability giving no forethought to future adaptation, *the asset is designed initially without express adaptability features, but still may be capable of being adapted in some way, perhaps fortuitously, in the future'* (Carmichael, 2015, p. 9).

From the systems approach presented, designed-in adaptability means no more than a deliberate change in the initial values of the controls, u(0), at any system level, creating and/or leaving other controls to possibly be influenced later in response to altered infrastructure performance. For example, this might be a change in the fabrication method of a house (e.g., use of prefabricated steel frames) during the initial design, creating and leaving other controls; namely, building element reuse, the house location or floor level to be decided upon later (Dobes, 2010); or an initial addition to an airport's land area and substructure, leaving the runway length to possibly be extended in the future (Ohama, 2008). However, the choice of suitable controls and the associated initial values requires ingenuity as well as a deep understanding of infrastructure engineering and interactions within a changing environment (Wang and de Neufville, 2005; Carmichael, 2014).

Designed-in adaptability gives an alternative sequence of decisions or controls throughout the lifetime of the infrastructure. The initial influence on these controls may lead to a change in their ongoing values. However, the extent to which any designed-in adaptability feature affects future adaptation may be different depending on the specifics of each case.

There are many suggestions in the literature on designing in adaptability. These can be interpreted in terms of changes in the initial values of controls, as given earlier in Tables 4.2a and 4.2b. Similarly, designed-in adaptability features providing various types of adaptability or options lie under a single, universal concept implying 'initial, deliberate influence on controls, creating and/or leaving the ability or option to influence other controls in future'.

4.5 Case example: Rock seawall adaptability

Seawalls, as the last line of defence against sea water, protect the land behind from overtopping and flooding and shore erosion (Yip et al., 2002; Carmichael, 2015). Climate change induced seal level rise with the attached uncertainty poses a threat to seawall performance (DECCW, 2010a; NCCOE, 2012a). Where seawalls become inadequate against rising sea levels, the issue of adaptability arises.

This section looks at seawall adaptability from the systems approach. Different types of seawalls exist, but the case example here is focused on the adaptability of rock seawalls, as these are widely used in Australia with its ready availability of rock material.

4.5.1 Rock seawall system/subsystems

Considering a rock seawall as a system, the system boundaries are characterised as the physical boundaries separating the structure—typically comprising the core, rock toe, underlayer, rock armour layer and parapet wall—from the external environment (NCCOE, 2012a).

Any system can be defined as a set of subsystems. Although the definition of the subsystems may be different depending on the modeller's viewpoint, they should be determined as the physical elements requiring adjustment due to changing environmental impacts. With rising sea levels, the required height of protection changes; this requirement must be met typically through an increase in the crest level together with an increase in the parapet wall height (Burcharth et al., 2014). In the Australian coastal protection context, with shallow water and breaking wave conditions, increasing water depth also intensifies wave height, requiring a greater mass of rock armour (Townend, 1994; Isobe, 2013). Hence, the rock seawall subsystems turn out to be 'seawall crest', 'parapet wall' and 'rock armour'. Other adaptation methods, such as slope reduction (Townend and Burgess, 2004; Burcharth et al., 2014), as well as other design requirements, such as stability against toe scour (USACE, 1995), may be present but are not considered here.

Subsystems interactions. Subsystems generally, but not necessarily, interact with each other. The adopted subsystems interact in parts: the size of the rocks added at the top determines the crest level, which itself determines the parapet wall height and its associated foundation size. Such technically logical relations reflect the subsystems' interactions, as indicated by the arrows in Figure 4.4.

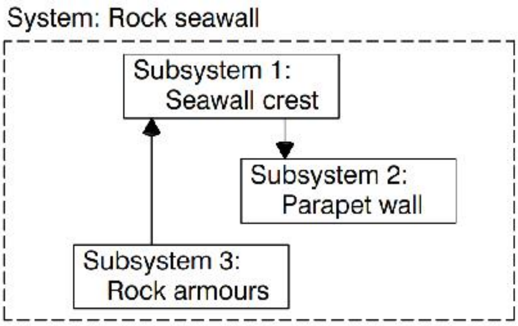

Figure 4.4. Representation of the rock seawall system, subsystems and their interactions.

System variables. A definition of the rock seawall system variables, comprising inputs, states and outputs follows.

- *Non-influenceable inputs* consist of the water depth at the toe of structure, h, and sea level rise, Δ. Constants exist in the design formulation; namely, the minimum acceptable ratio of freeboard to water depth, c_1, minimum acceptable parapet wall stability, c_2, and minimum acceptable rock armour stability, c_3.
- *Influenceable inputs (controls)* comprise the design variables of crest level, parapet wall height, P_w, parapet wall foundation size, P_f, and individual rock armour mass.
- *States* representing the seawall internal performance include freeboard, F; that is, the difference between the sea level and the crest level; parapet wall stability against overturning, S_P, and rock armour stability, S_R.
- *Outputs* characterising the seawall external performance include the volume of overtopped water, parapet wall settlement and rock armour displacement; however, here they are assumed to be the same as states.

4.5.2 Rock seawall adaptability: Closed-loop control

Rising sea level uncertainty, manifested in *disturbance*, may lead to the rock seawall becoming inadequate in terms of height of protection and stability against wave loads. This creates a need for the seawall to be upgraded. As a result, adaptability is incorporated to adjust the altered performance. This is carried out through a change in design variables, based on the difference between the desired and actual (denoted A) performance.

For a systems representation of rock seawall adaptability, the controls are here determined as change in the design variables; namely, additional seawall height (crest level), u_C, additions to the parapet wall height, u_w, and foundation size, u_f, and additions to the rock armour mass, u_M. The definitions of the other system variables remain the same. The rock seawall adaptability can be shown in the form of closed-loop control as in Figure 4.5.

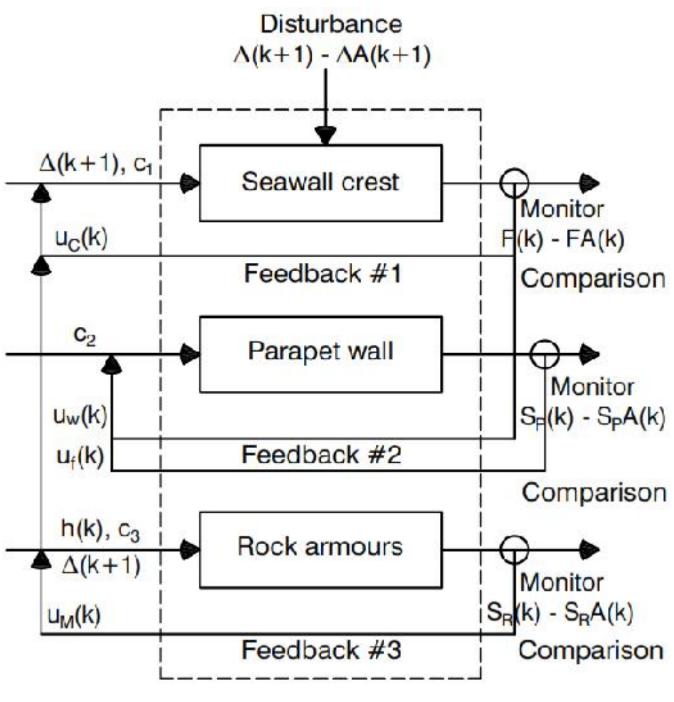

Figure 4.5. Rock seawall adaptability: closed-loop control representation.

The formulation of the usual three components of closed-loop control; namely, the system model, objective function and constraints is given for rock seawall adaptability in the following section.

4.5.2.1 System model

The system model is detailed here for each subsystem. This consists of state equations and feedback functions. In the state equations, the transition between consecutive states is seen, even implicitly, such that the state at k + 1 depends only on the immediately previous state and control at k, k = 0, 1, 2, …, N – 1. Associated with the system formulation are boundary conditions on the states and controls, but these are not presented here for conciseness. Initial condition for individual rock armour mass (control) $M(0) = c_3 \cdot h^3(0)$; and initial condition for parapet wall stability against overturning (state) $S_P(0) = 1$ are the examples though.

Rock armour. According to Hudson’s equation, the required mass of individual rock is proportional to the cube of breaking wave height, which itself is proportional to water depth (Isobe, 2013). The rock armour stability, S_R, is thus assumed as the ratio of rock mass, M, to water depth cubed, h^3. Water depth at k+1 equals the sum of water depth and planned-for sea level rise at k. The current mass of rock and the required addition to mass at k specify the following mass at k+1. The addition to the mass of rock in response to reduced stability also follows Hudson’s equation, being determined on the basis of the difference between the cubes of actual (denoted A) and planned-for water depth.

State equation: $$S_R(k+1) = \frac{M(k) + u_M(k)}{(h(k) + \Delta(k+1))^3} = \frac{S_R(k) \cdot h^3(k) + u_M(k)}{(h(k) + \Delta(k+1))^3}$$

Feedback function: $$u_M(k) = c_3 \cdot [hA^3(k) - h^3(k)]$$

Seawall crest. Any following freeboard, F(k+1), would equal the sum of the current freeboard, F(k) and additions to the crest level, $u_C(k)$, taking into account the reduction due to planned-for sea level rise, Δ(k+1). The additional height is a response to the difference between the planned-for and actual freeboard, FA.

State equation: $F(k\,\Gamma 1)\;X F(k)\,\Gamma\, u_C(k)\; Z\Delta(k\,\Gamma 1)$

Feedback function: $u_C(k)\;X c_1\;|\,[F(k)\;Z FA(k)]$

Parapet wall. Stability against overturning, S_P, is assumed to be the ratio of the foundation size, P_f, to the height of the parapet wall, P_w. The parapet wall's dimensions and additions at k specify its dimensions at k+1. Following rock placement on the crest, an addition to parapet wall height, $u_w(k)$, is made as much as the crest level increase, $u_C(k)$, maintaining safe use of the land behind. There would also be an addition to the parapet wall foundation size, $u_f(k)$, should the stability fall below the minimum acceptable due to increasing the wall height.

State equation: $S_P(k\;\Gamma 1)\;X\,\frac{P_f(k)\;\Gamma\,u_f(k)}{P_w(k)\;\Gamma\,u_w(k)}\;X\,\frac{S_P(k)\;|\;P_w(k)\;\Gamma\,u_f(k)}{P_w(k)\;\Gamma\,u_w(k)}$

Feedback functions: $u_w(k)\;X u_C(k)$; $u_f(k)\;X c_2\;|\,u_w(k)$

4.5.2.2 Objective function

The purpose of the rock seawall adaptation is to nullify the effects of disturbance on its performance. The objective function is thus the difference between the planned-for and actual performance associated with the seawall elements, being minimised repeatedly over time.

$$\min J = x(k) - xA(k) \qquad x \quad \{F, S_P, S_P\}$$

Other objective functions might exist, including costs or social or environmental impacts. These are dependent on the changes in design elements and the associated work quantities and are minimised throughout the rock seawall's service life.

4.5.2.3 Constraints

Non-negativity constraints are present for the controls. The minimum requirements must be met by the state variables of freeboard, parapet wall stability and rock armour stability. The minimum possible addition to the crest level is restricted by the rock size should a layer of rock be added on the seawall crest: the nominal diameter equals the mass of rock divided by density, ρ. There might also be a limitation on the maximum rock size or mass due to rock availability.

$$C, P_w, P_f, M, u_C, u_w, u_f, u_M \mid 0$$

$$F(k) \mid c_1 \mid h(k)\,;\; S_P(k) \mid c_2\,;\; S_R(k) \mid c_3$$

$$u_C(k) \mid \frac{M(k)\,\Gamma\, u_M(k)}{\rho}\,;\; M_{max} \mid M(k)$$

4.5.3 Designed-in adaptability

With creative thought, there may be many possible methods for incorporating adaptability in rock seawall design. For the system defined below, designed-in adaptability features implying a deliberate change in initial values of controls can be conceived.

- Choose an initial addition to the rock armour mass, $u_M(0)$, except zero, leaving the additional seawall height, $u_C(k)$, k = 1, 2, …, N – 1, to be decided upon at a later time in response to freeboard measurements.
- Choose an initial addition to the parapet wall foundation size, $u_f(0)$, except zero, leaving the additional parapet wall height, $u_w(k)$, k = 1, 2, …, N – 1, to be decided upon at a later time in response to crest level measurements.

4.6 Adaptability valuation: Systems mechanism

This section clarifies how the given systems definitions are linked to adaptability valuation, where the designed-in (A) form is compared to the non-designed-in (NA) form. The adaptability value is basically established through Real Options Analysis (ROA). The preferable ROA method, presented in Chapter 3, is in line with conventional cash flow calculations (Carmichael et al., 2011; Carmichael, 2014). The set of control values chosen produces cash flows. As such, any cash flow component at period k, Y_k, is characterised as a function, g, of the associated control values at k. That is,

$$Y_k = g[u_Y(k), k] \qquad k = 0, 1, \ldots, T, \ldots, N \tag{4.4}$$

where $u_Y(k)$ is the control value at period k associated with Y_k cash flow component, and $Y \in \{NA, A\}$.

Assuming the same situations for the two forms during infrastructure operation and subsequent to the time of adaptation, T, only cash flows at T are considered in the option analysis. The net cash flow at time T, X_T, then becomes

$$X_T = NA_T - A_T \tag{4.5}$$

where A_T and NA_T are the costs, at T, of A and NA respectively. Cash flow uncertainty is captured by estimating the moments (expected values and variances) of the cash flow components for both A and NA at T. These give the moments of net cash flow and total present worth, PW, based on which the adaptability value is calculated (see Section 3.2 for more details).

This adaptability value is then compared with the cost of building in adaptability at time 0, that is $A_0 - NA_0$ (a function of initial controls). Viability is established for adaptability when the adaptability value exceeds this initial cost. This approach to adaptability valuation will be discussed in detail and demonstrated in three infrastructure case examples in the next chapters.

4.7 Discussion and conclusion

The chapter adopted a systems approach to infrastructure adaptability. It was implicitly suggested that adaptability contributes to infrastructure sustainability as it transforms a linear (open loop control) to a cyclic (closed-loop control) pattern of development, which is the philosophy behind sustainability (Miyatake, 1996; Fiksel, 2006). The chapter also showed, using the systems approach, that different types of infrastructure adaptability and real options can be interpreted as a single universal concept; that is, the 'ability or option to influence the controls'. The interpretations were demonstrated in a case example involving rock seawall adaptability. The infrastructure adaptability valuation, as linked to the concept of controls, was also presented.

Any type of infrastructure requires individual consideration; however, it is believed that the associated adaptability can be modelled and valued in a similar way. The systems approach was used only for clarification purposes; infrastructure adaptation with a discrete, long timescale may not require detailed modelling as used in the computation style.

An uncertain changing environment, such as changing climate, demographics or technologies, may lead to infrastructure becoming inadequate or obsolete, creating the need for adaptability. The literature widely attempts to incorporate infrastructure adaptability, but lack of a holistic approach has led to confusion and incoherence in the context of infrastructure adaptability. This chapter has clarified and added to the current literature through adopting a systems approach to infrastructure adaptability.

The chapter’s approach and inclusive interpretations of infrastructure adaptability linked to the ROA are original. This approach will be useful to people in the construction field looking for an improved understanding and informed decision-making on infrastructure adaptation.

Chapter 5: Valuing Seawall Adaptability to Climate Change Effects

5.1 Introduction

Seawalls, as the coastal defence against seawater, protect the land behind them from overtopping and flooding and shore erosion (Yip et al., 2002; DEHP, 2013). A large and growing proportion of people inhabit coastal areas around the world (Bulleri et al., 2005). In Australia, a large part of the coastline is protected by the seawalls; for example, in Sydney Harbour seawalls constitute almost half of the foreshore (Chapman and Bulleri, 2003). With rising sea levels, Sydney councils and the state government together spend billions of dollars on seawall construction or strengthening (Davies, 2013). The local government's expenditure on coastal protection works and infrastructure upgrading has been over $10M, with a budgeted amount of up to $1.25M per year (Gurran et al., 2011). This also indicates massive construction-related environmental and social impacts. Thus, seawall failure and the way seawalls are upgraded represent a significant sustainability issue.

Seawalls are conventionally built for the projected sea level and associated wave loads at the time, with no foresight of changes in future conditions. With the inadequacy of current seawalls against the effects of climate change on sea levels and possible severe conditions (DECCW, 2010a; NCCOE, 2012a; DEWNR, 2015), the issue of adaptability arises. Adaptability here refers to the capability to be changed and upgraded in line with future circumstances. As sea levels rise, seawalls need to be upgraded. This may be done through building a new structure after a retreat from, or an advance into, the seawater, or if a new seawall is not desirable, an enlargement of the existing structure (Fletcher et al., 2013; Burcharth et al., 2014).

The literature acknowledges protection and adaptability so that the seawalls continue to function, but falls short of their valuation (Dobes, 2008; Flocard and Blacka, 2012; NCCOE, 2012a; Burcharth et al., 2014). This chapter addresses the financial valuing of adaptability through Real Options Analysis (ROA) (Carmichael et al., 2011), and evaluates social and environmental intangibles using life cycle analysis. A comparative study is carried out between the two forms of adaptation; namely, the designed-in (A) form versus the non-designed-in (NA) form. Rock seawalls able to be upgraded without compromising the structural integrity are examined as a case example. This is done in an Australian coastal protection context, with respect to changes in regional sea levels. The method, but not necessarily the designs and associated numbers used in the case example, are applicable to other situations and locations.

The outcomes will be useful to people involved in coastal development and protection schemes, typically planned by local governments and councils. The chapter presents an approach for valuing infrastructure adaptability from the sustainability viewpoint. The given approach to establishing the viability of adaptability within seawall construction is original, where specific adaptability can be incorporated in design and construction and valued. The chapter does not examine the specifics of design; but rather, valuation based on design concepts.

The chapter firstly provides a review on the notion of seawall adaptability or flexibility, and whether adaptability has been incorporated and valued in terms of sustainability. It then comments on future sea level changes and the need for adaptable seawalls. Finally, the analytic approach given in Chapter 3 (Sections 3.2 and 3.3) is demonstrated on adaptable rock seawalls as a case example, putting forward some arguments on the viability of seawall adaptability.

5.2 Terminology: Seawall adaptability/flexibility

The literature uses the term adaptability or flexibility in different ways. Some regard seawall adaptability as the ability to make managerial decisions, or so-called 'adaptive management' as sea levels changes (Peterson et al., 1997; DEFRA, 2006; Hallegatte et al., 2011; Headland et al., 2011; Conrad, 2012; Conrad and Raucher, 2013). Peterson et al. (1997), after Walter (1997), refer to adaptive management as '*a* *structured process of learning by doing'* (Peterson et al., 1997, p. 4). Conrad and Raucher (2013) suggest, in broader terms, that adaptive management is *'an iterative process for improving and revisiting management policies and practices by learning through monitoring and from outcomes of rigorously designed investigations'* (Conrad and Raucher, 2013, p. 3). This notion concerns managerial flexibility giving the option to delay or stage adaptation action. However, physical design requirements are also of high importance when adapting real assets, such as seawalls.

Others refer to seawall adaptability as the ability embedded in their design that creates an option, but not an obligation, to upgrade in response to rising sea levels (Dobes, 2008; Woodward et al., 2011). Woodward et al. (2011, 2013) use flexibility to mean the capability incorporated in the design for future modifications, even though seawalls with no built-in ability for adaptation may still be able to be adapted as climatic effects exert extreme economic and social damage. Short et al. (2010), after Wilbanks et al. (2007), define adaptability as the '*ability of a system to evolve in order to accommodate external changes'* (Short et al., 2010, p. 8).

In this chapter, the sense of the terms flexibility and adaptability is taken to be the same, referring to the capability (of any type; whether managerial or engineering, built-in or non-built-in) to change in line with future circumstances.

The changing climate and subsequent effects on sea levels and extreme events impact the longevity of coastal infrastructure. Adaptability can give continuing relevance to infrastructure against climate change (Short et al., 2010). Adaptability features can either be built-in (A form) or not built-in (NA form), as discussed in the following.

The literature on seawall adaptation mostly falls under the NA form. For example, this may be adding to the seawall height; because of a decrease in freeboard or increase in potential overtopping or wave runup as effects of sea level rise (Headland et al., 2011; Burcharth et al., 2014; Neumann et al., 2014). However, the A form is the focus of this chapter, and the NA form is used as a base case for comparison purposes.

5.3 Seawall upgrades: The non-built-in (NA) form

The choice of proper reaction to the effect of sea level changes on seawalls has been a matter of notice. In general, the possible solutions include land protection, abandon and retreat with resettlement elsewhere, or accommodation with changes in the existing settlement (NCCOE, 2012b). Among these, protection measures preventing substantial social and economic damage are typically preferred (Ng and Mendelsohn, 2005; Hallegatte et al., 2011; Kontogianni et al., 2014; Neumann et al., 2014). With protection, upgrading of existing seawalls is preferable to retreat and new construction behind the existing seawall since most seawalls are readily upgradable (NCCOE, 2012a).

Changes in sea levels, wave loads and the intensity of extreme events create the need for alterations in the geometry of seawall structures and elements, which may be made as described below.

Heightening to accommodate the required freeboard and mitigate potential overtopping (Headland et al., 2011; Flocard and Blacka, 2012; NCCOE, 2012a). This may include raising the seawall crest and/or changing the crest details with an incorporated parapet wall or wave deflector (NCCOE, 2012a; Burcharth et al., 2014).

Increasing the crest width may contribute to diminution of the overtopping potential (NCCOE, 2012a). However, this measure fails to accommodate sufficient freeboard, may require adjusting the use of the land immediately behind the seawall, and hence may not be used in practice.

Flattening the slope to maintain structure stability against increased wave forces and reduce overtopping (Townend and Burgess, 2004; Headland et al., 2011). However, in common practice this is complemented by a measure meeting freeboard requirement, since the experiments necessitate this (Isobe, 2013; Burcharth et al., 2014).

Increasing thickness implies increasing the vertical wall thickness (Townend and Burgess, 2004) or adding a layer of bigger armour on the sloping wall face (Flocard and Blacka, 2012; Burcharth et al., 2014) to ensure structural stability and prevent seawalls or armour displacement due to increased wave loads. This measure may also mean increasing the seawall embedment depth against intensified scouring (USACE, 1995).

Other measures relating to the modifications external to the seawall structure, including consolidation of the backfill, adding sheet piles or building a rock berm in the seawater apart from the existing structure to alleviate wave effects (Flocard and Blacka, 2012; Maybee et al., 2012; Burcharth et al., 2014). However, these may be difficult and costly to implement.

To address the issues arising from sea level rise, including decreased freeboard, increased runup, overtopping and intensified wave loads, a combination of the above measures may be used as the seawall adaptation. For instance, rock seawalls are typically upgraded by adding a layer of bigger rocks on the outer face of the seawall with possible changes in the crest details (NCCOE, 2012a).

5.4 Adaptability: The built-in (A) form

Adaptability can be built in to the initial design of new seawalls to allow them to respond to climate change effects (Flocard and Blacka, 2012; NCCOE, 2012a). Zhao and Tseng (2003) suggest that given the sheer size and cost of civil engineering projects, which are irreversible once construction has been completed, not considering adaptation is not economically sound. Baron et al. (2008) talk of anticipatory adaptation where future climate change impacts are considered as likely to occur, and adaptations are already planned. Dobes (2008) and Woodward et al. (2011) suggest constructing seawalls that are wider or with stronger foundation so that they can be raised later if required. Woodward et al. (2011) argue that such adaptability offers significant economic benefits. The NCCOE (2012a) suggests that the design of new seawall structures should account for the likely impacts of climate change through, for example, oversizing the toe or foundations to facilitate possible future extensions. However, some types of seawalls may be upgraded with no need for foundation adjustments.

The typical adaptation measures discussed earlier may inspire solutions for incorporating adaptability in seawall design, such as increasing the thickness or flattening the seawall early in the design (Townend and Burgess, 2004; Flocard and Blacka, 2012). Built-in adaptability is anticipated to be created by an insignificant change in initial investment that is worthwhile when considering that the seawall may be inadequate under changed sea conditions.

5.5 Sustainability value of seawall adaptability

The literature acknowledges coastal protection and seawall adaptability, but falls short in putting a value on adaptability (Hoekstra and de Kok, 2008; Headland et al., 2011; Woodward et al., 2011; Neumann et al., 2014). For example, ROA using binomial lattices or equivalent Monte Carlo simulation has been attempted for financial valuation (Linquiti and Vonortas, 2012; Kontogianni et al., 2014). However, these methods are based on financial options with market underlyings and are not directly applicable to real assets (Damodaran, 1999; Howell et al., 2001; Kodukula and Papudesa, 2006; Mattar and Cheah, 2006; Lewis et al., 2008; Carmichael et al., 2011). A method suitable for valuing the flexibility of real assets must be employed. The literature also gives no attention to social and environmental issues, despite the fact that there may be considerable sustainability value in seawall adaptability, as briefly discussed below.

The larger disbenefits of not protecting the coastline, compared with the smaller cost of coastal protection, offer the choice of seawall adaptation in practice (Hallegatte et al., 2011; Kontogianni et al., 2014; Neumann et al., 2014; Carmichael, 2015). When compared to abandoning and/or new construction of a seawall, the contribution of existing seawall adaptability to sustainability can be perceived through saved resources and social costs (Linquiti and Vonortas, 2012; Neumann et al., 2014). Given that the two forms of adaptation (A and NA) differ in work quantities, the sustainability issues influenced by incorporating adaptability are similar to those of new construction (Moffatt and Russell, 2001). In case of a difference in the type of physical work, sustainability issues may vary. The relevant environmental issues involved in construction, with major discrepancy between two forms of adaptation, include:

- *Resource consumption:* materials and energy use.
- *Emissions/pollution:* equipment producing emissions; embodied emissions within the materials consumed; dispersion of soil particles and water pollution resulting in loss of habitat (DECCW, 2010b; Flocard and Blacka, 2012; Kirchner, 2013).
- *Waste generation:* material waste in construction.

A well-designed A form seawall allows for easier adaptation, leads to a reduced quantity of work and a subsequent reduction in environmental impact in terms of material consumption, embodied energy and emissions (Hong et al., 2014), solid waste generation (Yashuai et al., 2016) and loss of habitat due to disturbance to species via water pollution (Chapman, 2003; DECCW, 2010b). Such a design also leads to faster adaptation with lesser site time, resulting in reduced energy use, emissions (Hong et al., 2014), nuisance-related dust and noise (DECCW, 2010b).

With a modified design for the A form leading to a change in construction activities and quantities, some relevant social issues resulting from the physical and/or psychological impacts on stakeholders (Surbeck and Hilger, 2014) include:

- *Workers:* employment opportunities; health and safety in construction (Sawacha et al., 1999).
- *Neighbours:* disruption to traffic in the immediate neighbourhood (Gilchrist and Allouche, 2005); disturbance due to pollutants emitted, including dust, noise

and vibration (Gilchrist and Allouche, 2005, after Bein, 1997); aesthetics and sea view blockage (DECCW, 2010b; Burcharth et al., 2014).

- *Investors*: concern regarding seawall serviceability.

Due to the pre-planning in the initial construction phase an adaptable design requires a shorter site time, leading to less involvement of construction equipment and hence potentially fewer safety incidents (Sawacha et al., 1999), as well as less disturbance to neighbours through work-generated dust, vibration, noise and disruption to local traffic flow where the access behind the seawall is blocked during construction. The A form adaptation agility may also mitigate investors' concerns about the seawall's performance and serviceability. However, the shorter site time required for the A form may mean less employment for construction workers. As well, an additional seawall elevation, if any, may be aesthetically undesirable to the neighbours or users because it blocks the sea views (Burcharth et al., 2014). Putting a value on such measures is an issue requiring surveys of stakeholders' opinions.

This chapter presents an analytic approach for valuing adaptable seawalls from the sustainability viewpoint, as demonstrated in a case example. Prior to the analysis, the following comments clarify the situation in terms of the projected sea level rise suggesting the need for adaptable seawalls.

5.6 Sea level changes

With the changing climate, the global mean sea level is predicted to rise over the coming decades as a result of seawater thermal expansion, melting ice sheets and reduced water storage on land (IPCC, 2007, 2013; CSIRO–BoM, 2015). Despite this, the timing and extent of this sea level rise is highly uncertain (Lowe and Gregory, 2010; Rahmstorf, 2010). This uncertainty is exacerbated when estimating regional sea level rise, which is affected by variation in wind and air pressure and gravitational changes due to water mass redistribution (IPCC, 2013; CSIRO–BoM, 2015).

Within Australia, the benchmark value for sea level rise along the NSW coast, for example, is estimated to be 0.9 m by 2100 relative to the 1995 mean sea level (DECCW, 2010a; Flocard and Blacka, 2012). Based on a detailed estimate of sea level rise under the Representative Concentration Pathways provided by CSIRO–BoM (2015), the projected mean values and likely range of the sea level rise along the Sydney coastline is as shown in Figure 5.1.

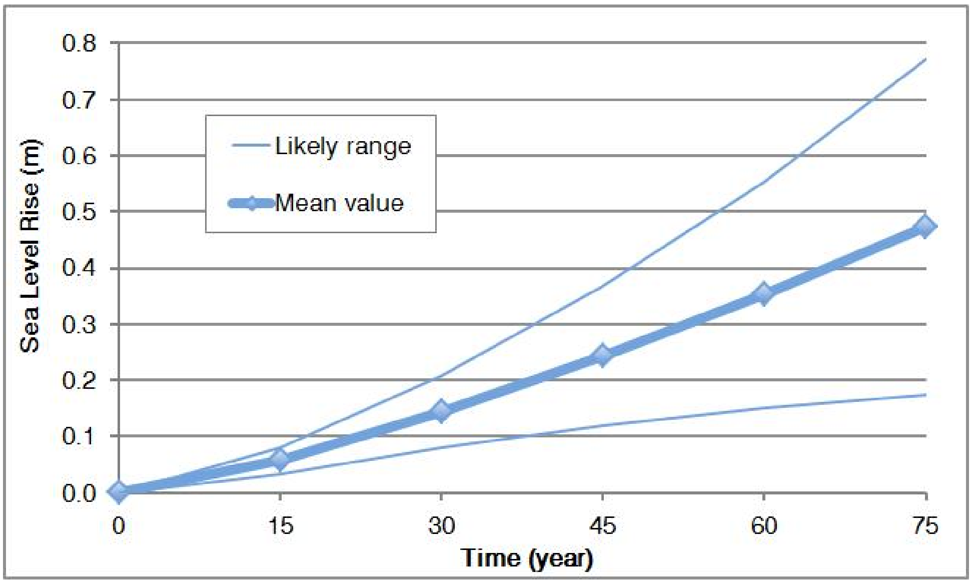

Figure 5.1. Change in projected sea level rise in Sydney with time (base year 2015: t = 0) (CSIRO–BoM, 2015).

In terms of extreme conditions, mean sea level rise is the main contributor to the increase in extreme sea levels, emanating from the combination of astronomical tides, storm surges and wind waves (CSIRO–BoM, 2015). ‘*Contributions to extreme sea levels from changes in weather events are projected to be small or negative… such that a 10% increase in tropical cyclone intensity produces only a small increase in the 1-in-100 year storm tide*’ (CSIRO–BoM, 2015, pp. 153–157, after Harper et al., 2009). However, in the Australian coastal protection context the shallow water or breaking wave conditions typically govern seawall design, in which increase in wave heights is proportional to sea level rise (Townend, 1994; Esteban et al., 2011). The uncertainty over sea level rise and associated wave heights may lead to seawall becoming inadequate and requiring adaptation.

5.7 Suggestions on adaptable seawalls

Possible adaptability suggestions might be inferred from the literature, as discussed earlier. As sea level and wave conditions change, the liable government may wish to upgrade seawalls so that they meeting different requirements in terms of protection heights and responses to wave loads and scour. This implies that there is a need, subject to viability, for the construction of adaptable seawalls.

Councils and local governments spend billions of dollars to construct or strengthen kilometres of the seawalls (Davies, 2013). Commonly, adaptively managed seawalls are useful where the investor can gain increased value through delayed investment (Headland et al., 2011). There is now a trend towards building adaptability in the initial design of new seawalls to accommodate the possible effects of climate change (Flocard and Blacka, 2012; NCCOE, 2012a). The considerable uncertainty over the projected sea level rise suggests that there is a need for the option to upgrade (expand) seawalls. A case example involving a rock seawall upgrade is given later.

The case example considers a rock seawall, built at time t = 0, with the potential to expand, at some time t = T in the future. Incorporating adaptability leads to a more informed and easier upgrade. However, the upgrade is an option—a right but not an obligation—and hence may not occur depending on the climatic conditions and managerial decisions in the future.

The analytic approach, given in Chapter 3 (Sections 3.2 and 3.3), is used in the following to value the adaptability of rock seawalls as an Australian case example.

5.8 Case example: Rock seawall upgrade

5.8.1 Design and construction

The case example here is a seawall subjected to a water depth of 3 metres at the toe, with associated breaking waves. A sloped seawall construction with rock armours of relative abundance is considered, though it is recognised that other forms of seawall construction, for example using concrete armour units, are also possible. The initial design needs to be capable of accommodating greater water depths and wave loads due to rising sea levels over the design life of about 35 years (AS 4997, 2005; NCCOE, 2012b; Couriel et al., 2013). Possible upgrade strategies are to flatten the slope or use larger rocks, facilitating structural stability against wave loads, while the seawall height must satisfy the wave runup limit using a sufficient freeboard (NCCOE, 2012a). The latter is adopted here as the more common practice, however the analysis and considerations for both situations are the same (engineering drawings are given in Appendix D).

The main structural elements of rock seawalls to be considered include the rock armour layer, the underlayer, core, rock toe and parapet wall (NCCOE, 2012a).

Rock armour layer. The primary layer of rocks of sufficient strength withstands wave actions. The required mass of individual rocks is proportional to the cube of the breaking wave height, which itself is proportional to the water depth (Isobe, 2013). The rock size is conventionally chosen based on the breaking wave height corresponding to the present water depth plus an allowance for the most likely sea level rise over the design life; here, this is 0.17 m. The assumption on this adaptability feature is that rocks of bigger size, corresponding to the sea level rise over double the design life, are used. This leads to an increase in the mass of individual rocks from 2.75 t to 3.50 t, allowing the solid rocks to be still operable when the sea level reaches the conventional design level.

Underlayer and core. A layer of smaller rocks underneath supports the primary rock armour, allows water to pass through the structure while prevents the underlying soil from being washed away. The mass of the individual rocks in the underlayer is about a tenth of the individual primary rock mass (CERC, 1984). The rock armour layer and underlayer rest on the seawall core with finer materials. Consultation with coastal engineers suggests that the seawall's outside face can undergo a transformation with no need to change the underlayer and core.

Rock toe. Toescour protection prevents undermining of the structure by seabed erosion. The common practice is to use toe rocks of the same size as the primary rocks. The assumption in the following is that the toes for both the designed-in (A) and non-designed-in (NA) forms are sufficient to bear scour; otherwise both can be rehabilitated similarly. However, the minimum toe width must be satisfied (USACE 1995) should addition to the rock armours lead to a considerable reduction in toe width.

Parapet wall. A reinforced concrete wave wall provides a more positive barrier to the flow of water up the seawall, and so facilitates safe use of the land immediately behind the structure. The parapet wall margin over the crest rocks must be maintained. The A form crest of larger rocks leads to a slightly higher elevation which may be aesthetically undesirable due to sea view blockage (Burcharth et al., 2014). However, putting a value on this decrease in aesthetics is difficult.

The possibility, with adaptability in mind, is that the parapet wall be constructed with a sufficiently larger foundation, but with the same height as that of a non-designed-in adaptable wall. This is done here by doubling the foundation width and depth. Thus, the parapet wall is already expandable, with no need for foundation rehabilitation and paving works should the height of protection be raised by adding rocks on the crest. For the non-designed-in form, the old foundation is enlarged such that a connection to the newly placed reinforced concrete is made using drilled anchors. This requires paving works including removal and rebuilding, which are excluded from the analysis here.

Other considerations. The above considers the engineering aspects of the designs. Other architectural considerations relating to coastal amenities, such as access to the sea, pedestrians or traffic behind the seawall are assumed to be in hand, with no significant difference between the two forms of adaptation.

5.8.2 Financial

Table 5.1 summarises the differences between the two adaptation forms that are costed in the analysis. It is acknowledged that others may look at seawall construction differently; the dollar values for construction activities will change, but the valuing methodology advanced in this thesis will not.

Time	**A: Designed-in form**	**NA: Non-designed-in form**
t = 0	Build an armour layer of larger rocks	
	Construct a larger parapet wall foundation	
t = T	Add rocks on the crest	Add larger rocks on the crest and slope, in front of the toe
	Enlarge the parapet wall—drilled anchors for the wall; reinforced concrete	Enlarge the parapet wall—drilled anchors for the wall and foundation; reinforced concrete

Table 5.1. Seawall case example: designed-in versus non-designed-in forms, only differences in construction given.

Optimistic, most likely and pessimistic estimates are made as mentioned above, leading to expected values and variances of the costs. Costing estimates follow RSMeans (2015) based on quantity take-offs from drawings, together with quotations from different coastal engineers and industry representatives.

Consider a 100-metre long section of the typical rock seawall. Based on the above assumptions and approach, cost estimates give the following:

E[NA_T] = \$297.9k, Var[NA_T] = (\$24.8k)^2

E[A_T] = \$102.8k, Var[A_T] = (\$8.6k)^2

Figures 5.2 and 5.3 show the change in adaptability value with r and T. The initial investment in adaptability is estimated as \$57.7k. It can be seen that building in adaptability is only viable for lower r and lower T. For r = 5% p.a., built-in adaptability is viable for adaptation times lower than 25 years, while even the pessimistic sea level rise scenarios give adaptation times of greater than this. This means that the A form is not viable for r values greater than 5% p.a. However, the lower the r, the longer the timespan within which the A form is viable. For a specific low r, the more severe the sea level rise and hence the lower T, the more viable built-in adaptability is.

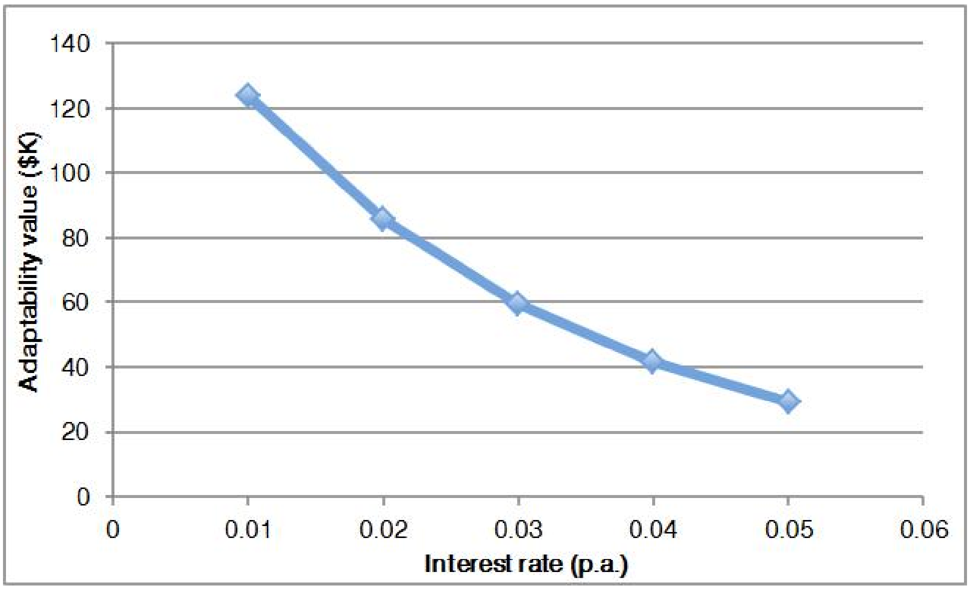

Figure 5.2. Seawall case example: Change in adaptability value with interest rate (p.a.), T = 35 years.

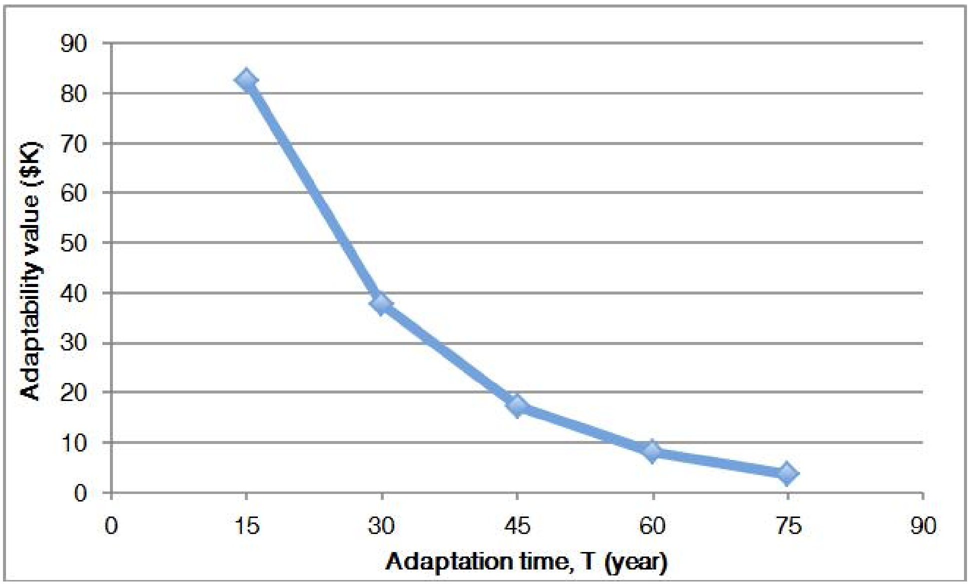

Figure 5.3. Seawall case example: Change in adaptability value with time of exercising T, r = 5% p.a.

The designed-in A form is seen to be more financially viable than the non-designed-in NA form in time periods corresponding to pessimistic sea level rise scenarios; this would be so even for optimistic scenarios when interest rates are low. The viability under these conditions is mainly due to a large saving in the A form adaptation cost, with a substantial decrease in the addition of larger rocks and no need for parapet wall foundation strengthening. However, since the initial cost and adaptability values are close, councils may not build in adaptability and may require an enhanced incentive for investment. It is anticipated that inclusion of sustainability intangibles in the analysis improves the viability of seawalls and further encourages investment.

5.8.3 Environmental

Environmental issues that are different between A and NA are noted in Table 5.2.

Time	A: Designed-in form	NA: Non-designed-in form
t = 0	More material use—embodied energy, emissions; more waste—water pollution; longer construction time—energy, emissions, noise	
t = T		More material use—embodied energy, emissions; more waste—water pollution; longer construction time—energy, emissions, noise

Table 5.2. Seawall case example: Comparison of environmental issues.

In the Life Cycle Assessment (LCA), inventory flows, consisting of materials and energy (environmental inputs), air emissions, solid waste and water pollution (environmental outputs) are tracked for the determined unit process of construction at times 0 and T (Figure 5.4).

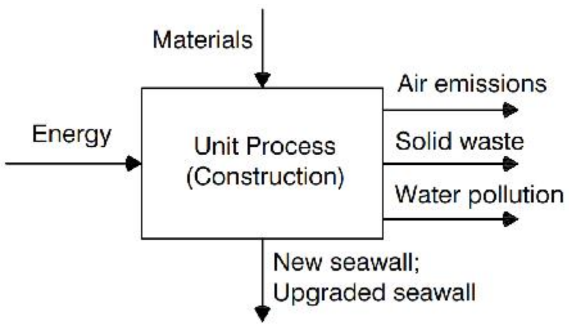

Figure 5.4. Seawall case example: Unit process and inventory flows for the LCA.

The estimates of differences in inventory flows between the A and NA forms follow. Rocks and reinforced concrete are the predominant materials used. The materials' embodied energy and emissions are calculated using the inventory database provided by Hammond and Jones (2011). The crawler crane used for the rock placement is the predominant construction equipment with regard to energy use and emissions, estimated based on fuel consumption. Water pollution or quality is expressed by a gravimetric estimate (in kg) of soil particles (The Open University 2014) dispersed due to the placement of submerged rocks.

Differences in inventory flows at t = 0

- *Materials*. Armour layer (A form) – extra rock consumption of 340 m^3 (or 544 t based on the bulk density of rocks) compared with the NA form. Parapet wall (A form) – additional reinforced concrete of 50 m^3 (or 120 t) for the oversized foundation, compared with the NA form. These give a net extra material consumption of 664 t for the A form over the NA form.
- *Energy*. Armour layer (A form) – assuming the rocks' embodied energy as 0.083 GJ per tonne of rock, the additional rock consumption gives 45.2 GJ more embodied energy. Placement of larger rocks for the A form leads to an extra 57 h of crane operation with an estimated fuel consumption of 15 l/h (Caterpillar, 2000); the stored energy of 0.036 GJ per litre of diesel oil (IPCC, 2006) gives 30.8 GJ more energy use. Parapet wall (A form) – assuming an embodied energy of 0.910 GJ per tonne of reinforced concrete, the extra amount of reinforced concrete leads to 109.2 GJ more embodied energy. In summary, the A form uses a net extra 185.2 GJ of energy.
- *Air emissions.* Armour layer (A form) – the rock embodied carbon is assumed as 0.0052 tonne of CO2-e (carbon dioxide equivalent) per tonne of rock; the additional quantity of rocks consumed leads to 2.8 tonne CO2-e more embodied emissions. Assuming a median carbon content of 0.0202 tonne CO2-e/GJ for diesel oil (IPCC, 2006), the extra fuel-based energy use for the A form leads to 0.6 tonne CO2-e more emissions. Parapet wall (A form) – assuming the embodied emissions of 0.140 tonne CO2-e per tonne of reinforced concrete, the additional amount of reinforced concrete for the A form leads to 16.8 tonne CO2-e more emissions. In summary, the A form causes a net extra 20.2 tonne CO2-e emissions.

- *Solid waste.* Armour layer (A form) – an estimated rock wastage of 5% of fill volume (Trenter, 2001) leads to 27.2 t more solid waste than the NA form. Parapet wall foundation (A form) – assuming concrete and steel reinforcement wastages as 1.5% and 5% of the total material quantity respectively (Yashuai et al., 2016), the extra amount of reinforced concrete for the A form compared to the NA form leads to more solid waste constituting 1.8 t of concrete and 0.3 t of steel reinforcement. In summary, the A form produces 29.3 t more solid waste than the NA form.
- *Water pollution.* Assuming half of the rock surface area is covered with 0.1 mm of fines, of which 50% is washed (Rambøll, 2008), gives a sediment spill rate of about 0.01% of the rock volume (or 0.25 kg per m^3 of rocks) for rock placement. Armour layer (A form) – the extra 140 m^3 of submerged rocks leads to an additional dispersion of soil particles of 35 kg compared with the NA form.

Differences in inventory flows at t = T

- *Materials*. Armour layer (NA form) – the consumption of 2060 m^3 (or 3296 t based on the bulk density) of new rocks placed on the entire outer face of the seawall. Parapet wall (NA form) – a reinforced concrete consumption of 90 m^3 (or 216 t) for wall heightening together with foundation enlargement. Armour layer (A form) – new rock consumption of 550 m^3 or 880 t for crest elevation alone. Parapet wall (A form) – reinforced concrete consumption of 40 m^3 (or 96 t) for wall heightening alone. In summary, the NA form consumes a net extra 2536 t of materials.
- *Energy*. Armour layer (NA form) – rock embodied energy is assumed to be 0.083 GJ per tonne of rock; new rock consumption gives an embodied energy of 273.6 GJ, while the A form uses fewer rocks with an associated embodied energy of 73 GJ. The different quantities of new rocks placed for the NA and A forms lead to crane operation time of 348 h and 93 h, respectively, with an estimated fuel consumption of 15 l/h (Caterpillar, 2000); the stored energy of 0.036 GJ per litre of diesel oil (IPCC, 2006) gives an energy use of 187.9 GJ

and 50.2 GJ for the NA and A forms, respectively. Parapet wall (NA form) – assuming an embodied energy of 0.910 GJ per tonne of reinforced concrete, the different amounts of the total reinforced concrete used in the NA and A forms lead to embodied energy values of 196.6 GJ and 87.4 GJ, respectively. Collectively, the NA form uses 658.1 GJ of energy versus an embodied energy of 210.6 GJ. In summary, the NA form uses 447.5 GJ more energy.

- *Emissions.* Armour layer (NA form) – assuming 0.0052 tonne of embodied CO2-e per tonne of rock gives 17.1 tonne of CO2-e emissions; while the A form leads to embodied emissions of 4.6 tonne of CO2-e associated with the placement of new rocks. Given a median carbon content of 0.0202 tonne CO2-e/GJ for diesel oil (IPCC, 2006), the fuel-based energy use causes emissions of 3.8 and 1 tonne of CO2-e for the NA and A forms, respectively. Parapet wall (NA form) – assuming 0.140 tonne of embodied CO2-e per tonne of reinforced concrete, the reinforced concrete consumed leads to emissions of 30.2 and 13.4 tonne of CO2-e for the NA and A forms respectively. The total embodied emissions would thus be 51.1 tonne of CO2-e for the NA form versus 19 tonne of CO2-e for the A form. In summary, the NA form produces 32.1 tonne CO2-e more emissions.
- *Solid waste.* Armour layer (NA form) – an estimate of rock wastage of 5% of fill volume (Trenter, 2001) gives 164.8 t of solid waste, while the A form reduces rock waste production to 44 t. Parapet wall foundation (NA form) – assuming concrete and steel reinforcement wastages as 1.5% and 5% of total material quantity, respectively (Yashuai et al., 2016), the reinforced concrete consumed gives solid wastes constituting 3.2 t of concrete and 0.5 t of steel reinforcement for the NA form versus 1.4 t of concrete and 0.2 t of steel reinforcement for the A form. Collectively, the NA and A forms produce solid wastes of 168.5 t and 45.6 t, respectively. In summary, the A form produces a net extra solid waste of 122.9 t over the NA form.
- *Water pollution.* Assuming half of the rock surface area is covered with 0.1 mm of fines, of which 50% is washed away (Rambøll, 2008), gives a sediment spill rate of about 0.01% of the rock volume (or 0.25 kg per m^3 of

rocks) for rock placement. Armour Layer (NA form) – 640 m^3 of submerged new rock being placed leads to sediment spill of 160 kg. Armour layer (A form) – requires rocks to be placed on the crest, which are not submerged, and thus do not contribute to water pollution.

The environmental impact categories are taken here to be the same as the above inventories. The differences in the environmental impacts between the A and NA forms are summarised in Table 5.3.

Environmental impact	**At t = 0**	**At t = T**	**Combined t = 0 and T**
Material consumption (t)	664	-2,536	-1,872
Energy use (GJ)	185.2	-447.5	-262.3
Emissions (tonne CO2-e)	20.2	-32.1	-11.9
Solid wastes (t)	29.3	-122.9	-93.6
Water pollution (kg)	35	-160	-125

Table 5.3. Seawall case example: Differences (A – NA) in environmental impacts.

It is seen that the A form performs better with respect to all of the environmental impacts considered, and hence when these impacts are combined, irrespective of whatever weightings are chosen (Bengtsson et al., 2010), the A form is environmentally preferable. Due to the pre-thought adaptation of the A form compared to the NA form, there is a reduction in material consumption, energy use, air emissions, solid waste production and water pollution.

5.8.4 Social

Social issues that differ between the A and NA forms are noted in Table 5.4.

Time	A - Designed-in form	NA - Non-designed-in form
t = 0	Longer construction time—dust, noise, vibration, neighbourhood disturbance, potential for accidents	
	Slightly less attractive aesthetics	
		Lower paid hours for workers
t = T		Longer construction time—dust, noise, vibration, neighbourhood disturbance, potential for accidents, serviceability concern
	Lower paid hours for workers	

Table 5.4. Seawall case example: Comparison of social issues.

The Social Life Cycle Assessment (SLCA) is used to assess social issues (UNEP/SETAC, 2009), except for aesthetics and council concerns about serviceability, which can be analysed based on surveys of stakeholders' opinions. Only those issues that can be dealt with using the SLCA are considered here.

With the same scope and unit processes as defined in the LCA, the relevant inventory flows examined are worker employment (social input), and safety incidents, health damage and traffic disruption (social outputs) (Figure 5.5).

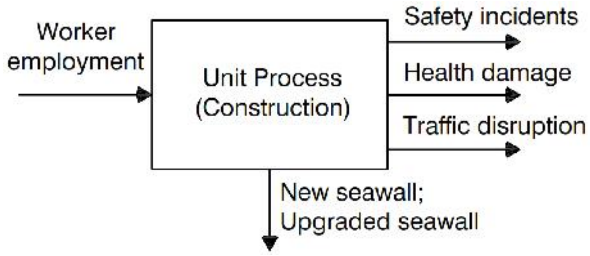

Figure 5.5. Seawall case example: Unit process and inventory flows for the SLCA.

Using data from RSMeans (2015) on construction crew and activity durations, the estimates of differences in inventory flows between the A and NA forms follow. Worker employment is measured in total worker hours (hours per worker multiplied by number of workers). Safety incidents are expressed based on a frequency; namely, the number of injury occurrences per hours worked by all workers (AS 1885.1, 1990). Given the same number of people affected in the vicinity of the construction site for the two forms, health damage due to exposure to construction noise varies with the activity equivalent continuous noise level (in decibels, dB) and duration of exposure (or activity) (BSI, 2009; SafeWork NSW, 2016), and is expressed as the number of exposure hours, h. Activity equivalent continuous noise level is defined as the *'sound pressure level determined at a distance of 10 m from, and over the period of, a given activity'* (BSI, 2009, p. 1). The time of exposure to the different noise levels are combined and expressed as total equivalent exposure to 85 dB noise level (SafeWork NSW, 2016). Workers are assumed to be equipped with suitable hearing protection; thus only people in the neighbourhood are disturbed. Rock and concrete placement, compaction and concrete drilling are the predominant activities generating noise. Traffic disruption is expressed as road travel delay (Gilchrist and Allouche, 2005) and is measured in vehicle hours, veh.h (total additional hours travelled per vehicle multiplied by number of vehicles). Rock and concrete placement are the predominant activities leading to road closure.

Differences in inventory flows at t = 0

- *Worker employment.* Armour layer (A form) – 1165 h, based on 8-hour days, 2 workers and about 73 days. Parapet wall (A form) – reinforcing: 121 h; concrete forming: 160 h; concrete placement: 36 h. Armour layer (NA form) – 1050 h. Parapet wall (NA form) – reinforcing: 45 h; concrete forming: 160 h; concrete placement: 14 h. In summary, the A form leads to 213 h more employment.
- *Safety incidents.* Assuming a construction injury frequency rate of 33 injuries per million working hours (SWA, 2012), the additional 213 h employment required for the A form could potentially result in 0.0070 more injuries.

- *Health.* Assume 100 people are constantly disturbed by construction noise in the neighbourhood. Armour layer (A form) – an estimated equivalent continuous noise of 79 dB (BSI, 2009) during the extra 57 h of lifting and placement operations compared with the NA form. Parapet wall (A form) – equivalent continuous noise of 86 dB (BSI, 2009) over the extra 5 h of concrete placement and compaction compared with the NA form. These lead to an extra total equivalent exposure of 31.3 h for the A form (SafeWork NSW, 2016).
- *Traffic disruption/inconvenience.* Assume a traffic flow rate of 500 veh/h (SKM, 2012); a detour route of additional 0.2 km length and average travel speed of 40 km/h. Armour layer (A form) – the extra 57 h road closure leads to 143 veh.h more travel delay than the NA form. Parapet wall concrete placement (A form) – the longer road closure of 5 h compared with the NA form leads to 12 veh.h more traffic disruption. In summary, the A form delays road travels by a net extra 155 veh.h over the NA form.

Differences in inventory flows at t = T

- *Worker employment.* Armour layer (NA form) – 695 h, based on 8-hour days, 2 workers and about 43 days. Parapet wall (NA form) – concrete drilling: 250 h; reinforcing: 136 h; concrete forming: 240 h; concrete placement: 41 h. Armour layer (A form) – 186 h. Parapet wall (A form) – concrete drilling: 83 h; reinforcing: 60 h; concrete forming: 160 h; concrete placement: 18 h. The total worker hours thus equal 1362 h and 507 h for the NA and A forms, respectively. In summary, the NA form creates 855 h more employment.
- *Safety incidents.* Assuming a frequency of 33 injuries per million working hours (SWA, 2012), the total worker hours for the NA and A forms cause 0.0449 and 0.0167 potential injuries for the NA and A forms, respectively. In summary, the additional 855 h employment for the NA form leads to 0.0282 more potential injuries.
- *Health.* Assume 100 people are constantly disturbed by construction noise in the neighbourhood. Armour layer (NA form) – an estimated equivalent continuous noise of 79 dB (BSI, 2009) during the 348 h of rock lifting and

placement operations; the exposure time reduces to 93 h for the A form. Parapet wall (NA form) – concrete drilling with equivalent continuous noise of 90 dB (BSI, 2009) for the activity duration of 250 h for the NA form versus 83 h for the A form; concrete placement and compaction with equivalent continuous noise of 86 dB (BSI, 2009) during the 9 h activity for the NA form versus 4 h activity for the A form. The total equivalent noise exposure impact would thus be 915.5 h and 295.1 h for the NA and A forms, respectively (SafeWork NSW, 2016). In summary, the NA form leads to a net extra noise exposure of 620.4 h over the A form.

- *Traffic disruption/inconvenience.* Assume a traffic flow rate of 500 veh/h (SKM, 2012); a detour route of additional 0.2 km length and an average travel speed of 40 km/h. Armour layer (NA form) – the site time for rock lifting and placement operations leading to road closure causes travel delays of 920 veh.h and 246 veh.h for the NA and A forms, respectively. Parapet wall concrete placement (NA form) – road closure for the duration of the activity leads to 22 veh.h and 10 veh.h travel delays for the NA and A forms, respectively. The total travel delay would thus be 942 veh.h for the NA form versus 256 veh.h for the A form. In summary, the NA form leads to an additional traffic disruption of 686 veh.h compared to the A form.

Differences in the social impacts between the A and NA forms are summarised in Table 5.5.

Social impact	**At t = 0**	**At t = T**	**Combined t = 0 and T**
Worker employment (h)	213	-855	-642
Safety incidents (number of injuries)	0.0070	-0.0282	-0.0212
Health damage (h)	31.3	-620.4	-589.1
Traffic disruption (veh.h)	155	-686	-531

Table 5.5. Seawall case example: Differences (A – NA) in social impacts.

The designed-in A form can be seen to be socially better than the non-designed-in NA form. This is so with respect to almost all the social issues raised in Table 5.5, which exempts the analysis from combining the impacts. The forethought given to the A form adaptation, compared to the NA form, leads to a reduction in safety incidents, health damage and traffic disruption, although it adversely affects worker employment.

5.8.5 Sustainability implication

For the assumptions considered, the designed-in A form is shown to be more sustainable than the non-designed-in NA form. The A form is financially more viable for adaptation times associated with most likely sea level rise scenario, let alone more severe scenarios leading to lower adaptation times. However, the viability for less severe scenarios with longer adaptation times would be ensured should interest rates remain low. The A form is demonstrated to predominantly be better than the NA form with respect to environmental and social criteria; hence, inclusion of such criteria enhances the viability of seawall adaptability. Accordingly, the A form would be considered a more sustainable alternative overall.

However, it is unclear as to how the councils interpret social and environmental criteria. Where the councils emphasise sustainability issues, the designed-in A form seawall would strongly be supported; otherwise they may not build in adaptability in this specific case, and may prefer a more predominant situation in terms of financial viability.

5.9 Discussion

Given the assumptions considered, designing seawalls for adaptability was shown to be financially viable for interest rates less than 5% p.a., where viability is established only for the lowest possible adaptation time associated with pessimistic sea level rise. However, with interest rates lower than 3% p.a., this ensured viability for longer adaptation times relating to the most likely and even optimistic sea level rise scenarios. Analysing the social and environmental intangibles reveals the potential for viability improvement. It was demonstrated that built-in adaptability is a more sustainable alternative and a suitable solution not only for climate change adaptation but also climate change mitigation, with particular attention to reduced emissions.

The initial investment in seawall adaptability is irreversible, as is the case for many other untradeable real assets, but it can be seen as a premium insuring an agile adaptation. However, it is unclear as to what extent investors intend to secure seawall serviceability. The estimated adaptability value, together with the reduced site time during adaptation, provides the investors with a benchmark for decision-making.

The financial value of adaptability increases with greater uncertainty regarding future costs. Building work will most likely be undertaken on a fixed price or lump sum basis, with a certain outcome, therefore not adding to the cost estimate uncertainty used in this chapter. Despite this, the uncertainty in the cost estimates may be assumed to grow with time, on the basis that estimates further into the future are less definite. This uncertainty must be much larger than that used relative to the expected cost value before it starts to change the broad conclusions in the case example. Moreover, considering uncertainty in the social and environmental estimates at T is anticipated to further improve the sustainability performance of adaptability, since this option is only exercised at the upside potential of the impacts.

5.10 Conclusion

The chapter presented a method for valuing the sustainability of adaptability in coastal protection under changing sea conditions. A comparative analysis was undertaken between the forms with built-in adaptability and those without built-in adaptability. The approach was demonstrated on a case example involving a rock seawall upgrade. For the case example, financial viability was established for smaller times to adaptation (corresponding to a pessimistic sea level rise scenario), but not for larger time to adaptation (corresponding to the most likely and optimistic sea level rise scenarios) unless the interest rates were low enough.

Adopting a sustainability viewpoint and including social and environmental intangibles was shown to improve the viability of seawall adaptability. This leads to further encouragement of design for adaptability; however, investors may be interested in the financial aspect of analysis, looking for alternative designs with greater financial viability. A general conclusion on the viability of designing in adaptability cannot be reached, but it requires an individual analysis for each situation, from the intended investors or council's viewpoint. The method presented, but not necessarily the specific designs and numbers, is applicable to any other situation. In some situations designing in adaptability will be worthwhile, in others it may not.

The literature acknowledges coastal protection and seawall adaptability, but does not quantify its value using proper methods (Woodward et al., 2011; NCCOE, 2012a; Neumann et al., 2014). This chapter advances the current literature by providing an analysis that quantifies the sustainability of adaptable seawalls. People in the construction industry, councils and local governments responsible for coastal protection and seawall upgrades will benefit from the given approach.

Chapter 6: Usage Adaptability in Housing

6.1 Introduction

Housing has great importance beyond catering to fundamental shelter and social needs. For example, within Australia: owner-occupied properties represent approximately 50% of people's net worth (ABS, 2015c), making it the largest asset/investment held by people; in 2015, Australian houses are estimated to be worth four times Australia's GDP (ABS, 2015a; CoreLogic, 2015; Trading Economics, 2015); new residential construction, alterations and additions represent a very large contribution to the Australian economy (ABS, 2015d). About one fifth of construction work undertaken between 1991 and 2001 was on existing buildings (Wilkinson et al., 2009). People's real and perceived redundancy or obsolescence of housing leading to alterations and additions represents a significant sustainability issue.

Obsolescence, referring to a decline in usefulness and desirability, may occur due to a wide range of factors which overlap to some extent; accordingly, various type of obsolescence are introduced, namely (Baum, 1991**;** Langston et al., 2008, 2013): 1) Physical obsolescence where a property gets aged and falls into natural decay; demolition might be carried out as a result of reduced performance, 2) Economic obsolescence when the use of a property is no longer the most cost-effective option, or in the other words, a surplus over operating costs no longer covers the cost of investment and a normal profit margin; this may lead to relocation or change in the way of economic exploitation such as conversion in use (Barras and Clark, 1996), 3) Functional obsolescence when changes in users' objectives, wants and needs take place, leading to a change in functional purpose ranging through usage conversion to extension, 4) Technological obsolescence where a property or services used is no longer the technologically most suitable alternative (Webb et al., 1997; Slaughter, 2001); hence, a replacement with new technology may be required, 5) Social or cultural obsolescence due to changes in users' behavioural patterns, fashion, style and aesthetic issues leading to refurbishment or replacement of a property (Barras and Clark, 1996; Slaughter, 2001), and 6) Legal or political obsolescence dealing with change in regulations, political constraints or environmental legislations that may impose property redevelopment (Arge, 2005; BERR, 2008).

Reed and Warren-Myers (2010), in addition to the above-mentioned forms of obsolescence, talk of ‘sustainable obsolescence’ form in which non-sustainable properties are perceived to be become obsolete as a result of increased importance of sustainability. Even though, this form can be embedded within technological obsolescence, or even social and legal obsolescence as the society becoming more conscious of sustainability (Langston et al., 2008). Housing adaptation may occur as a result any types of obsolescence; however, this chapter and case example presented specifically look at functional obsolescence in housing.

Adaptability is seen as a key issue within modern infrastructure in response to obsolescence, where the needs and wants, real and perceived, of the user change over time (Gann and Barlow, 1996; Heath, 2001). Adaptability here refers to a capability to be changed in line with future circumstances. With housing, the needs and wants of users change in line with their lifestyle and employment/family/income situation (Kendall, 1999; Schneider and Till, 2005; Matusik, 2014). However, traditional housing is built for a single purpose, which suits the owner at the time. As families grow, house owners look for more space; while when families decrease in size, the house owner may want to downsize. This might be accomplished by shifting neighbourhoods or, if moving to a new neighbourhood is not desired, changing the current house, with the extreme being complete demolition and replacement. This is expressed in the transitions of Matusik (2014), where house owners go from 'young renters → first home buyers → upgraders → downsizers → retirement → aged care'. There are financial, social and environmental impacts associated with altering and moving houses

The architecture literature acknowledges a need for adaptability within building/housing infrastructure, in order to remain timeless, but stops short in its valuation (Gann and Barlow, 1996; Heath, 2001; Moffatt and Russell, 2001; Slaughter, 2001; Till and Schneider, 2005). This chapter addresses the financial valuing of housing adaptability, through a real options analysis (Carmichael et al., 2011), while the social and environmental matters are evaluated along life cycle assessment lines. A case example involving a single-storey house adaptable to two storeys is given. This is done in an Australian housing context with respect to changes in house usage and requirements over time. It is acknowledged that other forms of adaptation are possible, and that housing practices are location-dependent. The methodology carries over to other situations and locations, but not the actual numbers used in the case example.

The outcome will be of interest to people within the housing and construction industries, as well as house owners. Through the approach given, it is possible to gauge the viability of including specific adaptability in any design and construction of houses.

This chapter firstly clarifies the notion of housing flexibility/adaptability, and provides a review on changing usage/demand, and attempts by writers at valuing adaptability. A case example is presented and the adaptability valued, and a general argument on the viability of adaptability given.

The approach to establishing the viability of adaptability within housing is original; specific underlying design and construction assumptions are costed and their impact on viability established.

6.2 Terminology: Housing flexibility/adaptability

The literature uses the terms adaptability and flexibility in different ways and sometimes interchangeably. Schneider and Till (2005) define housing adaptability, as the capability of accommodating various social uses, for example adapting to users' physical needs as they get older and lose mobility (Till and Schneider, 2005). By comparison, Schneider and Till (2005) define flexibility as the capability of accommodating various physical arrangements of spaces, for example in response to changing needs of users in terms of layout or use, or because of technology (Till and Schneider, 2005).

Some writers use both flexibility and adaptability to mean an ability to accommodate changes (Gann and Barlow, 1996; Slaughter, 2001; Greden, 2005), where knowledge on the change is unclear at the time of design and construction (Gosling et al., 2013, after Grewin, 1993 and Upton, 1994). For the purposes of this chapter, the sense of the terms flexibility and adaptability in housing is taken to be the same, referring to a capability to change in line with future circumstances.

The ever-changing natural, social and technological environments impact the longevity of structures, creating the need to extend their useful lives (Slaughter, 2001; Zhao and Tseng, 2003; Wilkinson et al., 2009). Housing adaptation mostly falls under the NA form. This NA form is not addressed in detail here, but rather used as a comparison with the A form, which is the focus of this chapter.

6.3 Typical housing adaptation

With housing, changes in people's life stages, the composition of families, social situations, personal circumstances and fashion, may lead to alterations in housing interiors and exteriors, volume and uses (Till and Schneider, 2005).

Changing interiors may be in terms of a reconfiguration in space layout from closed individual spaces to open-plan spaces, or vice versa (Greden, 2005; Till and Schneider, 2005). This adaptation aims to enhance space usage efficiency, reusability of spaces, and take advantage of existing space potential to accommodate minor changes in needs when, for example, a child is born or an older child gets married and leaves the family. Common practice involves a rearrangement of rooms by relocation of interior partitions, or via demountable partitions, with associated modification in ceiling and floor finishes (Friedman, 1993; Keymer, 2000; Moffatt and Russell, 2001; Till and Schneider, 2005).

Changing volume may be in response to an increase or reduction in demand. House expansion might be required by upgraders, and might occur either vertically or horizontally (Remøy et al., 2011). House volume contraction might be carried out by downsizers, for example, through subletting a part of the house space (de Neufville et al., 2008).

Examples of *changing use*, which might be referred to as adaptive reuse, include converting redundant offices into apartments, perhaps because of an oversupply of office space, changing technology or changing demands (Gann And Barlow, 1996; Heath, 2001; Wilkinson et al., 2009; Remøy et al., 2011). However, such changes are less relevant to houses than commercial buildings (Maury, 1999; Wilkinson, 2011), except for the incorporation of new technology, or change in usability due to a life transition for downsizers. Examples of this include making houses accessible throughout and more readily usable for aged people, particularly in bathroom and kitchen areas (Fänge and Iwarsson, 2005; NCSU, 2013).

6.4 Adaptability: Built-in (A) form

There is a belief, but generally not supported with analysis, that it is inefficient to construct buildings with a single use in mind; rather, there is a need to design buildings incorporating flexibility and adaptability (Gann and Barlow, 1996; Kendall, 1999; Slaughter, 2001; Zhao and Tseng, 2003; Engel and Browning, 2008). Zhao and Tseng (2003) suggest that the sheer size and cost of civil engineering projects such as dams, roads, bridges, and airports are irreversible once construction has been completed, such that not considering adaptation is not economically sound. Kendall (1999) talks of open buildings, with the façade being the only thing that changes, and easily accessible building services. Kendall (1999) argues that designing built infrastructure with the foresight for adaptation will cost no more in original outlay.

Slaughter (2001) broadly studies adaptability in buildings, involving various types of space usage such as residential, whether in public or private sector; she suggests that design for adaptability entails: physically separating major building systems and their subsystems; prefabrication of major system components; and designing certain systems significantly over capacity to meet future demand. With such an approach, Slaughter (2001) suggests that the total building cost would only increase by 1 to 2 percent (see Slaughter, 2001, pp. 212-214 for further detail), and this is regarded as insignificant when considering that the building may be obsolete if demand change.

The notion of adaptability overlaps with that of the 'universal design' concept (Karol, 2007; NCSU, 2013; Palmer and Ward, 2013), where a house is designed and built as user-friendly to all persons, including the disabled, young and old. The universal design concept addresses the changing needs of users. However, unlike this thesis's adaptability, it does not have a future time at which the design is changed; rather the design stays constant over the life of the dwelling. NCSU (2013) suggests that such designs will only add small extra costs, but rather could benefit in terms of longevity of owner's usage, and expanding the tenant pool if rentable housing.

Moffatt and Russell (2001) break down adaptability into a number of approaches, which can be achieved through changes in design, namely: flexibility in space planning; convertibility in space use; and expandability in space volume. Such adaptability is suggested to lead to longer service lives because changes can be achieved at lower cost. In a similar way, Arge (2005) looks at adaptability in terms of generality, flexibility and elasticity, which relate to the physical design of the building to meet changed needs.

Comments on incorporating adaptability in design are given by Keymer (2000), Wang and de Neufville (2005), Guma (2008) and Zhang (2010). de Neufville et al. (2004) suggest moving away from conventional design based on fixed specifications. Engel and Browning (2008) discuss architectural adaptability, with particular emphasis on modularity, to facilitate altered uses and stakeholder desires. Schneider and Till (2005) and Till and Schneider (2005) comment on the trade-off between possible up-front extra costs and long-term benefits, and the architectural and engineering aspects of adaptable design.

6.5 Housing changes

The housing-related transitions of Matusik (2014) illustrate how people of different ages are associated with different housing types, and how people progress from one housing need to another. On housing, Matusik (2014, p.1) breaks the market into six segments:

Children *– aged up to 17 years. Living mostly – one hopes – at home; and whilst not a direct influence on underlying demand, they are captured in the larger household sizes of first home buyers (3.3 people on average per dwelling) and the upgrading market (2.99 people per home).*
Young renters *– 18 to 29 years. Statistically, 77% of them rent, many rent apartments in our inner cities.*
First home buyer*s – 30 to 44 years. For many, it is not until their mid to even late 30s that they buy a home perhaps because of study loan reimbursement; partnering later; parents as friends; travel; options galore.*
Upgraders – *45 to 59 years. Having children later means that many, even well into their 50s, still have teenage children at home. With teenagers you want space – demand is highest for houses, with lots of bedrooms, a pool etc.*
Downsizers – *60 to 74 years. Many want to move into something with a nexus to the ground; in a small project and if possible in their existing neighbourhood. Living close to the grandchildren is also a strong locational consideration.*
Age-related care - *over 85 years. At this age – and it is mostly women who live this long – some form of assistance is often required. But many who live to 85 years, the statistics show, can expect another ten years of life in nursing homes.*

As people progress through different life cycle stages, and their family structures and financial situations change, so do their housing needs and preferences… As the *number and age of children increase, many families will upgrade to a larger house. After the children have left home, most home owners will probably remain in the same home at least until retirement, by which time most will own their home outright. After retirement, some will change location, and in doing so a few will choose a smaller home, possibly a unit in a retirement village. Later, some who are too old or frail to live in their own home will move into cared accommodation.* (ABS, 2012, p.1).

House spending peaks when people (upgraders) look to upgrade in search of more space, for example as teenagers demand their own bedrooms, families search for more entertaining space, or families wish to enhance their status. The money spent on housing, and the number of moves made, drops once people are in our mid-to-late 50s. ABS (2011) gives that 27% of people over 15 have lived in their houses for more than 15 years, 30% have lived in the same house for 5-14 years and 43% of people moved in the last 5 years. The decision to move or not move may be based on various factors, for example social factors relating to proximity to schools, shops, friends and family.

6.6 Sustainability and housing adaptability

It is perceived that building in housing adaptability influences some sustainability issues. Social issues, associated with adapting houses, result from the physical and/or psychological impacts on stakeholders (Surbeck and Hilger, 2014). Those issues connected with demolition and construction reflect the quantity and type of physical work involved in the adaptation. More deconstruction and construction activity is anticipated with the NA form compared with the A form. Some relevant social issues include:

- *Workers:* health and safety in construction; employment opportunities (Sawacha et al., 1999; Edwards and Turrent, 2000).

- *Neighbours:* disruption to traffic in the immediate neighbourhood (Gilchrist and Allouche, 2005; Surahyo and El-Diraby, 2009); emitted pollutants, dust, noise and vibration (Gilchrist and Allouche, 2005, after Bein, 1997).
- *Owners:* level of comfort; identity due to long-term inhabitancy (Guma, 2008); inconvenience due to compulsory move-out (Edwards and Turrent, 2000).

Environmental issues involved in deconstruction and construction include (Larsson, 1999; Moffatt and Russell, 2001):

- *Resource consumption:* materials and energy use.
- *Emissions:* equipment-producing emissions; embodied emissions within materials used or demolished.
- *Waste generation:* material waste in deconstruction and construction; material reuse.

When compared to full house demolition, the contribution of usage adaptability to sustainability through saved resources and energy is acknowledged, among other instances, through the quotation: *the greenest buildings are the ones we already have*. (Langston et al., 2013, p. 234, after Jacobs, 1961).

While there is reasonable agreement in the literature to move towards adaptability, most publications have not put a financial or any quantitative sustainability value on adaptability (Gann and Barlow, 1996; Heath, 2001; Moffatt and Russell, 2001; Slaughter, 2001). Sustainability value of housing adaptability is established in this chapter through a real options analysis, conjunct with social/environmental life cycle analyses.

6.7 Suggestions on adaptable housing

Matusik's (2014) identified transitions in housing lead to possible adaptability suggestions. As house owners transition through life, they may wish to upgrade or downgrade according to lifestyle choice. This would imply, subject to viability, that there is a need in the market for adaptable housing. A case example involving a single- to two-storey house extension is given below.

Some cities are constantly pushing their borders, leading to new land releases (McKenny, 2014). Many of the new developments cater for first time buyers who are looking to enter the market (Harvey, 2015). Commonly, affordability is important, possibly leading to houses with preset designs, and where the builder can gain economies of scale through replicated production (Devine, 2013).

While such houses may be adequate for immediate needs, Matusik (2015) suggests through the identified housing-related transitions, that there is a need for the option to grow a house, as growing families look for more space. This is the case example considered here.

In broader terms, the case example considers a single-storey house (built at time $t = 0$), with the potential to expand, at some time $t = T$ in the future, to a two-storey house. The case example looks at (A) the cost and environmental and social impacts of designing in adaptability and the subsequent adaptation, compared with (NA) the more usual situation of not designing in adaptability and its adaptation. There is a trade-off between financial, environmental and social impacts now and those in the future. Designing in adaptability facilitates an upper storey extension. The upper storey, however, need never occur, depending on the house owner's situation in the future. That is, the upper storey addition is an option – a right but not an obligation.

6.8 Case example: Single- to two-storey house extension

6.8.1 Design and construction

The initial construction is a single-storey house. The initial design is assumed to be structurally capable of carrying an additional storey. The main structural elements to be considered are the foundations, roofing, walls and upper storey flooring. Timber-framed construction is assumed, though it is recognised that other forms of house construction, for example using bricks, could be used.

Possible approaches are that the new construction sits on top of the old, or that the old is raised in total by jacking and placing the new underneath, provided the original construction makes this possible (Hulse, 2007). The former practice is adopted here, however the broad analysis and considerations for both situations are the same (engineering drawings given in Appendix E).

Foundations. There are a number of methods of constructing house foundations include strip footings, waffle pods, and suspended concrete slabs supported on concrete piers (Fitzgerald, 2010). Consultation with structural engineers (see Appendix G for advisers' details) suggests that the extra cost of increasing the size of the piers and slab depth in going to a two-storey design, over a single-storey design, is very small while there is a belief that current slabs may be over-designed.

Roofing. Pitching a roof might be done with conventional timber struts and beams, or with prefabricated trusses. Conventional framing relies on internal load bearing walls, while trusses are able to span between external walls if required. Trusses allow for internal room flexibility, and so-called 'open plan living'. A truss might be re-used in whole or re-assembled in parts (Reardon, 2013) in going from a single-storey house to a two-storey house, however an industry opinion is that the deconstruction and reconstruction of a roof is not straightforward, due to the deformation and warping of timber roof trusses caused by heating and cooling. Steel-framed roofs with suitable choices of fasteners may present a possible solution to this.

Internal/external walls. For timber stud walls, the main difference between single-storey and two-storey houses is the stud size. Common practice for single storey houses is to use 90x45mm for external walls and 70x35mm for internal walls; in two-storey houses, the first storey is constructed with 90x45mm timbers for both internal and external walls, and the upper storey uses the same as a single-storey house. The assumption in the following is that both the designed-in and non-designed-in walls are sufficient to carry an upper storey, and hence the wall costing is the same and can be omitted from the calculations. Should this not be so, then the difference in wall costs would be included in the calculations.

Upper storey flooring. The possibility, with adaptability in mind, is that the ceiling for the single storey house be constructed as a floor for the potential upper storey. This requires using more substantial beams than would ordinarily be used for ceilings, together with flooring boards. By doing this, the lower storey remains habitable throughout adaptation, avoiding distasteful moving and temporary rental elsewhere (James, 2015), and creates less disruption and dust. In the interim, the space above can also be used for storage.

For the non-designed-in form, timber infills and timber beams sitting on these are commonly used such that the upper storey flooring can be built without disrupting the existing ceiling. This does however lead to a noticeable distance between the lower storey ceiling and the upper storey floor, which may be aesthetically undesirable in locations such as stairwells. Also, it is generally the view that while this construction is taking place, the house is not habitable, requiring temporary vacating and rental of an alternative dwelling by the owner. The intangibles associated with any temporary relocation of the owner would be difficult to assess accurately.

Other considerations. The above outlines the engineering aspects of the designs. Other considerations relating to the architectural design of the original and modified dwelling, including people movement, room juxtapositions, external access, stairwells and so on are assumed to be in hand. The separation and recycling of used building materials is assumed as adopted practice.

6.8.2 Financial

Table 6.1 summarises the differences that are costed in the analysis. It is acknowledged that others may look at house construction differently - the actual dollar values will change, but the valuing methodology advanced here will not change.

Time	**A: Designed-in form**	**NA: Non-designed-in form**
t = 0	Construct upper storey timber floor	Construct ceiling
t = T	Disassemble roof	Demolish roof
		Construct upper storey timber floor
	Reassemble (salvage, new) roof	Construct roof
		Renting cost

Table 6.1. Housing case example: designed-in versus non-designed-in forms, only differences in construction given.

Optimistic, most likely and pessimistic estimates are made, as mentioned above, leading to expected values and variances of the costs. Costing estimates follow Cordell (2014b) and Rawlinsons (2015) based on quantity take-offs from drawings, together with quotations from various builders, engineers, tradespeople and industry representatives (see Appendix G for advisers' details). House size selected is average for the market in Sydney at year 2015. A typical photo of the timber-framed house is given in Appendix E (Figure E1).

Consider a typical single storey house. Based on the above-given assumptions and approach, cost estimates give the following:

$$E[NA_T] = \$69.9k, \; Var[NA_T] = (\$5.4k)^2$$

$$E[A_T] = \$26.2k, \; Var[A_T] = (\$2.0k)^2$$

Figures 6.1 and 6.2 show the change in E[PW] with r and T. For all calculations, Φ is very close to 1 implying that the adaptability value is very close to E[PW]. The initial investment in adaptability is estimated as $28.6k. It is seen that building in adaptability is only viable for lower r and lower T. However, since the initial cost and E[PW] are close, house owners may prefer to keep their initial borrowings as low as possible and not build in adaptability.

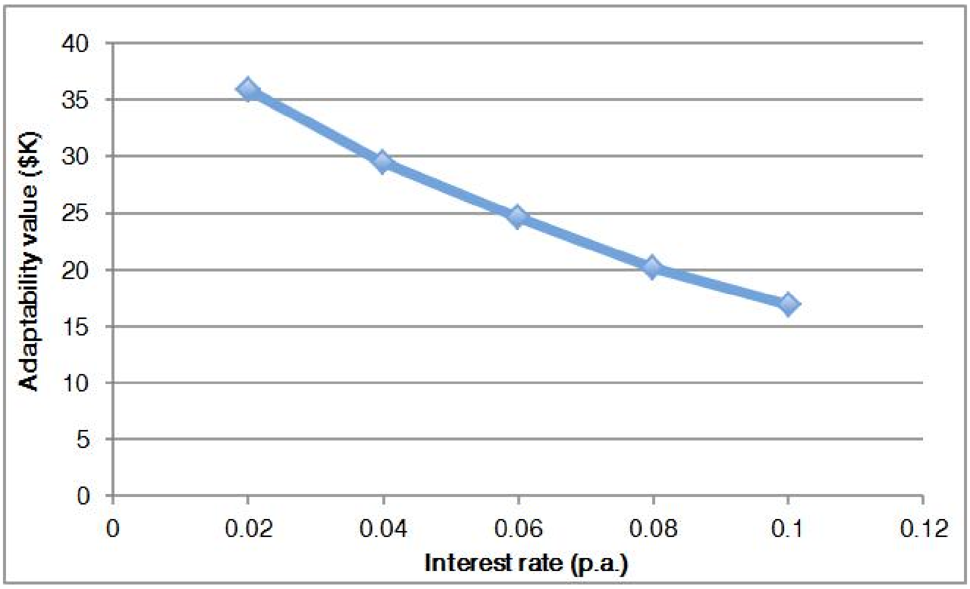

Figure 6.1. Housing case example: Change in adaptability value with interest rate (p.a.), T = 10 years.

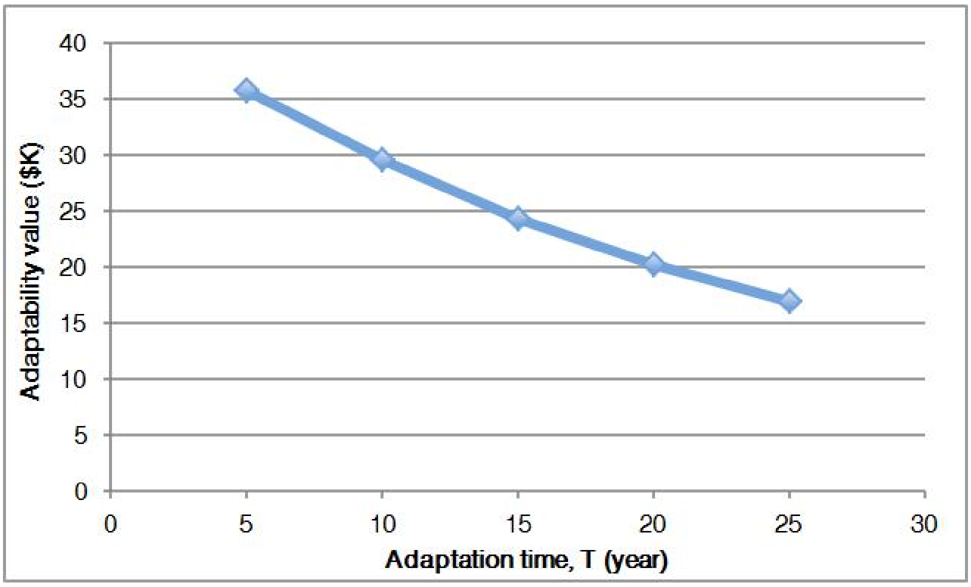

Figure 6.2. Housing case example: Change in adaptability value with time of exercising T, r = 5% p.a.

The designed-in A form is seen to be financially more viable than the non-designed-in NA form within time periods where people typically look to upgrade. This is mainly due to a large saving in the A form adaptation cost, with no need for upper storey flooring and the partial reuse of existing roof trusses. However, since the initial cost and E[PW] are close, house owners may not build in adaptability and may require an enhanced incentive for investment.

6.8.3 Environmental

Environmental issues that are different between the A and NA forms are noted in Table 6.2.

Time	A: Designed-in form	NA: Non-designed-in form
t = 0	More solid waste; more material use; longer construction time—embodied energy, emissions, noise	
t = T	Part reusable roofing	Non-reusable roofing
		More solid waste—existing house materials and new construction; more material use; longer construction time —embodied energy, emissions, noise

Table 6.2. Housing case example: Comparison of environmental issues.

Inventory flows, consisting of materials and energy (environmental inputs); and emissions and solid wastes (environmental outputs), are tracked for the determined unit processes of construction and deconstruction at times 0 and T (Figure 6.3).

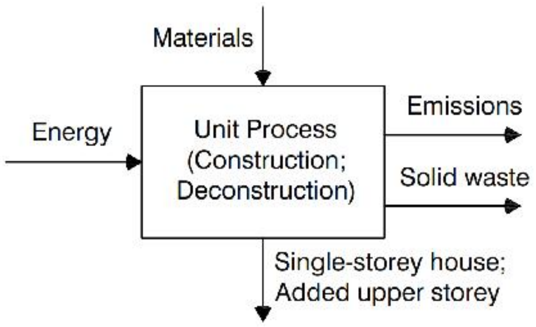

Figure 6.3. Housing case example: Unit processes and inventory flows for the LCA.

Using data from RSMeans (2015), together with information from builders, engineers, tradespeople and industry representatives, the estimates of differences in inventory flows between the A and NA forms follow (see Appendix G for advisers' details). Timber is the predominant material used.

Differences in inventory flows at t = 0

- *Materials*. Trussed roof (A form) – timber consumption reduction of 1 m^3 or 500 kg compared with NA form. Ceiling (A form) – additional timber of 20 kg/m^2 of floor plan area (total 5000 kg) resulting from the use of more substantial beams together with flooring boards (Spanman, 1992), compared with the NA form. This gives a net extra consumption of timber of 4500 kg for the A form over the NA form.
- *Energy*. The sawn timber embodied energy is assumed as 1.5 MJ per kg of timber (Australian Government, 2004); the differing amount of the total timber used between the A and NA forms gives 6750 MJ more embodied energy for the A form. Given that the embodied energy values account for construction-related energy use (Australian Government, 2004), the effect of a slightly longer site time for the A form gives only a slight increase in energy use for temporary services, and this is neglected here.
- *Emissions.* The sawn timber embodied carbon (taking carbon storage potential into account) is assumed as 0.53 kg of CO2-e (carbon dioxide equivalent) per kg of timber (Australian Government, 2004). The additional quantity of the total timber consumed in the A form leads to 2400 kg CO2-e more emissions. As for the energy calculation, the slight increase in emissions due to a longer site time for the A form is neglected.
- *Solid waste.* Ceiling (A form) – assuming a median estimate of carpentry wastage of 9% of work quantity (Reddrop et al., 1997) leads to 450 kg more timber waste than the NA form. Trussed roof (A form) – timber waste reduction of 140 kg resulting from the use of prefabricated trusses compared with the built-in-situ NA form (Reddrop et al., 1997). This gives a net extra timber waste of 310 kg for the A form over the NA form.

Differences in inventory flows at t = T

- *Materials*. Pitched roof (NA form) – timber consumption of 3000 kg for new roof construction. Upper storey flooring comprising beams and boards (NA form) – timber consumption of 24.5 kg/m^2 of floor plan area (Spanman, 1992) results in 6125 kg of timber consumed. Trussed roof (A form) – timber consumption of 2500 kg for new roof construction (Carre, 2011). However, a 50% truss reusability leads to a consumption reduction of 1250 kg of timber for the A form. In summary, the NA form consumes a net extra 7875 kg of timber.

- *Energy*. Assuming 1.5 MJ of embodied energy per kg of timber (Australian Government, 2004), the extra 7875 kg of timber used in the NA form roofing and upper storey flooring leads to 11800 MJ more embodied energy. As at t = 0, the construction time-related energy use is considered small and is neglected here.
- *Emissions.* Assuming 0.53 kg of embodied CO2-e per kg of timber (Australian Government, 2004), the additional 7875 kg of timber consumed in the NA form leads to 4175 kg of CO2-e emissions. As at t = 0, the construction time-related energy use is considered small and is neglected here.
- *Solid waste.* Pitched roof (NA form) deconstruction – 3000 kg of timber waste. Upper storey flooring (NA form) – assuming a median estimate of carpentry wastage of 9% of work quantity (Reddrop et al., 1997) leads to 550 kg of timber waste. In-situ frames and pitched roof construction (NA form) – timber waste of 370 kg (Reddrop et al., 1997). Trussed roof (A form) deconstruction – assuming a 50% truss reusability leads to 1250 kg of waste. Built-in-situ frames and off-site constructed trusses (A form) – 230 kg of timber waste (Reddrop et al., 1997). In summary, the NA and A forms produce the timber waste of 3920 kg and 1480 kg, respectively. This leads to a net extra timber waste of 2440 kg for the NA form over the A form.

The environmental impact categories are taken here to be the same as the above inventories, and are consistent with those adopted in rating systems such as NABERS or Green Star (Rawlinsons, 2015). Differences in the environmental impacts between the A and NA forms are summarised in Table 6.3.

Environmental impact	At t = 0	At t = T	Combined t = 0 and T
Material consumption (kg)	4,500	-7,875	-3,375
Energy use (MJ)	6,750	-11,800	-5,050
Emissions (kg CO2-e)	2,400	-4,175	-1,775
Solid waste production (kg)	310	-2,440	-2,750

Table 6.3. Housing case example: Differences (A – NA) in environmental impacts.

It is seen that the A form performs better with respect to all environmental impacts considered, and hence when all impacts are combined, irrespective of whatever weightings are chosen (Bengtsson et al., 2010), the A form is preferable against all environmental criteria. For the A form because of the pre-thought adaptation, compared to the NA form, there is a reduction in material consumption, energy use, emissions and solid waste production.

6.8.4 Social

Social issues that are different between the A and NA forms are noted in Table 6.4.

Time	A: Designed-in form	NA: Non-designed-in form
t = 0	More construction time—dust, noise, vibration, neighbourhood disturbance, potential for accidents	
		Lower paid hours for workers
t = T		Temporary displacement of occupants; temporary rental elsewhere
		Poorer design for people flow within the house
		Slightly less attractive aesthetics
	Owner's exposure to dust, noise and vibration	More construction time—dust, noise, vibration, neighbourhood disturbance, potential for accidents
		Larger site clean-up post-deconstruction and construction
	Lower paid hours for workers	

Table 6.4. Housing case example: Comparison of social issues.

The Social Life Cycle Assessment (SLCA) approach is used here, except for those issues such as people flow within the house and aesthetics, which might be analysed based on surveys of stakeholders' opinions. With the same scope and unit processes as defined in the Life Cycle Assessment (LCA), the relevant inventory flows examined are worker employment (social input), and safety incidents, health damage and inconvenience (social outputs) (Figure 6.4).

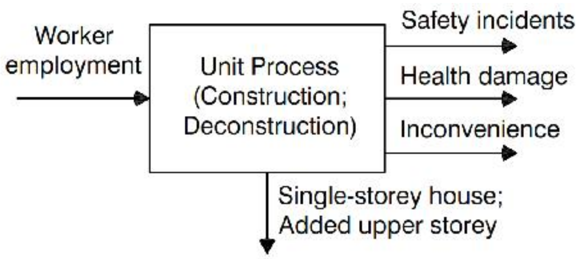

Figure 6.4. Housing case example: Unit processes and inventory flows for the SLCA.

Using data from RSMeans (2015), together with information from builders, engineers, tradespeople and industry representatives (see Appendix G for advisers' details), the estimates of differences in inventory flows between the A and NA forms follow. Worker employment is measured in total worker hours (hours per worker multiplied by number of workers). Safety incidents are expressed as a frequency, namely the number of injury occurrences per hours worked by all workers (AS1885.1, p. 20). Health damage due to exposure to construction noise varies with activity-equivalent-continuous-noise level (in decibels, dB) and number of exposure hours (hours per person multiplied by the number of affected people) (BSI, 2009, p. 6), and has units of dBh. (Activity-equivalent-continuous-noise level is defined as the sound pressure level determined at a distance of 10 m from, and over the period of, a given activity - BSI, 2009, p. 1.) Inconvenience to people during construction implies disruption.

Differences in inventory flows at t = 0

- *Worker employment.* Trussed roof (A form) – 160 h, based on 8-hour days, 4 workers and 5 days. Ceiling and upper storey floor (A form) – 160 h. Pitched roof (NA form) – 160 h. In summary, the A form leads to 160 h more employment.
- *Safety incidents.* Assuming a construction injury frequency of 33 injuries per million working hours (SWA, 2012), the additional 160 h employment for the A form could potentially result in 0.0053 more injuries.
- *Health.* Assuming 5 neighbouring families, each comprising 3 persons, being subjected to equivalent continuous construction noise of 82 dB (BSI, 2009),

the extra site time of 40 h for the A form leads to an additional 49200 dBh noise impact. Workers exposed to noise are assumed to be equipped with suitable hearing protection.

- *Inconvenience.* It is assumed that there is no differential disruption to the neighbours' everyday life due to the A and NA forms initial construction, while the owners are not present at t = 0.

Differences in inventory flows at t = T

- *Worker employment.* Pitched roof (NA form) deconstruction – 80 h, based on 8-hour days, 2 workers and 5 days. Upper storey floor (NA form) – 160 h. Pitched roof (NA form) new construction – 160 h. Trussed roof (A form) deconstruction – 40 h. Trussed roof (A form) new construction – 160 h. In summary, the NA form creates 200 h more employment.
- *Safety incidents.* Assuming a frequency of 33 injuries per million working hours (SWA, 2012), the additional 200 h employment for the NA form leads to 0.0066 more potential injuries.
- *Health.* Assume 5 neighbouring families, each comprising 3 persons, and the owner family comprising 3 persons. Pitched roof (NA form) deconstruction – equivalent continuous noise of 88 dB (BSI, 2009) over the extra 20 h site time compared with trussed roof (A form) deconstruction. Additions (NA form) – equivalent continuous noise of 82 dB (BSI, 2009) during the extra 120 h construction time (80 h for upper storey flooring and extra 40 h for new roof construction). Assume the owner family comprising 3 persons. Trussed roof (A form) deconstruction – equivalent continuous noise of 88 dB (BSI, 2009) over the 20 h activity. Additions (A form) – equivalent continuous noise of 82 dB (BSI, 2009) during the entire 480 h construction. Workers exposed to noise are assumed to be equipped with suitable hearing protection. In summary, the excess of noise effects for the NA and A forms are 174000 dBh and 123360 dBh, respectively. This leads to an additional noise impact of 50640 dBh for the NA form over the A form.
- *Inconvenience.* The owner vacates the house for the NA form throughout the assumed 16-week construction, and is assumed to pay $8,000 total in rental of

an alternative house (Rawlinsons, 2015). Cost of moving into the alternative house and moving back to the expanded house is assumed to be $1500. Cost of occupiers' commute to work is assumed not to be affected significantly. Clean-up of the lower storey after the NA form addition is estimated to cost $500 for the owner. This gives an extra cost for the NA form adaptation of $10000. It is assumed that there is no differential disruption between the A and NA forms to the neighbours' everyday life.

Differences in the social impacts between the A and NA forms are summarised in Table 6.5.

Social impact	**At t = 0**	**At t = T**	**Combined t = 0 and T**
Worker employment (h)	160	-200	-40
Safety incidents (number of injuries per 10^6 h)	0.0053	-0.0066	-0.0013
Health (dBh)	49,200	-50,640	-1,440
Inconvenience ($)	0	-10,000	-10,000

Table 6.5. Housing case example: Differences (A – NA) in social impacts.

The designed-in A form can be seen to be generally better than the non-designed-in NA form against social criteria. This is so with respect to all the (combined) social issues raised in Table 6.5, except employment.

6.8.5 Sustainability implication

It is demonstrated that the designed-in A form is better than the non-designed-in NA form according to financial, environmental and social criteria. Accordingly, the A form would be considered a more sustainable alternative, irrespective of how the multicriteria and subcriteria are dealt with collectively (Carmichael, 2013b).

Environmental and social criteria enhance the financial value of usage adaptability in housing.

The sustainability argument in favour of the designed-in A form over the non-designed-in NA form is not strongly influenced by whether the analysis is carried out from the owner's viewpoint or the community's viewpoint. However, the owner's decision making would undoubtedly be strongly influenced by personal interest.

6.9 Discussion

The average time between people moving houses is approximately 10 years (ABS, 2011). Building in adaptability, for the assumptions considered, was shown to be financially viable up to this time period, but not longer time periods unless the interest rates are low. But social and environmental issues increase the viability. However, it is unclear as to how house owners will interpret the favourable financial, social and environmental measures and what unstated decision making processes house owners go through.

The resale value of a house containing built-in adaptability should in principle be greater than a house without such a feature. However, it is unclear as to what value the market would place on this; to a buyer considering possible future adaptation, its worth follows Figures 6.1 to 6.2, but in any negotiation between buyer and seller this information would be unknown to the seller.

The adaptability financial value increases with uncertainty about future costs. The predominant source of this uncertainty lies in the building work method adopted and the scope of the work. The building work would more than likely be undertaken on a cost reimbursable basis because an existing house is being modified, rather than a fixed price basis as is more common with new houses. The final outcome cost for cost reimbursable work is never definite.

6.10 Conclusion

In this chapter, the application of a method for valuing designed-in adaptability in housing was demonstrated on a case example, using actual data, involving typical upgrading of a house. The built-in adaptability form was compared with the non-built-in adaptability form. For the case example, financial viability was demonstrated for smaller interest rates and smaller times to adaptation, but not for larger interest rates and/or time to adaptation.

Whether designing-in adaptability is viable or not, from the house owner's financial viewpoint, cannot be said in general terms, but rather requires an individual analysis for each situation. Intangibles and sustainability arguments increase the viability of building in adaptability, but at the present time it is believed that few house owners would apply much weighting to these intangibles and sustainability compared to the financial aspects.

The study adds to current literature by providing an analysis that gives the value of adaptable housing. The approach will be useful to the construction industry and house owners contemplating prolonging the useful life of a house through adaptation over time.

Chapter 7: Sustainability of Open Plan Buildings

7.1 Introduction

Building infrastructure is of crucial importance in terms of accommodating social needs through providing residential, office or commercial spaces, while it requires massive outlay of money and resources. In Australia, buildings lead the economic and social infrastructure development, accounting for a large share of investments with major contributions to country's productivity growth (Master Builders, 2015). The value of work done for buildings construction is estimated to be $25B in 2015 (ABS, 2015e); and is predicted to cumulatively be worth $1.25T (just below Australia's GDP) over the next decade (Master Builders, 2015; Trading Economics, 2015). Also, a great deal of building work has been done on existing buildings in Australia – constitute about a fifth of construction work in 1990s (Wilkinson et al., 2009). Buildings adaptation in the forms of alterations, additions and conversions represents a considerable portion of investments in building activities (ABS, 2015d; 2016a), environmental issues associated with resource consumption as well as disruption to buildings operation. Thus, shortage or redundancy of buildings spaces leading to adaptations implies a significant sustainability issue.

Buildings adaptability is now introduced as a key concept in construction, in response to the changing needs and wants of the user (Gann and Barlow, 1996; Heath, 2001). Changing demand in terms of desire and/or number of users implies a change in space requirements, enforcing floor plan adaptations (Kendall, 1999; Moffatt and Russell, 2001). However, the building floor plan is conventionally designed fit for a single purpose, fulfilling user's needs at the time of design. As demands grow, user seeks more efficient and larger spaces. This might be realised by changing the internal layout of spaces (Greden, 2005; Till and Schneider, 2005) or space additions, either within the existing building or in a new neighbourhood (de Neufville et al., 2008; Guma et al., 2009). As demands fall, a loose arrangement of spaces may suffice in the first place, followed by conversion in use, with the extreme being complete demolition (de Neufville et al., 2008).

The architecture literature suggests open plan buildings as an effective strategy for incorporating adaptability in building infrastructure, and continuing relevance, but there is a profound lack of effort to value its associated adaptability (Gann and Barlow, 1996; Attfield, 1999; Slaughter, 2001; Till and Schneider, 2005; Schmidt et al., 2010). This chapter fills the literature gap by valuing open plan buildings adaptability, using Real Options Analysis (ROA) for financial valuation (Carmichael et al., 2011), and life cycle approaches for evaluation of social and environmental intangibles.

A hypothetical case example involving an educational building (Civil Engineering Building at the University of New South Wales, UNSW) adaptable to a new internal layout is given. The methodology, but not necessarily the design with associated numbers used in the case example, is applicable to any other situations and locations.

People within the building and construction industries, particularly building owners/managers deciding on developments whether in private or public sectors, will benefit from the study. They will be able to assess the viability of open plan buildings, with any combination of designed-in adaptability features, using the given approach.

The chapter's approach to establishing the viability of open plan buildings adaptability, which is quantitative assessment from sustainability viewpoint, is original.

The chapter outline is as follows. First, a review on the key concepts and valuation of open plan buildings adaptability is undertaken. Then, a comment is drawn on the projected demand on building spaces in Australia with possibility of open plan buildings construction. Finally, the adaptability is valued for a case example, followed by a general argument on the viability of open plan building.

7.2 Adaptability/flexibility and open plan building

Open plan building, as a method of incorporating flexibility/adaptability, is viewed in different ways in the literature. Schneider and Till (2005) uses so-called ‘frame construction’ to imply open plan design as what allows for change in floor plans with minimal disruption. Schmidt et al. (2010) after Gelis (2000) define open plan as an adaptability meaning where a universal floor plan allows for space configuration in accordance with the needs.

Some writers use open plan to mean a floor plan of spacious layout with a large, open (in the sense of a shared, unconcealed) space and no partitions (Oldham and Brass, 1979; Attfield, 1999; Ilozor et al., 2001; Cieraad, 2002; Dowling, 2008). Attfield (1999) talks of modern open-plan design as a substitute for the conventional plan with separated rooms. She also mentions that designers have originally seen *open plan as synonymous with free plan, providing easy adaptability* (Attfield, 1999, p. 76). Dowling (2008) adds that open *plan is a softer space valued for its functionality as much as its form* (Dowling, 2008, p. 537).

The notion of open plan should not be confused with open buildings, with independence of building elements where the façade being the only thing that changes (Kendall, 1999; Larsson, 1999; Moffatt and Russell, 2001; Schneider and Till 2005). However, the elements independence overlaps with the concept of open plan when it contributes to an enhanced capability of change in the floor plan.

The sense of the term open plan refers here to the floor plan with capability to change in line with future circumstances.

The inevitable changes in building space demand create the need for modifications; this can readily be realised through open plan design, which avoids building infrastructure obsolescence and extends its useful life (Slaughter, 2001; Wilkinson et al., 2009; Schmidt et al., 2010). The open plan building allowing for the designed-in A form adaptation is the focus of this chapter, and the non-designed-in NA form is used as a base case for comparison. The following review covers typical adaptation measures within building floor plan, proactive design of open plan buildings and valuing associated adaptability.

7.3 Floor plan adaptation

With building floor plan, changes in demands – number or composition of users group and/or users' wants and preferences in accordance with modern architectural style – may lead to adaptation in the form of additions, alterations and conversions (Moffatt and Russell, 2001; Till and Schneider, 2005).

Additions to the built space in floor plan may occur through horizontal expansion such that increasing building footprint by a new construction besides (de Neufville et al., 2008). Alternatively, a common practice may be providing additional space elsewhere; however, this may raise issues of users commute or loss of consolidated asset for the owner (Guma, 2008). Associated with this adaptation method are reductions, opposite to additions, through demolition or subletting part of space, which may occur as a result of decreasing demand.

Interiors alterations indicate replanning of space layout, which may be carried out by switching between closed individual spaces and open-plan spaces, based on the variation in demand (Attfield, 1999; Greden, 2005; Till and Schneider, 2005). This adaptation method is basically intended to capture areas for active use and maximise the usage efficiency with minor changes in the existing floor plan, so that meeting changing demand (Attfield, 1999; SMG, 2006). Alterations are commonly made by elimination of less active areas such as corridors and rearrangement of rooms through relocation of internal walls (Friedman, 1993; Keymer, 2000; Moffatt and Russell, 2001; Till and Schneider, 2005; Dowling, 2008).

Change of use in response to declining demands, which is sometimes referred to as adaptive reuse, can be made either within the whole building or individual spaces in a floor plan. Examples include: preserving heritage buildings following the obsolescence in terms of their original use (Greden, 2005; Langston et al., 2013), or converting redundant offices into apartments perhaps because of an oversupply of office space (Gann And Barlow, 1996; Heath, 2001; Wilkinson et al., 2009; Remøy et al., 2011). Conversions within the floor plan in effect of increased demands may also imply using spaces for multiple functions at different times (SMG, 2006; Taneja et al., 2012); this needs special attention to the timing of space usage. The adaptations dealing with conversion in use are very likely to require interiors alterations as well (Gann and Barlow, 1996).

7.4 Open plan building: Built-in adaptability (A) form

There has been an intellectual, but not theoretical, justification for constructing open plan buildings with enhanced adaptability in lieu of designing floor plans capable of accommodating a single layout and/or use (Gann and Barlow, 1996; Attfield, 1999; Moffatt and Russell, 2001; Slaughter, 2001; Till and Schneider, 2005; Schmidt et al., 2010). Moffatt and Russell (2001) introduce strategies of flexibility in space planning and convertibility in space use to incorporate adaptability in design of building's floor plan. They suggest that such adaptability leads to longer service life because adaptations can be realised at lower costs. In a similar way, Arge (2005) looks at buildings adaptability, and open plan design, as what relates to the physical design of buildings' architecture to meet changing needs; this design may facilitate multifunctional use of spaces and/or rearrangement of architectural elements. de Neufville et al. (2004) suggest shifting away from conventional design based on fixed specifications towards flexible design. For example, de Neufville et al. (2008) acknowledge designing open-plans using *shell space, where areas are built but not yet equipped… or through flexible layout of rooms allowing a change of usage in future* (de Neufville et al., 2008, p. 1).

Attfield (1999) suggests rethinking conventional methods of construction for open plan buildings; namely, greater use of glass, elimination of internal walls, spanning large areas with no masonry and hand construction, and connection to the outside nature. She argues that *open plan buildings free us from the limitations of load-bearing walls* (Attfield, 1999, p. 75). SMG (2006) suggests incorporating requirements for space usage efficiency early in design and feasibility studies; a solution recommended is creation of versatile space with open plan areas and/or usability for different activities.

Till and Schneider (2005) acknowledge designing open plan buildings with indeterminate spaces and wide structural spans, allowing light, non-loadbearing partitions to be put in and removed at will. Schneider and Till (2005) also talk of ‘frame construction’ with load-bearing elements situated along the perimeter of floor plan and fixed wet-spaces, leaving the remaining space free for infinite variety of layouts. Column-free design gives deliberate indeterminacy, which offers numerous uses for a space including exhibits or events (ASAE, 2005). Schneider and Till (2005) and Till and Schneider (2005) comment on the trade-off between possible up-front extra costs and long-term benefits of such adaptable design.

Slaughter (2001) suggests design-for-disassembly approaches, namely physical separation and/or prefabrication of building components to bring ease of alterations. With open plan, she also talks of *situating the building core at either end of the plan to open the centre of the floor as useable space* (Slaughter, 2001, p. 215). Slaughter (2001) argues that such strategies negligibly add to initial construction costs, which seems worthwhile to bear when comparing with significant losses due to obsolescence under changed demands. Engel and Browning (2008) acknowledge adaptability in architecture, with particular emphasis on modularity, to facilitate inexpensive changes in response to altered desires of stakeholders. Schmidt et al. (2010) suggest that adaptability can be incorporated in initial configuration before the building is occupied via industrialised building systems; this might be achieved for open plan buildings using modular construction and demountable elements (Friedman, 1993; Keymer, 2000; Moffatt and Russell, 2001).

7.5 Sustainability value of open plan buildings

Despite the literature acknowledges open plan buildings as a means to enhance adaptability in building space use (Gann and Barlow, 1996; Attfield, 1999; Moffatt and Russell, 2001; Slaughter, 2001; Till and Schneider, 2005; Schmidt et al., 2010), there is no effort to quantitatively evaluate its contribution. A few attempted examining adaptable buildings; however, used inadequate methods and considered adaptability as a whole concept or noticed other means of incorporating adaptability than open-plan design (Gann and Barlow, 1996; Moffatt and Russell, 2001). Given that open-plans provide an option (a right, but not an obligation) to change floor plans, ROA is basically utilised for financial valuation. There is also a profound lack of open plan buildings valuation in social and environmental aspects, while such design may positively address associated sustainability issues, as discussed below.

Adaptability, through open plan buildings, can avoid demolition due to obsolescence and extend building useful life; thus, there is potential to mitigate social issues such as disruption to operation as well as environmental issues through saved resources and energy and reduced emissions and wastes (Moffatt and Russell, 2001; Langston et al., 2013).

An open plan building is also able to influence sustainability issues in building operation phase via accommodating various space layouts. It allows for switching between multi-cellular and integrated spaces, affecting environmental issues associated with energy use through utilisation of natural lighting and thermal energy (Shahzad et al., 2016). In terms of social issues, open plan buildings give the option to take advantage of a multi-cellular layout with improvements in users' thermal comfort (Shahzad et al., 2016), privacy, occupation density and associated indoor air quality, occupants' health and productivity (Oldham and Brass, 1979; Saari et al., 2006), or alternatively benefit from integrated, large spaces with improved social interactions between users (Oldham and Brass, 1979).

However, the above issues are not considered here, since they are affected equally by the NA and A forms of adaptation. As well, the possibility of complete demolition is excluded, as the NA form will most likely be adapted fortuitously. The adaptation forms differ in the quantity and type of physical work involved; more deconstruction and construction activity is anticipated for the NA form compared to the A form.

The relevant environmental issues, involved in the deconstruction and construction activities, are anticipated to be similar to those of complete demolition and replacement (as the extreme condition), but with different amounts; namely (Larsson, 1999; Moffatt and Russell, 2001):

- *Resource consumption:* materials and energy use.
- *Emissions:* equipment-producing emissions; embodied emissions within materials used or demolished.
- *Waste generation:* material waste in deconstruction and construction; material reuse.

An open plan building (A) form typically takes advantage of modular construction, leads to the reuse of building elements and materials during adaptation and subsequently alleviates the environmental impacts in terms of waste, material consumption, embodied energy and emissions (Kats et al., 2003). These environmental benefits even increase due to the lower work quantity for the A form adaptation because of a forethought given to possible changes. This proactive design also accelerates adaptation process (Gosling et al., 2013), leading to a reduction in construction energy use and emissions (Hong et al., 2014).

Based on the different types and quantities of works between the two forms of adaptation, the relevant social issues are deemed to be:

- *Workers:* employment opportunities; health and safety in construction (Sawacha et al., 1999).

- *Neighbours:* emitted pollutants including dust, noise and vibration; disruption to traffic in the immediate neighbourhood (Gilchrist and Allouche, 2005).
- *Occupants/users:* inconvenience in terms of reduced level of comfort or productivity due to prolonged move-out (Edwards and Turrent, 2000; Guma, 2008).

A well-designed open plan building, which takes advantage of new technology, involves easier and more efficient construction methods with less on-site construction activities (Commonwealth of Australia, 1979); this leads to less potential safety incidents (Sawacha et al., 1999) and less disturbance to neighbours and local traffic (Gilchrist and Allouche, 2005).

The open plan building (A) form is well prepared, at time of design, for possible future alterations, and hence will require a shorter total site time for implementation. This reduces the extent of any inconvenience to the stakeholders during adaptation time; namely, shortens the time the occupants have to vacate the building and reside in a space prepared temporarily (Edwards and Turrent, 2000; Guma, 2008) or limits pollutions endangering neighbours' and workers' health. However, a reduction in total employment is anticipated due to the shorter site time and more efficient use of human resources for the A form (Commonwealth of Australia, 1979; Edwards and Turrent, 2000).

In the following, sustainability valuation of open plan building is illustrated on a case example, after a brief comment on projected situation of Australian building sector with possibility of open plan buildings construction.

7.6 Buildings in Australia

7.6.1 Changing demands: Projections

Building demands are anticipated to vary with demographic changes in terms of occupants' population and wants. These may differently affect demands on buildings of various space usages, namely residential and non-residential such as commercial, office, educational and hospitals.

Demand on residential building space, which provide people with fundamental shelter, is basically affected by the number of users or households within any target community (Smith, 2003). In Australia and majority of the states and local government areas, the demand is predicted to rise with growing total population and number of households over the coming decades, but to an uncertain extent (ABS, 2013; Johnstone et al., 2013; Commonwealth of Australia, 2015). Evidences comprise the rapid development of residential apartments occurring now (Cummins, 2015) and recent tendency towards building compact apartments with so-called 'open plan living' for efficient use of space (Chua, 2015).

Demand on non-residential building space is also anticipated to increase with growing population and associated needs for provision of products and services. A case in point is the Sydney CBD *with recent planning for greater office/commercial developments that include greater site consolidation and building redevelopment* (Cummins, 2015, p. 1). However, some industry practitioners warn of possible office oversupply, with subsequent conversions to residential or more modern office spaces (Brown, 2014).

There has also been a growing trend in the Australian education sector, posing infrastructure challenges (Commonwealth of Australia, 2013; Universities Australia, 2013). *With the mining investment boom now over, other industries such as education services gather momentum… the increasing demand for education facilities means there will be growth in building activity for Australian universities* (Deda, 2015, p. 1). As well, the changing structure (or age) of population implies change in types of goods and services being consumed; given that Australia's population is getting older, greater demand on aged-care services and hospitals is anticipated (Commonwealth of Australia, 2015).

Overall, it is believed that change in demands has to be recognised for each specific situation through identification of target community and estimation of associated population and wants.

7.6.2 Suggestions on open plan building

Possible adaptability suggestions may be inferred from the policies adopted to shape the building's targeted community and associated business. As demands change in effect of development policies, the building owners/managers may wish to make alterations in interiors so that meeting space requirements. This would imply that there is a need, subject to viability, in the construction industry for open plan buildings.

Although current design of buildings may be adequate for immediate needs, changing demands in the light of policy decisions suggest that there is a need for the option to switch buildings' interiors, looking for up-to-date and spacious layouts. A case example involving an educational building refurbishment is given here.

The case example considers a building floor plan of conventional layout (built at time $t = 0$) with the potential to switch, at some time $t = T$ in the future, to a new layout. Designing in adaptability facilitates an easier change in space layout. However, the refurbishment may never occur, depending on the building demands and owners' or managers' situation in the future. Thus, the refurbishment is an option – a right, but not an obligation.

The application of the preferred analysis method for valuation of adaptability of open plan buildings is demonstrated here on an Australian case example.

7.7 Case example: Civil Engineering Building refurbishment, UNSW

The school buildings at University of New South Wales (UNSW) have undergone major refurbishments in response to increased number of users and changed wants. Seemingly, this has been due to a high profitability of developing education/research services. Examples include the Heffron Building and Mechanical Engineering Building, which were constructed in early 1960s and refurbished substantially in 2006 and 2013, respectively. The Civil Engineering Building is likely to require similar alterations. This nine-storey building was constructed in 1964 with a conventional floor plan having a string of cellular rooms either side of a central corridor as was common practice before the 1980s (Gann and Barlow, 1996).

The Civil Engineering Building is considered here as a hypothetical case example to investigate if it could be designed and constructed as an open plan building. The case study is also applicable to future refurbishment of a new construction if it is designed with a similar floor plan.

7.7.1 Design and construction

The initial construction is a concrete structure building with a central core carrying lateral actions and rest of the structure designed for gravity actions. The initial design is assumed to be structurally and architecturally capable of alterations in the floor plan to accommodate changing needs. The assumption in the following is that the alterations have insignificant effect on the mass of building, the subsequent imposed loads and required size of foundation. Thus, the main building elements to be considered are the columns, floors and internal walls.

The building refurbishment involves relocation of internal walls to create more spacious layout by capturing areas such as corridors for active use (SMG, 2006). In terms of developing a large lecture theatre with no obstructive interior columns, possible approaches commonly used at UNSW include renting a venue elsewhere, horizontally expanding the existing building, or combining spaces in two consecutive storeys by floor demolition and creation of a space with inclined, raised floor (UNSW website, 2015a). The latter practice is adopted here; however, the broad analysis and considerations for all the situations are the same (engineering drawings given in Appendix F).

Columns. The conventional layout of columns forms a structural grid of 2x7 spans. The possibility, with adaptability in mind, is that an interior column at the lowest storey be eliminated from the grid to create a single, clear span space capable of accommodating the greatest variety of layouts. This leads to 80% increase in the loads on adjacent perimeter columns due to load transfer from above interior columns (WebTechTix, 2014) and additional weight (permanent action) of the strengthened floor (AS/NZS 1170.1, 2002). As a result, the perimeter columns of typical section 0.3x1.2m are enlarged creating 0.45x1.4m. Alternative methods of increasing columns' strength such as using composite columns exist (Clark, 1994; Shanmugam and Lakshmi, 2001), but not considered as applicable here. Also, a transfer beam of great depth necessitates building all the columns at the lowest storey with an extra 0.4m height.

Floors. There are a number of methods of constructing floors; the choice of type and depth of flooring system depends on the span length selected (CCAA, 2003). The open plan of longer span requires changing flooring system in part of the lowest floor from the traditional slab and beam of 600mm depth (i.e., include 200mm deep slab) to a prestressed flat plate of 400mm depth. Flat plate is chosen since it keeps the average depth of floor and the complexity of formwork at minimal level; however, use of other systems such as flat slab or waffle slab is also possible. The slab together with a transfer beam of 1.0x1.4m section size acts as a transfer floor, supporting upper interior columns and distributing loads to lower perimeter columns continuous to the footing level (WebTechTix, 2014).

For the non-designed-in NA form, the typical floor allows for creating openings after completion (Remøy et al., 2011). While, a spandrel beam of 0.3x0.6m section size must be built where the slab is cut to support the loads of internal walls and connect the adjacent columns.

Internal walls. Floor space may be divided by conventional, solid walls or modular, demountable walls. Solid walls have been commonly used, while there is now an increasing application of demountable walls. The possibility, with adaptability in mind, could be to construct all the internal walls with modularity using prefabricated panels attached to a metal or timber frame (Keymer, 2000). This leads to easier construction and deconstruction of the internal walls. The modular walls, and particularly the supporting frames, can be re-used or re-assembled in parts (SSG, 2016) during rearrangement of spaces through internal walls relocation.

7.7.2 Financial

Table 7.1 summarises the differences that are costed in the analysis. It is acknowledged that others may look at building construction differently – the actual dollar values will change, but the valuing methodology will not.

Time	A: Designed-in form	NA: Non-designed-in form
t = 0	Build modular internal walls	Build solid internal walls
	Construct perimeter columns of larger size—add to columns' height	Construct interior column
	Construct prestressed flat plate floor with a transfer beam	Construct beam and slab floor
t = T	Disassemble internal walls	Demolish solid internal walls
	Reassemble (salvage, new) modular internal walls	Build modular internal walls
		Demolish floor in part – build spandrel beams
		Construct inclined, raised floor

Table 7.1. Building case example: designed-in versus non-designed-in forms, only differences in construction given.

Optimistic, most likely and pessimistic estimates are made leading to expected values and variances of the costs. Costing estimates follow Cordell (2014b) and Rawlinsons (2015) based on quantity take-offs from drawings (see Appendix F – initial construction and potential alterations inspired by similar refurbishment projects and consultations with various builders, engineers and industry representatives).

Based on the above-given assumptions and approach, cost estimates give the following:

$E[NA_T]$ = \$325.9k, $Var[NA_T]$ = (\$27.2k)^2

$E[A_T]$ = \$102.4k, $Var[A_T]$ = (\$8.5k)^2

Figures 7.1 and 7.2 show the change in adaptability value with r and T. For all calculations, Φ is close to 1 implying that the adaptability value is close to E[PW].

The initial investment in adaptability is estimated as \$89.0k. It is seen that building in adaptability is only viable for lower r and lower T.

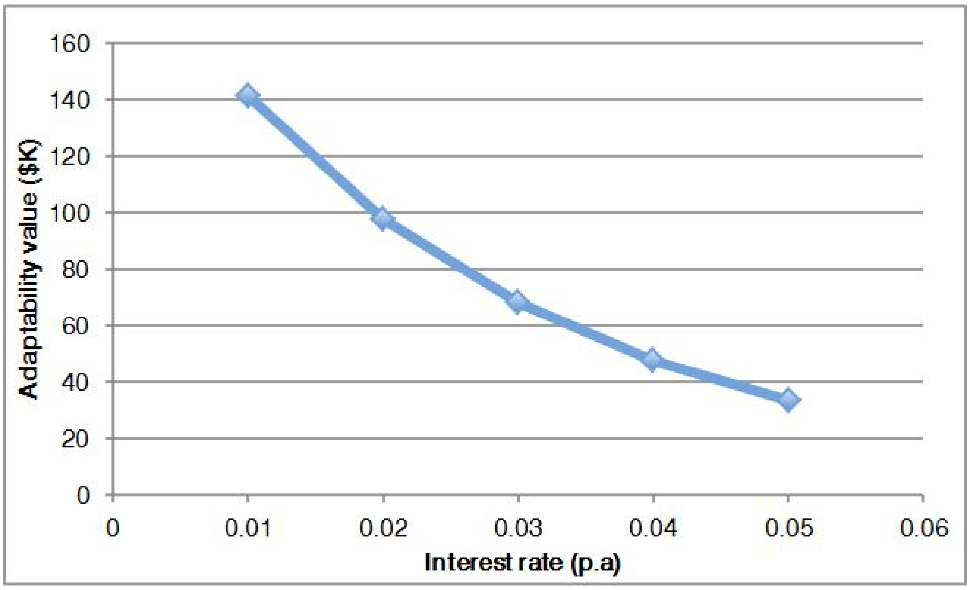

Figure 7.1. Building case example: Change in adaptability value with interest rate (p.a.), T = 35 years.

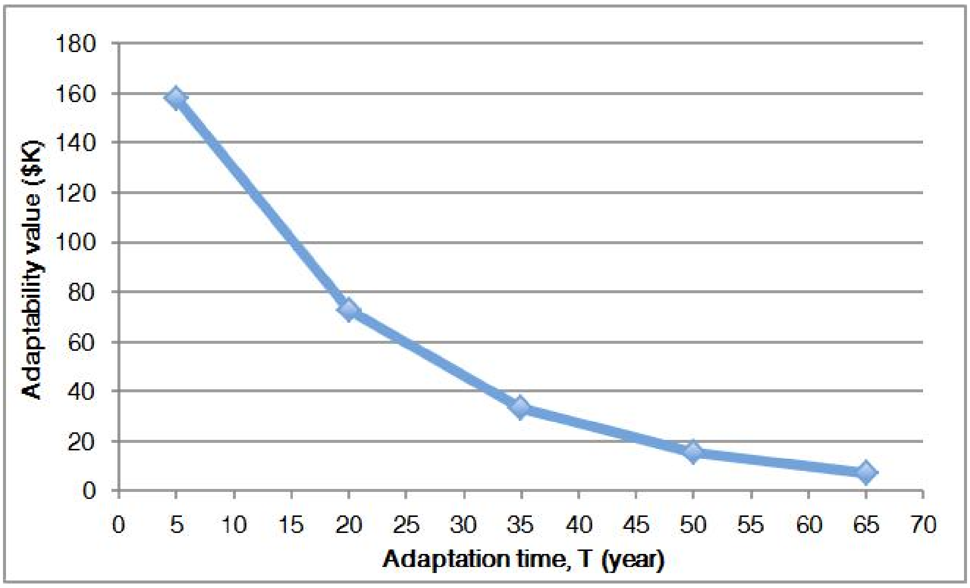

Figure 7.2. Building case example: Change in adaptability value with time of exercising T, r = 5% p.a.

The designed-in A form is seen to be financially more viable than the non-designed-in NA form for the adaptation time up to 15 years. This is mainly due to a saving in the A form adaptation cost, with partial reuse of internal walls and no need for floor demolition to create a large, free-column space. However, the A form is not viable for the average time the school buildings have typically undergone major refurbishments that is 35 to 50 years, unless the interest rate is low. Thus, the managers or investors may not build in adaptability and may require an enhanced incentive for investment. The inclusion of the intangibles is anticipated to improve the viability.

7.7.3 Environmental

Environmental issues that are different between A and NA are noted in Table 7.2.

Time	**A: Designed-in form**	**NA: Non-designed-in form**
t = 0	More solid waste, more material use, longer construction time—embodied energy, emissions for superstructure construction	More solid waste, more material use, longer construction time—embodied energy, emissions for internal walls construction
t = T	Part reusable internal walls	Non-reusable internal walls
		More solid waste—existing materials and new construction More material use, longer construction time—embodied energy, emissions

Table 7.2. Building case example: Comparison of environmental issues.

Inventory flows, which consist of materials and energy (environmental inputs) and emissions and solid wastes (environmental outputs), are tracked for the unit processes of construction and deconstruction at times 0 and T (Figure 7.3).

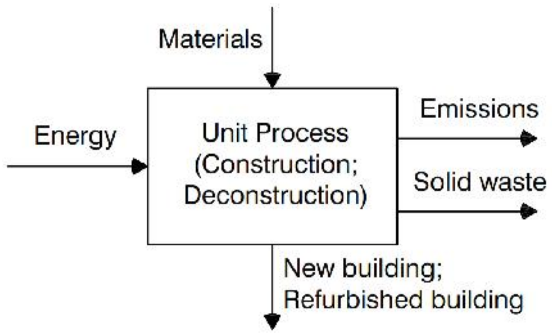

Figure 7.3. Building case example: Unit processes and inventory flows for the LCA.

Using data from RSMeans (2015), the estimates of differences in inventory flows between the A and NA forms follow. Timber, plasterboard, brick and reinforced concrete are the predominant materials used. Embodied energy and emissions are calculated using the inventory database provided by Hammond and Jones (2011); an average of embodied values for timber and plasterboard is used for modular walls. The effect of longer site time for the NA form on energy use and emissions is assumed to be negligible here; this is because the labour-intensive activities require low energy-consuming equipment, and a longer site time gives only a slight difference in energy use for temporary services. Assembling the prefabricated timber wall-frames is assumed with no on-site wastage.

Differences in inventory flows at t = 0

- *Materials*. Modular internal walls (A form) – walls of 820 meter run use 98 t of materials based on the unit mass of 40 kg/ m^2 of wall i.e., timber frame, plasterboard and insulation (Knauf, 2014). Floor and columns (A form) – additional reinforced concrete of 58 m^3 (or 139 t) for enlargement, taking the eliminated column into account, compared with the NA form. Solid internal walls (NA form) – 517 t based on the unit mass of 210 kg/ m^2 of brick wall (AS/NZS 1170.1, 2002). In summary, the NA form leads to a net extra material consumption of 280 t over the A form.
- *Energy*. Modular internal walls (A form) – the embodied energy is assumed as 8.4 GJ per tonne of wall; the consumed materials give 827 GJ of embodied

energy. Floor and columns (A form) – assume an embodied energy of 1.2 GJ per tonne of reinforced concrete; the differing amount of the total reinforced concrete used between the A and NA forms gives 167 GJ more embodied energy for the A form. Solid internal walls (NA form) – assuming 3 GJ of embodied energy per tonne of wall gives the total 1550 GJ of embodied energy. In summary, the NA form leads to 556 GJ more embodied energy.

- *Emissions.* Modular internal walls (A form) – the embodied emission is assumed as 0.56 tonne of CO2-e (carbon dioxide equivalent) per tonne of wall; the total mass of wall gives 55 tonne of CO2-e emissions. Floor and columns (A form) – assume 0.19 tonne CO2-e of embodied emission per tonne of reinforced concrete; the additional quantity of the total reinforced concrete used in the A form leads to 26 tonne CO2-e more emissions. Solid internal walls (NA form) – assuming 0.24 tonne CO2-e of embodied emission per tonne of wall, the total mass of wall gives 124 tonne of CO2-e emissions. In summary, the NA form leads to 43 tonne CO2-e more emissions.
- *Solid waste.* Modular internal walls (A form) – an estimated wastage ratio of 4% (Tam et al., 2007) for attaching plasterboards (i.e., unit mass of 20 kg/m^2 of wall) leads to solid waste production of 2 t. Floor and columns (A form) – assuming a wastage of 2% of reinforced concrete used (Yashuai et al., 2016) gives the total waste of 3 t. Solid internal walls (NA form) – assuming an average wastage of 4.5% of brick work quantity (Tam et al., 2007) leads to 23 t of solid waste. These give a net extra solid wastes of about 18 t for the NA form over the A form.

Differences in inventory flows at t = T

- *Materials*. Modular internal walls (NA form) new construction – new walls of 266 meter run use 32 t of materials based on the unit mass of 40 kg/m^2 of wall; A form requires same quantity, however a 50% frame reusability of disassembled walls (of 428 meter run with timber frame of 20 kg/m^2 of wall) for the A form leads to a timber consumption reduction of 13 t. Spandrel beams (NA form) – reinforced concrete consumption of 3.5 m^3 (or 8.5 t) after floor demolition. Raised floor (NA form) – assuming a timber consumption of 20 kg/m^2 of constructed floor area (Spanman, 1992) gives the total timber consumption of 2.5 t. In summary, the NA form consumes a net extra 24 t of materials.

- *Energy*. Modular internal walls (NA form) new construction – assuming embodied energy of 8.4 GJ per tonne of wall gives the total embodied energy of 267 GJ for the consumed materials; the reduction in timber consumption for the A form leads to 130 GJ less embodied energy, assuming a 10 GJ of embodied energy per tonne of timber. Spandrel beams (NA form) – assuming 1.2 GJ of embodied energy per tonne of reinforced concrete, the consumed reinforced concrete leads to 10 GJ of energy use. Raised floor (NA form) – total embodied energy of 25 GJ for the consumed timber. In summary, the NA form uses 165 GJ more energy.
- *Emissions.* Modular internal walls (NA form) new construction – an assumed embodied emission of 0.56 tonne CO2-e per tonne of wall gives the total embodied emission of 18 tonne CO2-e for the consumed materials; the A form with 13 t reduction in new timber frame use leads to 9.5 tonne CO2-e less emissions, based on the embodied emission of 0.72 tonne CO2-e per tonne of timber. Spandrel beams (NA form) – the embodied carbon of 0.19 tonne CO2-e per tonne of reinforced concrete gives the total emissions of 1.5 tonne CO2-e. Raised floor (NA form) – total embodied emissions of 2 tonne CO2-e for the consumed timber. In summary, the NA form leads to a net extra 13 tonne of CO2-e emission.
- *Solid waste.* Solid internal walls demolition (NA form) – 257 t of waste materials, based on 408 metre run wall removal. Modular internal walls (NA form) new construction – an estimated wastage ratio of 4% (Tam et al., 2007) for attaching plasterboards (of 20 kg/m^2 of walls of 266 meter run) leads to solid waste production of 0.6 t; the same applies to the A form. Floor demolition (NA form) – 38.5 m^3 (or 92.5 t) of reinforced concrete waste. Spandrel beams construction (NA form) – assuming a wastage of 5% of reinforced concrete used (Yashuai et al., 2016) gives the total waste of 0.4 t.

Raised floor construction (NA form) – assuming a median estimate of carpentry wastage of 9% of work quantity (Reddrop et al., 1997) leads to 0.2 t of timber waste. Modular internal walls deconstruction (A form) – 51.5 t of waste materials, based on 428 metre run wall removal (i.e., extra 20 m over the NA form for creation of a large theatre); assuming a 50% frame reusability of disassembled walls reduces solid wastes to 38.5 t. In summary, the NA form produces a net extra solid waste of 312 t over the A form.

The environmental impact categories are taken here to be the same as the above inventories. Differences in the environmental impacts between the A and NA forms are summarised in Table 7.3.

Environmental impact	**At t = 0**	**At t = T**	**Combined t = 0 and T**
Material consumption (t)	-280	-24	-304
Energy use (GJ)	-556	-165	-21
Emissions (tonne CO2-e)	-43	-13	-56
Solid waste production (t)	-18	-312	-330

Table 7.3. Building case example: Differences (A – NA) in environmental impacts.

It is seen that the A form performs better with respect to all the environmental impacts considered, and hence the A form is environmentally preferable irrespective of the choice of the weightings (Bengtsson et al., 2010). There is a reduction in material consumption, energy use, emissions and solid waste productions because of the pre-thought adaptation for the A form. Also, the results at t = 0 demonstrate that built-in adaptability is not necessarily accompanied by increased environmental loadings in initial design and construction. The adaptability features considerably contribute to improvement of environmental performance of the A form.

7.7.4 Social

Social issues that are different between A and NA are noted in Table 7.4.

Time	**A: Designed-in form**	**NA: Non-designed-in form**
t = 0	Longer construction time for superstructure—dust, noise, vibration, neighbourhood disturbance, potential for accidents	Longer construction time for internal walls—dust, neighbourhood disturbance, potential for accidents
	Lower paid hours for workers	
	Modular construction of internal walls – noise, vibration	
t = T		Temporary displacement of occupants—productivity reduction
		Longer construction and deconstruction time—dust, noise, vibration, neighbourhood disturbance, potential for accidents
	Lower paid hours for workers	

Table 7.4. Building case example: Comparison of social issues.

With the same scope and unit processes as defined in the Life Cycle Assessment (LCA), the relevant inventory flows examined are worker employment (social input), safety incidents, health damage and inconvenience (social outputs) (Figure 7.4).

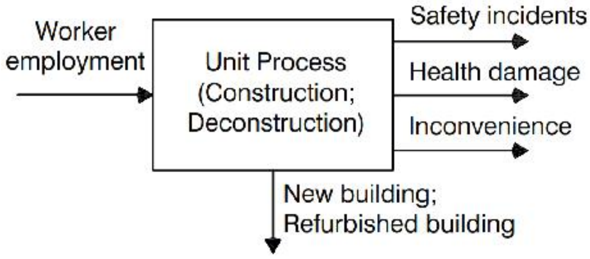

Figure 7.4. Building case example: Unit processes and inventory flows for the SLCA.

Using data from RSMeans (2015), together with information from industry representatives, the estimates of differences in inventory flows between the A and NA forms follow. Worker employment is measured in total worker hours (hours per worker multiplied by the number of workers). Safety incidents are expressed based on a frequency, namely the number of injury occurrences per hours worked by all workers (AS1885.1, p. 20). Health damage due to exposure to construction noise varies with activity-equivalent-continuous-noise level (in decibels, dB) and number of exposure hours (hours per person multiplied by the number of affected people) (BSI, 2009, p. 6), and has units of dBh. (Activity-equivalent-continuous-noise level is defined as the sound pressure level determined at a distance of 10 m from, and over the period of, a given activity – BSI, 2009, p. 1.) The predominant activities generating noise include modular walls construction, concrete placement and compaction, brick walls and floor demolition and raised floor construction. Inconvenience implies disruption to people's everyday life during construction, measured in total working hours of delay or disruption. The construction site and related inconvenience are assumed to be confined to the university area.

Differences in inventory flows at t = 0

- *Worker employment.* Modular internal walls (A form) – 832 h, based on 8-hour days, 4 carpenters and 26 days. Floor and columns (A form) – extra 140 h concrete forming; 200 h reinforcing; 35 h concrete placing. Solid internal walls (NA form) – 4640 h, based on two groups of 5 workers and 58 days. In summary, the NA form leads to 4265 h more employment.

- *Safety incidents.* Assuming a construction injury frequency of 33 injuries per million working hours (SWA, 2012), the additional 4265 h employment for the NA form could potentially result in 0.1407 more injuries.
- *Health.* The occupants are not present at t = 0. Modular internal walls (A form) – total 832 worker hours of exposure to an estimated equivalent continuous noise of 78 dB (BSI, 2009) due to indoor drilling and screwing. Floor and columns (A form) – assume 30 people in the vicinity (20 inside and 10 outside the university) together with 8 workers subjected to the equivalent continuous noise of 86 dB (BSI, 2009) over the extra 5 h of concrete placing and compaction compared with the NA form. In summary, the A form leads to 81236 dBh more noise impact.
- *Inconvenience.* The occupants are not present at t = 0. Assume a traffic flow of 200 persons per hour for the adjacent pedestrian currently blocked, a detour of additional 0.1 km length and average walking speed of 5 km/h. Construction of solid internal walls (NA form) takes 256 h longer than that of modular walls (A form); while enlargement in columns and floor for the A form causes extra 87 h construction time. In summary, the longer site time of 169 h for the NA form leads to an additional travel delay of 676 h over the A form.

Differences in inventory flows at t = T

- *Worker employment.* Solid internal walls demolition (NA form) – 736 h, based on 8-hour days, 4 workers and 23 days. Floor demolition (NA form) – 120 h. Spandrel beams construction (NA form) – 60 h concrete forming; 5 h reinforcing; 12 h concrete placing. Raised floor construction (NA form) – 60 h. Modular internal walls deconstruction (A form) – 352 h. Modular internal walls (A form) new construction – 288 h, based on 8-hour days, 4 carpenters and 9 days; the same applies to the NA form. In summary, the NA form creates 641 h more employment.
- *Safety incidents.* Assuming a frequency of 33 injuries per million working hours (SWA, 2012), the additional 641 h employment for the NA form leads to 0.0212 more potential injuries.

- *Health.* People in the neighbourhood are assumed not subjected to the noise of activities, being carried out indoors. The occupants vacate the building during the refurbishment; so there is no health impact on them. Solid internal walls demolition (NA form) – 736 worker hours exposed to the equivalent continuous noise of 89 dB (BSI, 2009). Floor demolition (NA form) – 120 h of exposure to the equivalent continuous noise of 91 dB (BSI, 2009). Spandrel beams construction (NA form) – 12 worker hours subjected to the equivalent continuous noise of 86 dB (BSI, 2009) during concrete placing and compaction. Raised floor construction (NA form) – 60 worker hours of exposure to the equivalent continuous noise of 82 dB (BSI, 2009) due to carpentry activities. Modular internal walls (A form) new construction – total 266 worker hours of exposure to an estimated equivalent continuous noise of 78 dB (BSI, 2009) due to indoor drilling and screwing; the same applies to the NA form. In summary, the NA form leads to an additional noise impact of 82376 dBh over the A form.
- *Inconvenience.* Removal of modular internal walls (A form) – activity duration of 85 h, while demolition of solid internal walls (NA form) takes 96 h longer. Construction of new modular internal walls – 67 h for both A and NA forms. Developing a large lecture theatre (i.e., floor demolition, construction of spandrel beams and raised floor) for the NA form adds 65 h to the site time. The total site time is obtained as 152 h and 313 h for the A and NA forms, respectively. Assume a traffic flow of 200 persons per hour for the adjacent pedestrian blocked, a detour of additional 0.1 km length and average walking speed of 5 km/h. The longer total site time of 161 h for the NA form leads to an additional travel delay of 644 h over the A form. Assume 500 occupants having to vacate the building during the refurbishment, with 10% productivity reduction in temporarily prepared office. The extra site time of 161 h for the NA form causes a longer disruption of 8050 h. Overall, the NA form leads to a net extra inconvenience of 8694 h over the A form.

Differences in the social impacts between the A and NA forms are summarised in Table 7.5.

Social impact	At t = 0	At t = T	Combined t = 0 and T
Worker employment (h)	-4265	-641	-4,906
Safety incidents (number of injuries)	-0.1407	-0.0212	-0.1619
Health (dBh)	81,236	-82,376	-1,140
Inconvenience (h)	-676	-8,694	-9,370

Table 7.5. Building case example: Differences (A – NA) in social impacts.

It can be seen that the designed-in A form is generally better than the non-designed-in NA form against social criteria. This is so with respect to all the (combined) social issues raised in Table 7.5, except employment. The results at t = 0 demonstrate that built-in adaptability does not necessarily exacerbate social issues in initial design and construction.

7.7.5 Sustainability implication

The results show that the designed-in A form adaptation, through open plan building, performs better than the non-designed-in NA form adaptation in all sustainability aspects of environmental, social and financial, particularly for lower interest rates and adaptation times. Thus, a conclusion on sustainability can be made in favour of the A form, with no need to combine the multiple criteria and sub-criteria.

The viability of adaptability in open plan buildings is implicitly demonstrated to be improved by adopting a sustainability viewpoint rather than a financial-only viewpoint. The financial value of the A form increases by considering environmental and social criteria, except the social sub-criterion of employment. The positive influence of all other sub-criteria on the outcome is perceived to overwhelm the effect of this sub-criterion.

7.8 Discussion

On average, the school buildings at UNSW undergo major refurbishments 35-50 years after initial construction. Building in adaptability, for the assumptions considered, was shown not to be financially viable for this time period, unless the interest rates are low. However, considering social and environmental issues in the analysis increases the viability.

Following Kyoto protocol on climate change (United Nations, 1998), the Australian universities have targeted towards climate change mitigation; for example, USNW sought mitigation ideas for implementation at the university (UNSW website, 2015b). The idea of built-in adaptability through open plan buildings was shown to be an effective solution with particular emphasis on the reduced energy use and emissions. This may also add value to school buildings containing built-in adaptability as a result of increased reputation for the university. However, it is unclear as to what value the university facilities managers would place on this.

The results demonstrated that, unlike the common attitude, designed-in adaptability does not necessarily lead to extra upfront environmental or social loadings. Incorporating adaptability features in open plan building could create a more sustainable design in terms of material consumption, energy use, emissions, waste production, safety and inconvenience issues. The alleviation of environmental or social issues in initial construction is mainly due to the use of modularity, which reduces resource consumption and site time.

The financial value of adaptability increases with uncertainty about future costs. A major source of this uncertainty is the building work that is undertaken on a cost reimbursable basis (for an existing building refurbishment) with highly uncertain outcome. Hence, much larger uncertainty may even be used and greater adaptability values than those estimated may be anticipated.

7.9 Conclusion

The chapter presented a method for valuing adaptability of open plan buildings. This was demonstrated on a case example involving interiors alterations in an educational building. The built-in adaptability form was compared with the non-built-in adaptability form. For the case example, financial viability was demonstrated for lower interest rates and shorter times to adaptation than that typically occurs.

Reasonably larger uncertainty of the costs adds to the financial value of open plan building. As well, taking environmental and social intangibles into account supports arguments in favour of building in adaptability. It is believed that university managers would apply considerable, but not explicitly specified, weighting to these intangibles and sustainability compared to the financial aspects. Despite this, no general conclusions on the viability of open plan buildings can be drawn, but rather requires an individual analysis for each situation. Open plan building will be worthwhile in some, but not necessarily all, situations.

This chapter advances current literature by presenting an analysis method that gives the value of open plan building's adaptability. The chapter's outcome will be useful to the building owners/managers and those in construction industry seeking enhanced efficiency in buildings construction and/or prolonged useful life of buildings through refurbishment.

Chapter 8: Sustainability Value of Adaptable Infrastructure – An Extension to ROA

8.1 Introduction

Infrastructure providing fundamental services for societies may become obsolete under uncertain changes in climate or demographics (Carmichael, 2014). Infrastructure can be adapted as a consequence of these changes as it is basically intended for long-term operation, with massive investment made in its initial construction. For example, in Australia, the '*built environment constitutes 44% of the country's net worth*' (Wilkinson et al., 2009, p. 47, after ABS, 2006). Infrastructure adaptation also incurs enormous costs (Parry et al., 2009), as well as resource consumption with the associated environmental issues, together with possible disruption to substantial services provided for a society, representing a significant sustainability issue.

Adaptability or flexibility has been suggested as a key solution in infrastructure engineering as design requirements change over time (Slaughter, 2001; Scholtes, 2007; de Neufville et al., 2008; Taneja et al., 2012; Conrad and Raucher, 2013). Adaptability here refers to the capability to be changed in line with future circumstances. Given that infrastructure will be adapted to changes some way into the future, developers are caught in the dilemma of whether to design infrastructure for adaptability or not. This implies the notions of *non-designed-in (or fortuitous)* adaptation versus *designed-in (or in-built)* adaptation (Carmichael, 2014, p. 8–12), where an option—a right, but not an obligation—is embedded in the design to accommodate uncertain changes (Wang and de Neufville, 2005).

There are some challenges to incorporating adaptability in infrastructure design (Walker, 2000; Geels, 2004; Brown et al., 2011), namely: Economic – often extra upfront cost is required, leading to investors' or developers' reluctance to invest in designing in adaptability (Newman, 2001), Technical – extra effort or manpower is required for implementation; also in case of insufficient skills and knowledge, significant investment is needed (Brown and Farrelly, 2009); Political – basically risk-based management supports a government to maintain stability; hence there would be resistance against a change in response (Giddens, 1999); Professional – individuals are required to follow their organisational and political leaders; hence their opinions in favour of change, if any, will be ineffective (Brown et al., 2011). All above challenges are crucial for incorporating adaptability and reflect the need for adjustments to regulatory and governance mechanisms. However, this thesis focuses on challenges due to extra upfront cost which may lead to investors' reluctance to invest in built-in adaptability, and so greater sustainability issues may be associated with possible fortuitous adaptation in the future. As a result, this chapter presents a method that gives investors a measure for actual value of adaptability.

Despite the fact that the literature acknowledges infrastructure adaptability to enhance sustainability through an extended useful life (Moffatt and Russell, 2001; Wilkinson et al., 2009; Taneja et al., 2012; Langston et al., 2013), it stops short of the valuation of adaptability (Gann and Barlow, 1996; Slaughter, 2001; Schneider and Till, 2005; Gosling et al., 2013). Real Options Analysis (ROA) is used to evaluate the financial viability of investing in adaptable infrastructure (Copeland and Antikarov, 2001; Carmichael et al., 2011), but takes no account of the social and environmental aspects. A few have attempted to incorporate sustainability issues in adaptability valuation using Life Cycle Assessment (LCA) tools (Moffatt and Russell, 2001; Fawcett et al., 2014), which has limitations in terms of the need for single-point estimates, the fact that it ignores uncertainty and the complexity involved in the interpretation of the results of this method (Fawcett et al., 2014).

This chapter presents an upgraded ROA, by integration with Social/Environmental Costing (SEC), to address the sustainability valuation of infrastructure adaptability. The approach gives a compatible extension to ROA as it takes the economic burden of sustainability issues into account and leads to a single measure for the sustainability of adaptable infrastructure suitable for comparison and decision-making purposes. An Australian case example, involving rock seawalls under changing climate effects illustrates the given approach. The methodology, but not necessarily the designs and assumptions used in the case example, can be applied to other situations and locations.

This chapter will be of interest to people within the construction industry, as well as investors and corporates with social or environmental liabilities. Using the approach given, they will be able to determine whether, and to what extent, incorporating specific adaptability in any design or construction is viable from the sustainability viewpoint.

The chapter's approach to establishing the viability of infrastructure adaptability in terms of sustainability, resulting in ROA extension, is original; relevant sustainability issues are costed for specific underlying design assumptions, and their effects on viability are demonstrated.

This chapter bridges the literature gap discussed in Chapter 2. It presents the proposed approach, introduces commonly used SEC techniques, and gives a method for dealing with the uncertainty of intangibles. This is followed by a description of the analytic approach. Finally, adaptability valuation is demonstrated on a seawall case example, with arguments on the contribution of the inclusion of sustainability issues to the viability of adaptability.

8.2 The proposed approach: ROA-SEC

8.2.1 Scope

ROA, using probabilistic Discounted Cash Flow (DCF) analysis with a second order moment approach, is proposed to be adapted for sustainability assessment. The extension is realised by an innovative integration of the ROA approach given in this thesis with the SEC method using LCA outputs (Figure 8.1). The diagram below depicts a comprehensive framework for sustainability assessment, even though this chapter examines the framework only within the given ROA-SEC scope. The ROA-SEC approach can be used to value adaptable infrastructure from sustainability viewpoint.

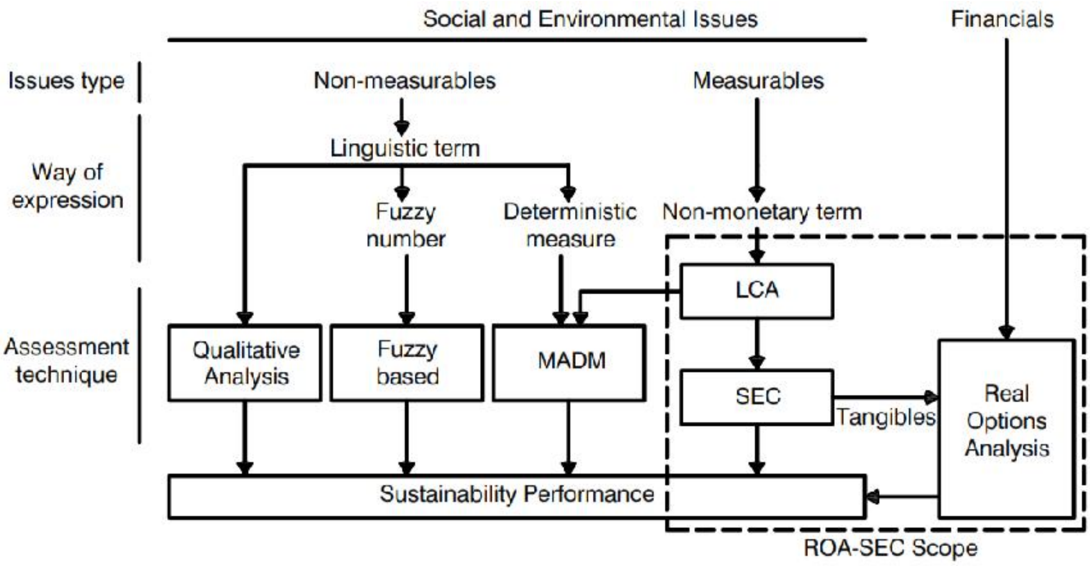

Figure 8.1. A framework for sustainability assessment: ROA-SEC scope.

The idea of using life cycle costing (LCC) in conjunction with LCA has been previously supported (Parker, 2000; Steen, 2005; de Beer and Friend, 2006; Dascalu et al., 2010), and was followed by a code of practice published by the Society of Environmental Toxicology and Chemistry (SETAC) for environmental LCC (Swarr et al., 2011). This is perhaps because money is the '*language of business and a powerful management motivator'* (Parker, 2000, p. 49); a sensible measure for the majority of the community, and hence suitable for sustainability reporting. Moreover, tracking sustainability costs over the long-term time horizon is of importance, particularly for real assets with a long lifespan; hence the results of the LCA approach should be used for monetisation (Raar, 2011, after White et al., 1993 and Parker, 1997). Among the existing methods of sustainability assessment, SEC is preferred for integration with ROA because:

- ROA is based on financial evaluations; thus the costing of sustainability issues complies with the present attitude.
- Sustainability assessment of real options is in its infancy, and so requires the choice of easy-to-use methods and consideration of tangibles for initiation.
- The use of SEC within this innovative framework eliminates the need for impact categories and weighting of inventory data (Swarr et al., 2011), and gives a single quantitative measure suitable for interpretation, comparison and decision-making purposes (Dompere, 1995; Lohmann, 2009).
- Expression of a concept in numbers, and preferably monetary terms, makes it more sensible and realistic. SEC can sensibly reveal adaptability benefits by giving a sustainability measure to be paid (Dascalu et al., 2010).

8.2.2 SEC methods

Sustainability issues as adverse social or environmental impacts are expressed using intangibles. There are many approaches to the pricing of intangibles. However, the costing methods for sustainability issues can be categorised based on the types of costs incurred in dealing with the impacts; namely, prevention, toleration and restoration to the former situation (Parker, 2000, after CICA, 1993; Dascalu et al., 2010). This categorisation is intended to give an organised insight to readers, but not to limit possible costing methods.

The methods basically estimate people’s willingness to pay for maintaining benefits or willingness to accept the costs incurred (Mirasgedis et al., 2000; Clarkson and Deyes, 2002; Gilchrist and Allouche, 2005). A selective overview of the SEC methods commonly used in each category follows.

Prevention costing approach

Policy tools include taxes, subsidies, penalties and fees or charges on environmental loadings (Parker, 2000; Dascalu et al., 2010); e.g., permission fees for waste disposal (Parker, 2000), penalties on excessive wastewater discharges (de Beer and Friend, 2006) or noise/water pollution offences (NSW Legislation, 1997); the cost of preparing mandated impact assessments; or fines or grants withheld in case of breach (Hollick, 1981, 1986). *Insurance value* is the premium paid in advance in proportion to potential damages to individuals, materials and biodiversity (Leopold and Leonard, 1987; de Beer and Friend, 2006). *Pollution/hazard control costs* include expenditures on control measures preventing damage due to pollution or safety incidents (Parker, 2000), such as building noise barriers or using loading platforms (AS 2434, 2010). *Disturbance prevention value* is the reward/penalty assigned in the bidding process to early/late completion (Gilchrist and Allouche, 2005, after Herbsman, 1995).

Toleration costing approach

Health/safety costs include the direct costs of using health services; i.e., charges for using hospital treatment facilities and medical staff wages (Gilchrist and Allouche, 2005). *Loss of productivity/contribution* represents the earnings lost due to disturbance to operation, such as a fall in a machine's production, or loss of human capital, such as lower employment levels or reduced productivity due to health and safety issues (Sah and Stiglitz, 1985; Leopold and Leonard, 1987; Dinwiddy and Teal, 1992; Gilchrist and Allouche, 2005). *Delay costs* include losses due to delays caused by construction work, such as the lost earning of those affected by the work, together with the cost of the extra fuel consumption due to traffic disruption within a construction area (Gilchrist and Allouche, 2005).

Restoration costing approach

Remediation costs represent cost of the remedial processes of unwanted construction by-products, such as the removal and treatment of waste materials or pollution in the form of air emissions, soil and water contamination (Parker, 2000; de Beer and Friend, 2006). For example, these might include the clean-up cost of post-construction dust pollution. *Replacement costs* represent the costs incurred to the minimise inconvenience caused by construction projects through replacing damaged or out-of-service facilities nearby with suitable similar alternatives, whether temporarily or permanently (Gilchrist and Allouche, 2005).

There may be many other pricing methods, but the choice of a suitable method is suggested for each specific situation. This chapter acknowledges thorough counting of the sustainability impacts with associated shadow prices where an issue has an impact on more than one sustainability aspect. For instance, electricity usage is accounted for in not only the consumer's financial balance but also in damage to the environment via emissions (Mirasgedis et al., 2000). The use of the Pareto principle, taking major costs into account, is helpful and sufficient for feasibility studies. Double-counting of the same impacts is avoided (Steen, 2005; Swarr et al., 2011).

The choice of the target community and the subsequent identification of the social and environmental costs (Raar, 2011) is also important for rational costing of sustainability issues. Different people may emphasise different sustainability issues, perhaps only considering those issues they are affected by or pay for (Dompere, 1995; Steen, 2005), and may put different values on each issue.

8.2.3 Treatment of uncertainty in intangibles

Shadow prices, and the subsequent SEC outputs, are highly uncertain (Mirasgedis et al., 2000, Steen, 2005; de Beer and Friend, 2006). The uncertainties associated with the estimation of intangible costs should thus be integrated into valuation models (Clarkson and Deyes, 2002). Some sustainability issues may be difficult to monetise; others can be priced using one or more methods. It is proposed to deal with uncertainties in intangibles monetisation in either of two ways, as follows.

Proposition 1. In case an intangible, X, can be costed using a single method because of limited data availability or general agreement on reliability of the method, the estimated shadow price is used as the most likely estimate (e). The method's accuracy can be characterised by deviations of the lower and upper bounds from (e), giving optimistic (d) and pessimistic (f) estimates. As for the financial estimates, the expected value, E[X], and variance, Var[X], of the intangible cost become:

$$E[X]\ X(e\ \Gamma 4d\ \Gamma f)/6 \qquad (8.1)$$

$$\mathrm{Var}[X] = [(f - e)/6]^2 \tag{8.2}$$

Proposition 2. In case there exist multiple methods for estimating an intangible cost, each method gives a most likely estimate, x_i, i = 1, 2, …, n, with accuracy characterised as above, giving the method's expected value, E[x_i], and variance, Var[x_i]. There may be quite large differences between the estimated values. Each estimate is given a normalised weight w_i, i = 1, 2, … , n, based on the method reliability identified. The normalised weights reflect the existing view on the reliability of the corresponding SEC methods. The reliability weights can alternatively be given as inversely proportional to the variance, since a method with less variance in estimates is more accurate and reliable (Taylor, 1997; Strutz, 2016). The weights then become:

$$w_i = \frac{1/\mathrm{Var}[x_i]}{\sum_{i=1}^{n} 1/\mathrm{Var}[x_i]} \tag{8.3}$$

For uncorrelated estimates, the expected value, E[X], and variance, Var[X], of intangible cost then become:

$$E[X] = \sum_{i=1}^{n} w_i \times E[x_i] \tag{8.4}$$

$$\mathrm{Var}[X] = \sum_{i=1}^{n} w_i^2 \times \mathrm{Var}[x_i] \tag{8.5}$$

The above propositions cannot be used where there is no estimation method established or no data available. In these situations, the associated intangible has to be excluded from the analysis till further knowledge is available.

8.2.4 Analysis

8.2.4.1 Outline

In the following analysis, the methodology is emphasised rather than the design and estimation and the associated numbers. The numbers are indicative, but will change with different reader assumptions. The analysis considers and compares two forms of adaptation (denoted A and NA):

> A. Where adaptability features have been designed and built in *ab initio*, with the view that adaptation may (but not necessarily) take place in the future depending on future circumstances.
>
> NA. Where infrastructure has been designed and built without adaptability features in mind, but where future adaptation may still be fortuitously possible.

For the case example, the assumptions on adaptability features, together with identification and quantification of sustainability issues, were already made (in Chapter 5); these are relaxed here, and the analyses are performed using the LCA results.

For the purpose of this chapter, the sustainability-related costing is carried out from the viewpoint of the target communities of ‘the public’ and ‘investors’. Given the extensive media attention and reports on the significance of sustainability, which has resulted in strong public awareness (Parker, 2000), the public is assumed to ascribe value to all sustainability issues. This approach seems rational since the costs are spent from the government treasury belonging to the public. Thus, any identified issue is costed according to the prices that are not necessarily seen in the market, but represent the economic worth of social and environmental assets. Even if the so-called ‘shadow prices’ are not currently considered, the assumption here is that they will likely be so before long (Dascalu et al., 2010). The investors, however, mainly adopt a narrower viewpoint and are concerned about their own expenditure; so only those sustainability issues they pay for, based on the market price, are accounted for.

8.2.4.2 Formulation

Financial estimates follow Cordell (2014a, 2014b), Rawlinsons (2015) or RSMeans (2015), and are based on quantity take-offs from drawings, together with quotations from various builders, engineers, tradespeople and industry representatives (see Appendix G for advisers' details). Social and environmental estimates follow commonly used life cycle inventory databases, and RSMeans (2015) for construction crew calculations, based on the quantity take-offs.

The option analysis follows Carmichael et al. (2011) and Carmichael (2014). Only monetary flows at T, when adaptation might occur, are considered in the option analysis; T is allowed to vary to show the relationship between time of adapting and adaptability value. Expected values, E[ ], and variances, Var[ ], of all monetary flows for both A and NA at T are estimated. This is done by estimating optimistic (a), most likely (b) and pessimistic (c) values, leading to expected value or mean = (a + 4b + c)/6 and variance = $[(c-a)/6]^2$ (see for example, Carmichael, 2006; Carmichael and Balatbat, 2008a). Because the estimates for A and NA are based on similar assumptions, it may be anticipated that there would be very strong correlation between the estimates for A and NA. The similar assumptions concern the same time of adaptation for A and NA, and associated unit costs or work quantities which are anticipated to vary similarly for the two form, as a result of a common set of affecting factors i.e. economic, political or technological. Also, for each adaptation form, the estimates of social and environmental issues are assumed to be perfectly correlated to those of financial flows, as they are all dependent and proportional to quantity take-offs.

To ascertain the value of adaptability over conventional practice, the difference between NA and A is examined. Let X_T be the net cost at time T. That is,

$$X_T \; X(NA_{T,F} \; ZA_{T,F}) \, \Gamma_{i} \; (NA_{T,SE_i} \; ZA_{T,SE_i}) \qquad (8.6)$$

where A_T and NA_T are the cost, at T, of A and NA, respectively; F denotes financial cost component and SE_i denotes social/environmental cost component of ith sustainability issue. Then,

$$E[X_T] = E[NA_{T,F}] - E[A_{T,F}] + \sum_i E[NA_{T,SE_i}] - E[A_{T,SE_i}] \tag{8.7}$$

$$Var[X_T] = \left(\sqrt{Var[NA_{T,F}]} - \sqrt{Var[A_{T,F}]} + \sum_i \sqrt{Var[NA_{T,SE_i}]} - \sqrt{Var[A_{T,SE_i}]} \right)^2 \tag{8.8}$$

These are discounted to give the present worth, PW, of the difference.

$$E[PW] = \frac{E[X_T]}{(1+r)^T} \tag{8.9}$$

$$Var[PW] = \frac{Var[X_T]}{(1+r)^{2T}} \tag{8.10}$$

where r is the interest rate. Calculation of the adaptability value follows,

$$\text{Adaptability value} = \Phi M \tag{8.11}$$

where Φ = P[PW] > 0 and is termed the investment feasibility (Carmichael and Balatbat, 2008a), P is probability and M is the mean of the present worth upside measured from PW = 0. To calculate Φ and M, and knowing E[PW] and Var[PW], any distribution can be fitted to PW, but it is anticipated that most people would use a normal distribution (Hillier, 1963; Tung, 1992).

This adaptability value is then compared with the total cost (including monetised social and environmental issues) of building in adaptability at time 0. Viability is established for adaptability when the adaptability value exceeds this initial cost.

8.3 Case example: Adaptable rock seawalls

The case example involves upgrading a 100-metre long section of a sloped seawall with rock armours of relative abundance and a water depth of 3 metres at the toe. Seawalls in Australia are conventionally designed to accommodate water depths and associated breaking wave loads for the most likely sea level rise over a design life that is approximately 35 years (AS 4997, 2005; NCCOE, 2012b). The crest level and mass of rocks are designed to satisfy the requirements of breaking wave runup and load, respectively, which are dependent on water depth.

The possibilities for adaptability are 1) to use rocks of a larger size, sufficient for greater breaking wave heights, corresponding to a sea level rise of a longer design life; this allows the A form not to need any additional rocks on the seawall face when the sea level reaches the conventional design level, and 2) to construct a parapet wall with sufficiently large foundations for the A form, but with the same height as that of NA form; this makes the parapet wall expandable in height with no need for foundation rehabilitation should the protection height be raised by adding rocks to the seawall crest.

The adaptability features for the A form lead to an extra upfront cost, together with more material use with the associated solid waste, water pollution, embodied energy and emissions, as well as a longer construction time, resulting in dust, vibration and noise pollution, neighbourhood disturbance and the potential for accidents, but more paid hours for workers. In return, the NA form seawall upgrade would raise similar issues as those described above, but to greater extent (see Chapter 5 for further details).

8.3.1 The SEC methods adopted

The identified sustainability issues for the case examples are monetised using SEC methods used in the literature; the number of methods used for each issue specifies how to deal with the estimate's uncertainty (Table 8.1).

Monetisation of all the issues is attempted to represent the public's viewpoint. However, the environmental costs associated with material consumption and energy use, representing resource misuse and depletion, are excluded here since the associated external costs have the lowest visibility among these issues, with no sufficient data and difficulties in their measurement (Parker, 2000). From the investor viewpoint, only those external costs that are likely be internalised in the decision timeframe are considered, reflecting the real monetary flows incurred (Swarr et al., 2011). For example, investors might be under no obligation to pay for job creation. Clearly, the treatment of an intangible uncertainty may alter when monetisation is limited to a single method from the investor viewpoint.

Sustainability issue	***Adopted SEC methods***	***Treatment of uncertainty***
Material consumption	-	-
Energy use	-	-
Emissions*	Abatement cost*, Damage cost	Proposition 2
Solid waste production*	Waste treatment cost*	Proposition 1
Water pollution	Remediation cost	Proposition 1
Worker employment	Contribution to society, comfort value	Proposition 2
Safety incidents*	Insurance value*, loss of contribution*	Proposition 2
Health (noise pollution)	Loss of productivity	Proposition 1
Inconvenience*	Delay cost, replacement cost*	Proposition 2

Table 8.1. Case example: adopted SEC techniques and uncertainty treatment methods. * indicates sustainability issues or costs examined from the investor viewpoint.

8.3.2 Shadow price estimates and uncertainties

This section gives estimates of the unit prices of the sustainability issues for the case example at the present time, with possible changes into the future. However, it is unclear as to how the unit price of some issues, including waste production, water pollution and inconvenience (replacement cost) will change; present time estimates are assumed for these issues, with no significant change over time.

Emissions

Abatement cost. A carbon tax can be seen to be representative of the cost of emissions abatement. A carbon pricing scheme was introduced in Australia in 2011 and repealed in 2014, when it was replaced with a fixed charge of about $25 per tonne of carbon (Australian Government, 2011); however, a carbon tax is likely to be re-established in the future within the decision timeframe (Steen, 2005). The abatement cost is estimated to reach $150–$500 by 2050, with an average of $260 per tonne of carbon (Ackerman and Stanton, 2012).

Damage cost. There is great uncertainty around the future social (damage) cost of carbon due to climate sensitivity and the subsequent economic impacts (Clarkson and Deyes, 2002, Ackerman and Stanton, 2012). The damage cost of carbon is predicted with high confidence to be greater than the abatement cost, even with rapid reductions in emissions; the associated carbon price is projected to range between $50 and $1500 per tonne of carbon in 2050 (Ackerman and Stanton, 2012). The distribution of the damage cost is assumed to be positively skewed because there is a higher probability of a more disastrous climatic outcome (Clarkson and Deyes, 2002), thus the central estimate is assumed as about $530 per tonne of carbon.

Solid waste production

Waste treatment cost. These estimates are made according to the treatment method; namely, reuse, recycling or landfilling (BDA, 2009). A high landfill gate fee of $120–180/tonne of waste is charged in Sydney; this is significantly higher than waste recycling/reuse fees, and so waste producers would not simply choose disposal

(Hyder, 2011). The gate fee commonly charged for recovery and reprocessing of concrete waste is $0–11/tonne (Hyder, 2011), assuming a likely estimate of $5.5/tonne of concrete. Steel and rock wastes are assumed to be reused, in landscaping for example. Excluding resale at salvage value, only the costs of collection and transport are accounted for in reuse. These are assumed to collectively cost $50±20/tonne of waste (Hyder, 2011). The collection and transport costs are also added to the landfill or recycling gate fees (BDA, 2009).

Water pollution

Remediation cost. The unit price varies according to the type of pollutant and the remediation method. Possible methods of sediment remediation involve dredging, capping and in-place treatment (Keillor, 2007; Rosengard et al., 2010). The former is commonly used for the removal of sediments with low chemical concentrations, followed by treatment processes; namely, dewatering, physical separation and disposal (Keillor, 2007). Dispersed particles will be removed as part of the dredged materials. The likely unit cost is approximated as \$220/m^3 of sediment involving hydraulic dredging and landfill disposal (adapted from Mohan et al., 2011). This estimate may vary widely, depending on the volume and type of dredging, particle size, chemical concentration or time and access for remediation process; these cause the estimate to range between \$15 and \$3300 per m^3 of sediment (adapted from Rosengard et al., 2010).

The disbenefits of water pollution to humans and the aquatic environment might also be considered; however, it is difficult to identify and measure the extent of the effects of pollution (Keillor, 2007). Alternative ways could be to estimate, for example, the admission price or replacement cost of lost recreational or fishing areas. However, the effects on such amenities are similar between the two adaptation forms in the case example, and hence are excluded here.

Employment

Contribution to society. The value of employment is characterised as the worker's contribution to the economy; however, the costs of employment creation should be excluded from the calculation (Sah and Stiglitz, 1985; Dinwiddy and Teal, 1992). Labour productivity, expressed as the contribution to real GDP per hour worked, is about $75/h (Pye, 2012), with a projected average growth rate of 1.5±0.1% per annum (Commonwealth of Australia, 2015). Employment costs are estimated as construction workers' average earnings, which are about $40 per hour worked (ABS, 2014) plus an extra 40% to account for on-costs, representing superannuation, employer taxes and workers' compensation (Toten, 2009; ABS, 2016b). Earnings are projected to grow at an average annual rate of 1.4±0.1% (Commonwealth of Australia, 2015).

Comfort value. The employment value can be seen as the payment to workers maintaining the same welfare level they would enjoy without a job; that is, the unemployment compensation subtracted from the minimum wage they would have to accept (Londero and Cervini, 2003). The minimum wage is assumed to be 56% of average earnings, as estimated above, and follows a similar projected trend (Commonwealth of Australia, 2014). The so-called 'Newstart allowance', as Australia's unemployment benefit, is around $6.5 per equivalent hour worked (Department of Human Services, 2017). The government's spending on this allowance is projected to decline, reaching $5.5/h in 2050 (Commonwealth of Australia, 2015), with assumed optimistic and pessimistic estimates of $5/h and $6/h, respectively.

Safety incidents

Insurance value. Costs associated with social liabilities for safety incidents can be estimated using the insurance premiums paid for employed workers (Leopold and Leonard, 1987; de Beer and Friend, 2006). The average insurance premium in non-building construction is assumed to be 3.1% of wages (NSW Government, 2015). The wage rate of $40/h for construction workers gives an average premium of $1.25

per hour worked (ABS, 2014). This is assumed to grow at the same rate as wages, at an average annual rate of 1.4±0.1% (Commonwealth of Australia, 2015).

Loss of contribution. During treatment of an injury, earnings are lost while the uninsured costs of treatment must be paid; either the employer or employee suffers these losses, depending on the contract type. Assuming a construction injury frequency of 33 injuries per million working hours and an average time lost from work (or recovery time) of 4.25 day (or 34 h) per work-related injury (SWA, 2012) gives a 0.11% loss of working hours due to injury. Assuming construction workers' average earnings of $40 per hour worked (ABS, 2014) leads to lost earnings of $0.05 per hour worked. The uninsured costs of treatment are estimated as about a fifth of the insurance value (Leopold and Leonard, 1987), giving $0.25 per hour worked. These lead to a total unit cost of $0.3/h of work for construction-related injuries. This unit price is dependent on wages, and hence is assumed to follow wage growth at an annual rate of 1.4±0.1% (Commonwealth of Australia, 2015).

Health

Loss of productivity. Construction noise can negatively affect people's productivity. The reduction in productivity may widely vary, depending on the type of task people do, the nature of noise and the individual's sensitivity to noise; it is assumed to range from about 1.5% (SWA, 2010, after Noweir, 1984) to 40% (Gilchrist and Allouche, 2005) for noise levels just above 80 dB disturbing people providing public services in the seawall neighbourhood. Assuming an average earnings of $30 per hour worked (ABS, 2014) leads to earnings loss of $0.5–12.0 per exposure hour due to reduced productivity; this can be assumed to grow with earnings at a rate of 1.4±0.1% per year (Commonwealth of Australia, 2015).

Risk of accidents. Workers' exposure to noise increases the risk of accidents through increased stress, masking of danger signals or hindering communication (Wilkins and Acton, 1982); construction noise and the associated hearing loss can constitute a considerable portion (up to almost a half) of injuries, illnesses and subsequent absenteeism (Noweir, 1984; SWA, 2010). However, it is assumed that these effects are already considered in the estimated frequency of injuries, and thus the loss of contribution due to safety incidents.

Inconvenience

Delay cost. Inconvenience to commuters as a result of traffic disruption-related delays can be measured based on the earnings lost (Gilchrist and Allouche, 2005). Earnings may widely vary between different employees; average earnings of $30 per hour worked/delayed is assumed here (ABS, 2014). Earnings are projected to grow at an average annual rate of 1.4±0.1% (Commonwealth of Australia, 2015).

Replacement cost. The cost of making a detour, as a replacement for blocked access roads facilitating traffic flow, may also represent inconvenience caused (Gilchrist and Allouche, 2005). For this example, this is assumed to comprise the rental costs of road signs erected, estimated as $4–8 per day (for four detour signs) and traffic barriers, estimated as $20–40 per day (for ten blocks, each 2m long), facilitating traffic flow (prices based on a quote taken from Coates Hire). The total replacement cost would thus range between $24 and $48 per day.

Table 8.2 below summarises the estimates of the unit prices and their associated reliabilities. Some issues, such as inconvenience in the case example here, may be monetised using different pricing approaches in different units; the associated variances can be compared based on the total price estimates.

Sustainability issue	Pricing approach	Unit price estimate			Reliability weight
		Opt.	Mos.	Pes.	
Emissions* ($/tonne CO2-e)	Abatement cost*	150	260	500	0.94
	Damage cost	50	530	1500	0.06
Solid waste production* ($/t)	Waste treatment cost*				
Rock	*Reuse*	30	50	70	1.00
Concrete – fresh	*Recycle*	30	55.5	81	1.00
Steel	*Reuse*	30	50	70	1.00
Water pollution ($/ m^3)	Remediation cost	15	220	3300	1.00
Worker employment ($/h)	Contribution to society	30.3	31.0	31.6	0.18
	Comfort value	27.6	27.9	28.2	0.82
Safety incidents* ($/h)	Insurance value*	1.82	1.86	1.91	0.05
	Loss of contribution*	0.44	0.45	0.46	0.95
Health (noise) ($/h)	Loss of productivity	0.7	9.3	18.3	1.00
Inconvenience*	Delay cost ($/h)	43.7	44.7	45.8	0.13
	Replacement cost* ($/day)	24.0	36.0	48.0	0.87

Table 8.2. Case example: unit price estimates and associated reliabilities. * indicates sustainability issues or costs examined from the investor/council's viewpoint.

8.3.3 Results

Table 8.3 illustrates the differences in monetary flows associated with sustainability issues between the A and NA forms, at times 0 and T.

Sustainability issue	**At t = 0**		**At t = T**					
	A-NA	$ value	A	$ value E[ ]	$ value Var[ ]	NA	$ value E[ ]	$ value Var[ ]
Emissions (t CO2-e)								
*Abatement cost**	20.2	505	19.0	5,352	1.2e6	51.1	14,393	1.4e7
Damage cost			19.0	11,622	2.1e7	51.1	31,256	1.6e8
Solid waste product. (t)								
*Rock (reuse)**	27.2	1,360	44.0	2,200	8.6e4	164.8	8,240	2.9e6
*Concrete (recycle)**	1.8	100	1.4	78	141.6	3.2	178	1.3e3
*Steel (reuse)**	0.3	15	0.2	10	1.8	0.5	25	23.4
Water pollution (m^3)	0.014	3	0	0	0	0.064	45	1.2e3
Employment (h)								
Contribution to society	213	-4,047	507	-15,709	1.2e4	1,362	-42,199	2.1e7
Comfort value			507	-14,145	2.6e3	1,362	-38,000	1.7e7
Safety incidents (worked, h)								
*Insurance value**			507	944	57.8	1,362	2,536	7.8e4
*Loss of contribution**	213	64	507	228	2.9	1,362	613	4.5e3
Health (noise expos., h)	626	3,913	5,902	55,282	3.0e8	18,310	171,504	3.0e9
Inconvenience								
Traffic delay (h)	310	-	512	22,895	3.2e4	1,884	84,246	1.1e8
*Road replacement (day)**	8	288	13	468	2.7e3	44	1,584	9.0e4

Table 8.3. Case example: adaptable seawalls—monetary flows and differences between A and NA at times 0 and T. * indicates costs of intangibles examined from council's viewpoint.

With the moments of intangibles prices and associated reliabilities at hand, the expected value and variance of cost of each sustainability issue at time T are obtained according to Section 8.2.3. Table 8.4 summarises the expected values and variances of the costs of the sustainability issues estimated from the public and investor (council) viewpoints.

Sustainability issue	**A**		**NA**	
	E[ ]	Var[ ]	E[ ]	Var[ ]
Public viewpoint				
Emissions	5,697	1.2e6	15,322	1.3e7
Solid waste production	2,288	9.4e4	8,443	3.0e6
Water pollution	0	0	45	1.2e3
Worker employment	-14,420	2.1e3	-38,737	1.2e7
Safety incidents	262	2.7	703	4.3e3
Health	55,282	3.0e8	171,504	3.0e9
Inconvenience	3,384	2.6e3	12,330	2.0e6
Investor (council) viewpoint				
Emissions	5,352	1.2e6	14,393	1.4e7
Solid waste production	2,288	9.4e4	8,443	3.0e6
Safety incidents	262	2.7	703.38	4.3e3
Inconvenience	468	2.7e3	1,584	9.0e4

Table 8.4. Case example: adaptable seawalls—moments of monetary flows of sustainability issues for A and NA at time = T—public and council viewpoints.

These expected values and variances of the social/environmental cash flow components, together with those of the financial cash flow components are used to calculate the moments of net cash flow at time T, as discussed earlier in Section 8.2.4. The financial cash flows estimates give the following moments:

$$E[\,NA_{T,F}\,] = \$297.9k,\ Var[\,NA_{T,F}\,] = (\$24.8k)^2$$

$$E[\,A_{T,F}\,] = \$102.8k,\ Var[\,A_{T,F}\,] = (\$8.6k)^2$$

Estimates of the social and environmental monetary flows from the public's viewpoint, give the following:

$$E[NA_{T,SE}] = \$169.6k,\ Var[NA_T] = (\$65.5k)^2$$

$$E[A_{T,SE}] = \$52.5k,\ Var[A_T] = (\$18.8k)^2$$

Estimates of social and environmental monetary flows from the council viewpoint, give the following:

$$E[NA_{T,SE}] = \$25.1k,\ Var[NA_T] = (\$5.9k)^2$$

$$E[A_{T,SE}] = \$8.4k,\ Var[A_T] = (\$1.5k)^2$$

Combining the moments of the social/environmental monetary flows with the financial cash flows gives the moments of net cash flow at T, which is discounted to time 0, giving the moments of total PW and the adaptability value. Figures 8.2 and 8.3 show the change in adaptability value with r and T and compare the results of financial-only analysis with those of sustainability analysis from the public and council viewpoints. The initial investment in adaptability is estimated as \$57.7k; inclusion of monetised social and environmental issues slightly increases the extra initial investment to about \$60.0k for both the public and council viewpoint analyses.

It can be seen from all viewpoints that building in adaptability is more viable for lower r and lower T. Compared to a financial-only analysis, assessing the sustainability of seawall adaptability from the public's viewpoint raises viability thresholds for interest rates from about 3.5% p.a. to 5% p.a., and for adaptation times from just below 30 years to above 35 years. However, from a council's viewpoint neither the initial cost nor the adaptability value changes considerably by inclusion of the social and environmental costs. Hence, the results indicate that there is no potential to encourage councils to invest in adaptability through the inclusion of paid sustainability issues; however, this potential would be developed should regulations be set to internalise further external costs (associated with worker employment, health issues and inconvenience due to traffic delay).

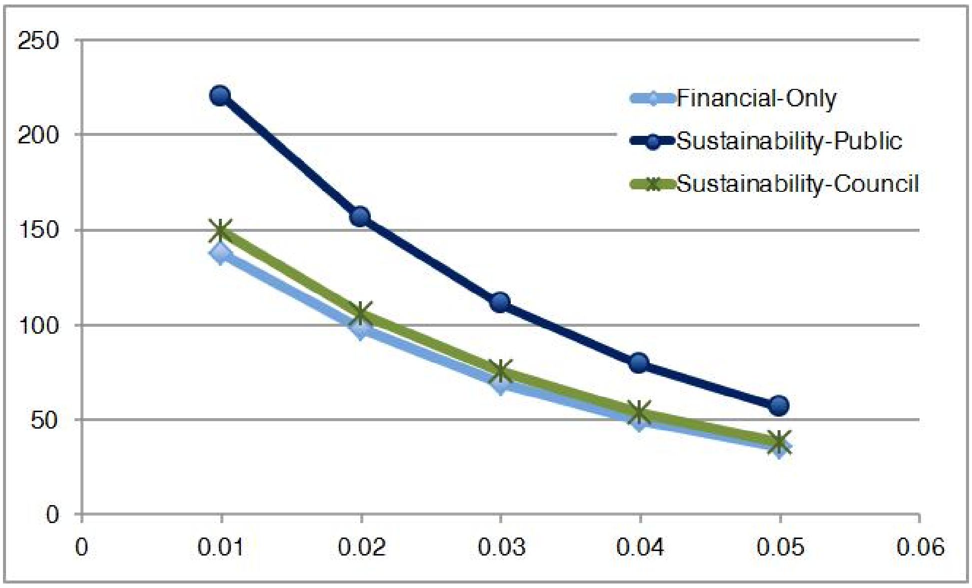

Figure 8.2. Case example: change in adaptability value with interest rate (p.a.), T = 35 years.

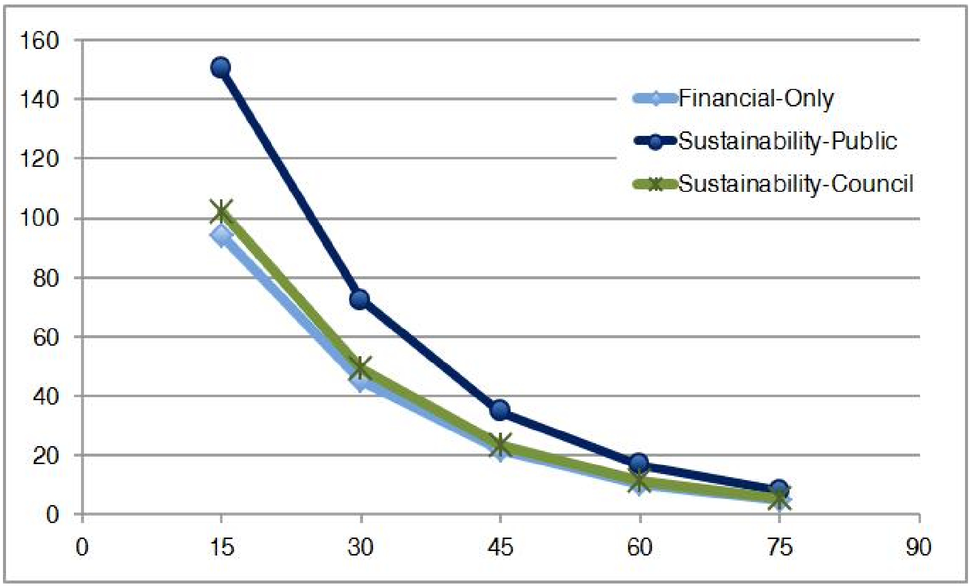

Figure 8.3. Case example: change in adaptability value with time of exercising T, r = 5% p.a.

From the public's viewpoint it can be seen that the designed-in A form could be more viable than the non-designed-in NA form for the adaptation time period associated with the most likely sea level rise, which is about 35 years (CSIRO–BoM, 2015). Over this time period, the A form is not viable in the financial-only and council viewpoint analyses unless the interest rates are low. The viability under the above conditions is mainly due to a large saving in the A form adaptation cost and mitigated sustainability (particularly social) issues, with no need to add rocks to the seawall face and parapet wall for foundation strengthening.

8.4 Discussion

The viability of building in adaptability, for the assumptions considered, was shown to be improved by the inclusion of sustainability issues in the analysis. This improvement was manifested in the maintenance of viability for longer adaptation times or higher interest rates. For this case example it was found that there was no potential to persuade investors to invest in seawall adaptability, but that the initiation of legislation compelling councils and corporates to pay for their liabilities might increase investment. This might be realised through public involvement in decision-making, enforcement of impact assessments and a shift in policies towards legal action forcing mechanisms (Hollick, 1981, 1986).

The inclusion of environmental costs associated with resource depletion; namely, material consumption and energy use, is anticipated to further improve the viability of adaptable infrastructure. However, this requires studies on possible methods of monetisation, based on strategies of tolerating the consequent damage or restoring resources or the introduction of preventive policies to attain more visible shadow prices.

The adaptability value increases with uncertainty regarding future costs. A major source of this uncertainty lies in the building work method adopted and the scope of the work. The building work would more than likely be undertaken on a cost reimbursable basis for adaptation. The final outcome cost for cost reimbursable work is never definite, adding to adaptation cost uncertainty. The uncertainty in the cost estimates might also be assumed to grow with time, on the basis that estimates further into the future are less definite, resulting in much larger uncertainty.

Shadow prices, and subsequent SEC outputs, are highly uncertain as a result of monetisation approximations (Mirasgedis et al., 2000, Steen, 2005; de Beer and Friend, 2006) and/or changing value systems in line with increasing public sustainability imperatives. This chapter has attempted to capture the growth in sustainability values and associated uncertainty over time; however, changes in the unit prices of some sustainability issues, such as waste production or water pollution, are unclear and were excluded from the analysis. Larger uncertainties imply that even greater sustainability values could be anticipated for building in adaptability before it starts to change the broad conclusions in the case example.

8.5 Conclusion

The chapter presented a method for incorporating sustainability in ROA for infrastructure adaptability valuation. This approach showed how to quantitatively analyse the sustainability of adaptable infrastructure. This was realised by integrating SEC with an options analysis method suitable for engineering applications. The chapter suggested examining the sustainability of adaptable infrastructure from the public's or a private investor's viewpoint to determine whether there is potential for encouraging investment in adaptability and/or initiating further legislation to support adaptability. The method was demonstrated on a seawall case example under changing climate effects. The built-in adaptability form was compared with the non-built-in adaptability form, and for the assumptions considered, it was shown that inclusion of sustainability issues can improve the viability of building in adaptability.

However, no general conclusion can be drawn on the viability of designed-in adaptable infrastructure; rather, each situation requires an individual analysis. The extent to which consideration of sustainability issues contributes to viability may be different for each situation. Designing in adaptability will be worthwhile in some, but not necessarily all, situations. The methodology will be the same for all situations, although the assumptions about the design and estimation may change.

Despite the acknowledgement of infrastructure adaptability to enhance sustainability evident in the literature, it lacks valuation of the sustainability of adaptability, although certain authors have used inadequate methods to assess this (Gann and Barlow, 1996; Moffatt and Russell, 2001; Fawcett et al., 2014). ROA, used for the financial valuation of investing in adaptable infrastructure, does not consider social and environmental aspects. This chapter advances the current literature by upgrading ROA through compatible incorporation of sustainability; this specifies whether, and to what extent, inclusion of sustainability issues may improve the viability of built-in adaptability.

This chapter will be useful to those in the construction industry, as well as investors and corporates with social or environmental responsibilities contemplating measuring adaptable infrastructure efficiency and seeking a rational analysis method for assisting decision-making on building in adaptability.

Chapter 9: Summary and Conclusions

9.1 Overview

The uncertain and changing environment, in terms of climate or demographics, for example, may cause infrastructure to become obsolete, creating the need to build in adaptability/flexibility. Adaptability has been acknowledged as contributing to sustainability, but this is not supported by systematic and quantitative analyses. Hence, this thesis has aimed to establish the viability of adaptable/flexible infrastructure from the sustainability viewpoint.

This thesis fulfilled the research aim, and advanced the literature, in three main steps by answering the three research questions as follows. *First question*: Are various methods of infrastructure adaptability semantically different/the same? Do they contribute to sustainability? Chapter 4 adopted a holistic systems approach, interpreted various methods of infrastructure adaptability as a common concept, and implicitly demonstrated its contribution to sustainability. *Second question*: Does building in adaptability improve infrastructure sustainability performance? Chapters 5, 6 and 7 used a combination of existing methods and performed quantitative, comparative analyses between designed-in (A) and non-designed-in (NA) adaptable infrastructure. The thesis demonstrated how to carry out these analyses for three infrastructure case examples under changing climate and demographics and to determine whether building in adaptability could improve viability from the sustainability viewpoint. *Third question*: To what extent is building in adaptability viable from the sustainability viewpoint? Chapter 8 proposes a new approach giving a single measure for valuing the sustainability of adaptable infrastructure. This approach specifies not only whether, but also to what extent, building in adaptability improves infrastructure sustainability performance. The main research findings are summarised according to the research steps in the next section.

9.2 Research findings

Clarify the notion of infrastructure adaptability

- Infrastructure adaptability was presented as closed-loop control. Hence, it was implicitly shown that infrastructure adaptability contributes to sustainability as it transforms a linear pattern (open loop control) to a cyclic pattern (closed-loop control) of development, which is the philosophy behind sustainability.
- Using the systems approach adopted, it was shown that different types of infrastructure adaptability, and real options, can be interpreted as a single universal concept: the 'ability or option to influence the controls'.
- Designed-in adaptability means no more than a deliberate change in the initial values of the controls, u(0), at any system level, creating and/or leaving other controls to possibly be influenced later in response to altered infrastructure performance. However, the choice of suitable controls and the associated values requires ingenuity as well as a deep understanding of infrastructure engineering and interactions with the changing environment.
- Infrastructure adaptability valuation is linked to the concept of controls where a set of control values chosen produces its associated cash flows.

Comparative (quantitative) analysis

- Knowledge of engineering is required to establish how and to what extent adaptability features should be incorporated in infrastructure design. For example, this might be how large rock armours should be in the initial design of adaptable seawalls.
- The analysis approach involving the combination of Real Options Analysis (ROA) and Life Cycle Assessment (LCA) can be used to quantitatively value the sustainability of designed-in adaptable infrastructure. The application of this method was demonstrated. No general conclusion can be drawn on the viability of adaptable infrastructure as this requires an individual analysis for each situation.

- For the case examples considered, building in adaptability was shown to be financially more viable for lower interest rates and adaptation times. Designed-in adaptability was also shown to be generally better than the non-designed-in form against social and environmental criteria. Hence, the inclusion of social and environmental issues can increase infrastructure viability, implying that built-in adaptability is more sustainable. This further encourages designing for adaptability; however, investors may seek designs with greater financial viability.
- For resalable assets, the adaptability values calculated in this thesis represent the additional resale value of adaptable infrastructure due to the incorporated adaptability features. The methodology gives the seller instructions on how to set the increase in resale value.
- With particular attention to reduced energy use and emissions, built-in adaptability could be a suitable solution for climate change mitigation. As such, in cases where infrastructure is designed to be adaptable to a changing climate, it simultaneously contributes to climate change adaptation and mitigation.
- As seen in the open plan building case example, unlike the common attitude, designed-in adaptability does not necessarily lead to extra upfront environmental or social loadings.

Extend options analysis to sustainability: ROA-SEC

- The proposed ROA-SEC approach can be used to incorporate the uncertainty associated with intangibles, give a single measure for the sustainability of adaptable infrastructure, and show to what extent the inclusion of social and environmental issues improves the viability of built-in adaptability. This viability, for the assumptions considered, was shown to be considerably improved by the inclusion of sustainability issues in the analysis. However, the case example results cannot be generalised; each specific case requires individual analysis from specific decision-maker's viewpoint.

- There could be potential for persuading investors of the benefits of investing in adaptability through incorporating the intangible costs they currently pay for. Further, increased support for adaptability could be generated by the initiation of further legislation compelling corporates to pay for their liabilities.

9.3 Future directions

Further research can be built on the research limitations or by using new ideas. These are summarised below as future directions.

- Adaptability could be modelled for other types of infrastructure. The concept given in Chapter 4 will not change, but the characterisation of the system variables will. Although infrastructure adaptation with a discrete long timescale may not require detailed modelling as used in the computations style, this helps engineers gain a clear perception of infrastructure adaptability.
- The constructability of the suggestions on designed-in adaptability features (influenced controls) could be studied, such that they become common practice. With creative thought, other features might also be identified and the possibility of incorporating these be studied. The analysis given will not change, but the numbers will. Comparing different adaptability features may give an optimum set of features for enhanced sustainability performance.
- It is unclear as to what value (whether monetary or non-monetary) the decision-makers or investors would place on certain subjective matters, such as infrastructure serviceability or corporate reputation. An attempt could be made to establish these values. The external costs of resource consumption, with lowest visibility or no sufficient data, were excluded from the analysis. Studies could also be made to identify possible methods of monetisation or introducing policies that compel corporates to pay for their social and environmental liabilities. These will further include intangibles in the analysis, possibly leading to increased viability of building in adaptability.

- Further extension of ROA to the sustainability context might be desirable when dealing with subjective sustainability issues for which it is impossible or extremely difficult to specify a shadow price. Fuzzy set ideas might be utilised.
- It is unclear as to how decision-makers interpret the favourable financial, social and environmental measures and what unstated decision-making processes they go through. This subjectivity can be seen as the weightings that might be applied to intangibles compared to the financial aspects in ROA-LCA, or estimated unit costs in the ROA-SEC approach. A study could clarify the situation by setting a benchmark involving different decision-makers' interpretations.
- It was assumed in the analyses that there would be very strong correlation between the estimates for A and NA. Also, the improvement in social and environmental issues despite the extra upfront cost (as for the open plan building case example) indicates that financial and social or environmental cash flows could be independent, or not perfectly correlated. Any assumption on correlations other than that made in the thesis, shifting from perfect correlation towards independence, will lead to an increase in variance of PW and adaptability value (refer to the formulation in Appendix A), and hence support in favour of A form adaptation. However, an attempt to clarify a way of characterising these correlation coefficients, and its effects on the results, would be informative.
- Some proposed designed-in adaptability was shown to contribute to climate change adaptation and mitigation simultaneously. A focused study, adopting a hybrid climate change adaptation-mitigation approach, could further illustrate the benefits of designing infrastructure for adaptability.
- Among the challenges to adaptable design, the thesis considered economic and technical challenges with extra upfront cost. While reluctance to invest in adaptability may reflect failure to manage the social and institutional challenges e.g. organisational resistance and lack of political or regulatory incentives (Mitchell2005; Saleth and Dinar 2005; Brown et al., 2011). Thus,

future research should be directed towards such challenges and required adjustments.

- Decision-making on building in adaptability in the presence of uncertainty implies facing risks that are dealt with in different ways. An attempt could be made to investigate the effect of various attitudes towards risk, namely risk-averse, risk-prone and risk-neutral, on valuation outcomes.
- The estimated uncertainty of future costs, and hence the adaptability value, may be larger than that assumed. A major reason for larger uncertainty in financial analysis is the building work method, where this is undertaken on a cost reimbursable basis with a highly uncertain final outcome. This uncertainty might be assumed to grow with time, on the basis that estimates further into the future are less definite. Similarly, the value placed on social and environmental issues is anticipated to increase with time as people readjust their value systems in line with increasing public sustainability imperatives. The case example in Chapter 8, attempted to capture this growing value and the associated uncertainty, but changes in the unit price of some sustainability issues, such as waste production, are unclear and thus were ignored. Sustainability issue monetisation using more pricing methods, where appropriate, might also add to the uncertainty. A study could be made to thoroughly incorporate such growing values and larger uncertainties and compare the results.

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Appendix

Appendix A. Real options analysis – general formulation

A general formulation is here given for valuation of adaptable infrastructure, using probabilistic Discounted Cash Flow (DCF) analysis with second order moment approach. Consider a general investment, with possible cash flows extending over the life, n, of the investment. Let the net cash flow at each time period, i = 0, 1, 2, ..., n, be the result of a number of cash flow components, k = 1, 2, ..., m. The cash flow components can be both revenue and cost related. There may be correlation between the cash flow components at the same period.

The net cash flow X_i in any period can be expressed as,

$$X_i = a_{i1}Y_{i1} + a_{i2}Y_{i2} + ... + a_{im}Y_{im} \tag{A1}$$

where Y_{ik}, i = 0, 1, 2, ..., n; k = 1, 2, ..., m, is the cash flow in period i of component k, with expected value $E[Y_{ik}]$ and variance $Var[Y_{ik}]$, and a_{ik} are constants. The expected value and variance of cash flow components can be obtained as below, using optimistic (a), most likely (b) and pessimistic (c) estimates as is done in PERT (see for example, Carmichael, 2006; Carmichael and Balatbat, 2008a):

$$E[\,]\,X(a\,\Gamma\,4b\,\Gamma\,c)/6 \tag{A2}$$

$$Var[\,]\,X[(c - a)/6]^2 \tag{A3}$$

The expected value and variance of X_i become,

$$E[X_i] = \sum_{k=1}^{m} a_{ik}E[Y_{ik}] \tag{A4}$$

$$Var[X_i] = \sum_{k=1}^{m} a_{ik}^2 Var[Y_{ik}] + 2\sum_{k=1}^{m-1}\sum_{\ell=k+1}^{m} a_{ik}a_{i\ell}Cov[Y_{ik}, Y_{i\ell}] \tag{A5}$$

Alternatively, the variance expression can be written in terms of the component correlation coefficients, $\partial_{k\ell}$, between Y_{ik} and $Y_{i\ell}$, $k, \ell = 1, 2, ..., m$,

$$\mathrm{Var}[X_i] = \sum_{k=1}^{m} a_{ik}^2 \mathrm{Var}[Y_{ik}] + 2\sum_{k=1}^{m-1} \sum_{\ell=k+1}^{m} a_{ik} a_{i\ell} \rho_{k\ell} \sqrt{\mathrm{Var}[Y_{ik}]}\sqrt{\mathrm{Var}[Y_{i\ell}]} \tag{A6}$$

For independence between Y_{ik} and $Y_{i\ell}$,

$$\mathrm{Var}[X_i] = \sum_{k=1}^{m} a_{ik}^2 \mathrm{Var}[Y_{ik}]$$

For Y_{ik} and $Y_{i\ell}$ perfectly correlated,

$$\mathrm{Var}[X_i] = \left(\sum_{k=1}^{m} a_{ik} \sqrt{\mathrm{Var}[Y_{ik}]} \right)^2$$

The present worth, PW, is the sum of the discounted X_i, i = 0, 1, 2, ..., n, according to,

$$PW = \sum_{i=0}^{n} \left[\frac{b_i X_i}{(1+r)^i} \right] \tag{A7}$$

where r is the interest rate, and b_i are constants. The expected value and variance of the present worth become,

$$E[PW] = \sum_{i=0}^{n} \frac{b_i E[X_i]}{(1+r)^i} \tag{A8}$$

$$\mathrm{Var}[PW] = \sum_{i=0}^{n} \frac{b_i^2 \mathrm{Var}[X_i]}{(1+r)^{2i}} + 2\sum_{i=0}^{n-1} \sum_{j=i+1}^{n} \frac{b_i b_j \mathrm{Cov}[X_i, X_j]}{(1+r)^{i+j}} \tag{A9}$$

Alternatively, the variance expression can be written in terms of the intertemporal correlation coefficients between X_i and X_j, namely ρ_{ij}, rather than the covariance of

X_i and X_j (see Carmichael, 2014). For independent cash flows, the covariance and subsequently the second term would be zero.

Equivalent expressions exist for other situations, namely continuous time discounting, interest rate being also a random variable, and calculating future worth (see for example, Carmichael and Bustamante, 2014; Carmichael and Handford, 2015). Interest rate and variances can change with cash flows and over time if desired.

In the given ROA approach, anything favourable to the investor is considered as a cash inflow, and anything unfavourable as a cash outflow. Hence, all options can be valued by using a single formula, here referred to as the Carmichael equation,

$$\text{Adaptability value} = \Phi M \tag{A10}$$

where Φ = P[PW > 0] and is termed the investment feasibility (Carmichael and Balatbat, 2008a), P is probability, and M is the mean of the present worth upside measured from PW = 0. To calculate Φ and M, and knowing E[PW] and Var[PW], any distribution can be fitted to PW, but it is anticipated that most people would use a normal distribution (Hillier, 1963; Tung, 1992), as shown in Figure A1.

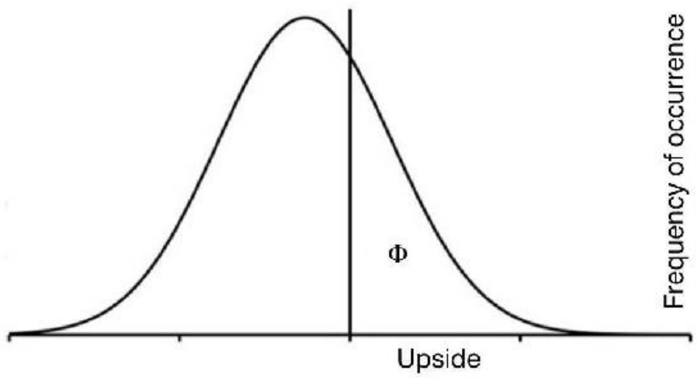


Figure A1. Example of normal distribution of PW of total cash flows – time 0 (Carmichael, 2014).

Appendix B. Infrastructure design – system variables identification

Control	State	Output	Source
Coastal defences – sea level rise			
Foundation size	Stability against overturning	Structure settlement	(Dobes, 2008; Woodward et al., 2011; NCCOE, 2012a)
Crest level	Freeboard	Volume of water overtopped	(Woodward et al., 2011; Burcharth et al., 2014)
Seaward slope	Overtopping; armours stability	Overtopped water; armours displacement	(Townend and Burgess, 2004; Burcharth et al., 2014)
Rubble toe size	Toe stability	Structure settlement	(Flocard and Blacka, 2012; NCCOE, 2012a)
Armuor layer thickness	ditto	ditto	(Flocard and Blacka, 2012; Burcharth et al., 2014)
Transport sector – sea level rise and/or extreme rainfall change			
Height of embankment besides roads/railways	Risk of flooding	Volume of overflow water	(Dobes, 2008; Headland et al., 2011)
Distance receded from coastal/low-lying areas	ditto	ditto	(Dobes, 2008)
Seaports deck elevation	Overtopping potential	Volume of water overtopped	-
Seaport fenders' fabrication method	Fender freeboard	Berth damage	-
Quay wall height	Freeboard	Volume of water overtopped	(Taneja et al., 2012)
Transport sector – air temperature rise			
Vehicles' air conditioning capacity	Occupants' level of comfort	Indoor temperature	(Dobes, 2008, 2010)
Aircraft engine power	Uplift force	Takeoff speed	(Dobes, 2008, 2010)
Runway length	ditto	ditto	(Dobes, 2008, 2010)
Buildings/real estate – air temperature rise			
Heat barriers capacity	Occupants' level of comfort	Indoor temperature	(Shashua-Bar and Hoffman, 2004; Dobes, 2008)
Cooling system capacity	ditto	ditto	(Greden, 2005; Howell et al., 2015)
Houses' bushfire protection	Risk of ignitation	Property damage	(Dobes, 2010)
Buildings/real estate – extreme rainfall change or sea level rise			
Lower floor elevation	Freeboard; Risk of flooding	Water seepage	(Dobes, 2010; Headland et al., 2011)
Solar panels' protection	Risk of failure	Cracks/damages	(Dobes, 2008)
Urban development – air temperature rise			
Heat (island effect) reflection	Heat transfer rate	Land surface temperature	(Taha, 1996; Shashua-Bar and Hoffman, 2004)
Urban development – rainfall change			
Settlements location	Risk of flooding	Flooded area	(Schuetze and Chelleri, 2011)

Table B1. More examples of variables of infrastructure system under changing climate.

Control	State	Output	Source
Water management systems – sea level rise or rainfall change			
Stormwater drain/canal capacity	Head difference; water flow rate	Volume of undrained water	(Headland et al., 2011; Gersonius et al., 2013)
Water management systems – rainfall change			
Water recycling capacity	Water supply	Service pressure	-
Rainwater retention capacity	Water supply; runoff	Service pressure; flooded area	(van Stokkom et al., 2005; Schuetze and Chelleri, 2011)
Dam's wall height	Flood risk	Overflow water; downstream damages	(Gersonius et al., 2013)
Dam's reservoir capacity	Water supply	Service pressure	(Gersonius et al., 2013)

Table B1. More examples of variables of infrastructure system under changing climate (continued).

Control	State	Output	Source
Buildings – change in users' population			
Number of storeys	Space congestion	Per capita space	(Moffatt and Russell, 2001; de Neufville et al., 2006; Guma, 2008)
Building footprint	Space congestion	Per capita space	(Rook et al., 1991; Lee, 2007; Ressler, 2014)
Structural members strength	Members stress/strain	Members deflection	(Keymer, 2000; Moffatt and Russell, 2001; Slaughter, 2001; de Neufville et al., 2006, 2008; Guma, 2008; Remøy et al., 2011)
Conveying system capacity	Lifts involvement	Awaiting time	(Guma, 2008)
Buildings – change in users' wants or population			
Clear-span space size	Space usage efficiency	Number of users accommodated	(Moffatt and Russell, 2001; Schneider and Till, 2005; Remøy et al., 2011)
Space layout (internal walls location)	Space usage efficiency	Active space area	(Moffatt and Russell, 2001; Slaughter, 2001; Arge, 2005; Greden, 2005; de Neufville et al., 2008)
Space use	Usage fitness	Occupancy rate	(Gann and Barlow, 1996; Kendall, 1999; Moffatt and Russell, 2001; Till and Schneider, 2005)
Floor height	Indoor air quality;	Carbon dioxide level	(Moffatt and Russell, 2001; Remøy et al., 2011)
Transport sector – change in users' population			
Number of road lanes	Traffic congestion	Travel time	(de Neufville, 2003)
Bridge's deck width	ditto	ditto	(Gesner and Jardim, 1998; Bennett et al., 2009)
Tunnels' width or number	ditto	ditto	(Ohama, 2008)
Airport/seaport terminal footprint	ditto	Awaiting time	(de Neufville, 1991; Ohama, 2008; Taneja et al., 2012)
Quay length	Quay congestion	ditto	(Taneja et al., 2012)
Transport sector – change in users' wants or population			
Port layout	Space usage efficiency	Active space area	(Taneja et al., 2012)
Water resources systems – change in users' population			
Capacity of water reservoirs/distribution network	Service pressure	Disruptions to operation	(Huang et al., 2010; Basupi and Kapelan, 2014, 2015; Marques et al., 2015)
Dams' hydropower station capacity	Voltage level	ditto	(Wang and de Neufville, 2006)
Capacity of rainwater retention/recycling	Freshwater consumption	ditto	-

Table B2. More examples of variables of infrastructure system under changing demographics.

Control	State	Output	Source
Mining projects – change in users' population or wants			
Ore extraction rate	Ore availability	Procurement delay	(Kazakidis and Scoble, 2003; Mayer, 2004; Groeneveld et al., 2012)
Processing plant and Storage capacity	ditto	ditto	(Kazakidis and Scoble, 2003; de Neufville, 2006; Mayer and Kazakidis, 2007)

Table B2. More examples of variables of infrastructure system under changing demographics (continued).

Appendix C. Infrastructure adaptability – systems interpretation

Control, u	Ability or option to	Source
Coastal defences – sea level rise		
Additional base width	extend	(Dobes, 2008; Woodward et al., 2011; NCCOE, 2012a)
Additional height (crest level)	upgrade; extend	(Woodward et al., 2011; Burcharth et al., 2014)
Reduction in slope	upgrade	(Townend and Burgess, 2004; Burcharth et al., 2014)
Addition to toe size	extend	(Flocard and Blacka, 2012; NCCOE, 2012a)
Addition to armour layer thickness	upgrade	(Flocard and Blacka, 2012; Burcharth et al., 2014)
Transport sector – sea level rise and or extreme rainfall change		
Additional height of adjacent embankment	extend; rise	(Dobes, 2008; Headland et al., 2011)
Addition to distance from coastal/ low-lying areas	relocate; recede	(Dobes, 2008)
Additional elevation of seaport deck	extend; heighten	-
Change in port fenders fabrication (e.g., use lightweight blocks with lockable fittings)	upgrade	-
Additional height of quay wall	extend; rise	(Taneja et al., 2012)
Transport sector – temperature rise		
Addition to vehicles' air conditioning capacity (i.e., space, support, AC units)	upgrade	(Dobes, 2008, 2010)
Addition to aircraft engine power	upgrade	(Dobes, 2008, 2010)
Additional length of runway (i.e., land, sublayers and pavement)	extend	(Dobes, 2008, 2010)
Buildings/real estate – temperature rise		
Additional heat barrier capacity (i.e., space, supports, barriers – shade blinds, trees)	expand; upgrade	(Shashua-Bar and Hoffman, 2004; Dobes, 2008)
Addition to cooling system capacity (i.e., space, supports, cooling unit equipment)	install; expand	(Greden, 2005; Howell et al., 2015)
Addition to houses' bushfire protection (i.e., space, preliminiriaries, fire shelters)	install; upgrade	(Dobes, 2010)
Buildings/real estate – extreme rainfall change or sea level rise		
Additional floor elevation	rise; upgrade	(Dobes, 2010; Headland et al., 2011)
Addition to solar panels' protection (i.e., fittings and wire mesh)	install; upgrade	(Dobes, 2008)
Urban development – temperature rise		
Addition to heat reflection (e.g., greening roadway medians and building surfaces)	expand	(Taha, 1996; Shashua-Bar and Hoffman, 2004)
Urban development – rainfall change		
Relocation of settlements (e.g., from low-lying to elevated areas)	move; relocate	(Schuetze and Chelleri, 2011)

Table C1. Controls suggested for adaptable infrastructure under changing climate.

Control, u	**Ability or option to**	**Source**
Water management systems – sea level rise or rainfall change		
Addition to stormwater drainage capacity (i.e., system elevation, section size, pumps)	install; upgrade	(Headland et al., 2011; Gersonius et al., 2013)
Water management systems – rainfall change		
Additional capacity of water recycling	expand	-
Addition to rainwater retention capacity	expand	(van Stokkom et al., 2005; Schuetze and Chelleri, 2011)
Addition to dam's reservoir and flood protection capacity (i.e., structure strength, crest level, spillway and floodgate size)	upgrade; expand	(Gersonius et al., 2013)

Table C1. Controls suggested for adaptable infrastructure under changing climate (continued).

Control, u	**Ability or option to**	**Source**
Buildings – change in users' population		
Additional storeys	expand/ shrink	(Moffatt and Russell, 2001; de Neufville et al., 2006; Guma, 2008)
Additional footprint (i.e., land, erections)	extend; expand	(Rook et al., 1991; Lee, 2007; Ressler, 2014)
Addition to structural members strength	expand	(Keymer, 2000; Moffatt and Russell, 2001; Slaughter, 2001; de Neufville et al., 2006, 2008; Guma, 2008)
Addition to conveying system capacity (i.e., space, opening, lifts)	install; upgrade	(Guma, 2008)
Buildings – change in users' wants or population		
Addition to clear-span space	expand/ shrink	(Moffatt and Russell, 2001; Schneider and Till, 2005; Remøy et al., 2011)
Change in space layout (interior walls location)	expand/ shrink; move; relocate	(Moffatt and Russell, 2001; Slaughter, 2001; Arge, 2005; Greden, 2005; de Neufville et al., 2008)
Change in space use	convert; switch; sublet	(Gann and Barlow, 1996; Kendall, 1999; Moffatt and Russell, 2001; Till and Schneider, 2005)
Additional floor height and/or load-bearing capacity	convert	(Moffatt and Russell, 2001; Remøy et al., 2011)
Transport sector – change in users' population		
Additional number of road lanes (i.e., land, substructure, pavement)	extend	(de Neufville, 2003)
Additional width of bridge's deck (i.e., capacity of piles, footings, abutments)	expand	(Gesner and Jardim, 1998; Bennett et al., 2009)
Additional number or width of tunnel (i.e., structure, sublayers, pavement)	expand	(Ohama, 2008)
Addition to terminal footprint (airport – land, buildings, taxiway or runway; seaport – piers, superstructure)	extend	(de Neufville, 1991; Ohama, 2008; Taneja et al., 2012)
Additional length of quay (i.e., piers, deck, warehouse)	extend	(Taneja et al., 2012)
Transport sector – change in users' wants or population		
Change in port marine layout	scale up/down	(Taneja et al., 2012)
Water resources systems – change in users' population		
Addition to water reservoirs/distribution network capacity (i.e., dams, control tanks, pipes)	expand	(Huang et al., 2010; Basupi and Kapelan, 2014, 2015; Marques et al., 2015)
Addition to dam's hydropower station capacity (i.e., space, footing turbine)	expand; upgrade	(Wang and de Neufville, 2006)
Addition to rainwater retention/recycling capacity (e.g., wetlands and green roofs)	expand	-

Table C2. Controls suggested for adaptable infrastructure under changing demographics.

Control, u	**Ability or option to**	**Source**
Mining projects – change in users' population or wants		
Additonal ore extraction rate (i.e., capacity of shaft, hoisting equipment, ore pass, truck fleet and crusher)	expand; upgrade	(Kazakidis and Scoble, 2003; Mayer, 2004; Groeneveld et al., 2012)
Addition to capacity of processing plant (e.g., number of handling circuits) and storage (e.g., bin for stockpiling)	expand; upgrade	(Kazakidis and Scoble, 2003; de Neufville, 2006; Mayer and Kazakidis, 2007)

Table C2. Controls suggested controls for adaptable infrastructure under changing demographics (continued).

Appendix D. Case example – rock seawall designs

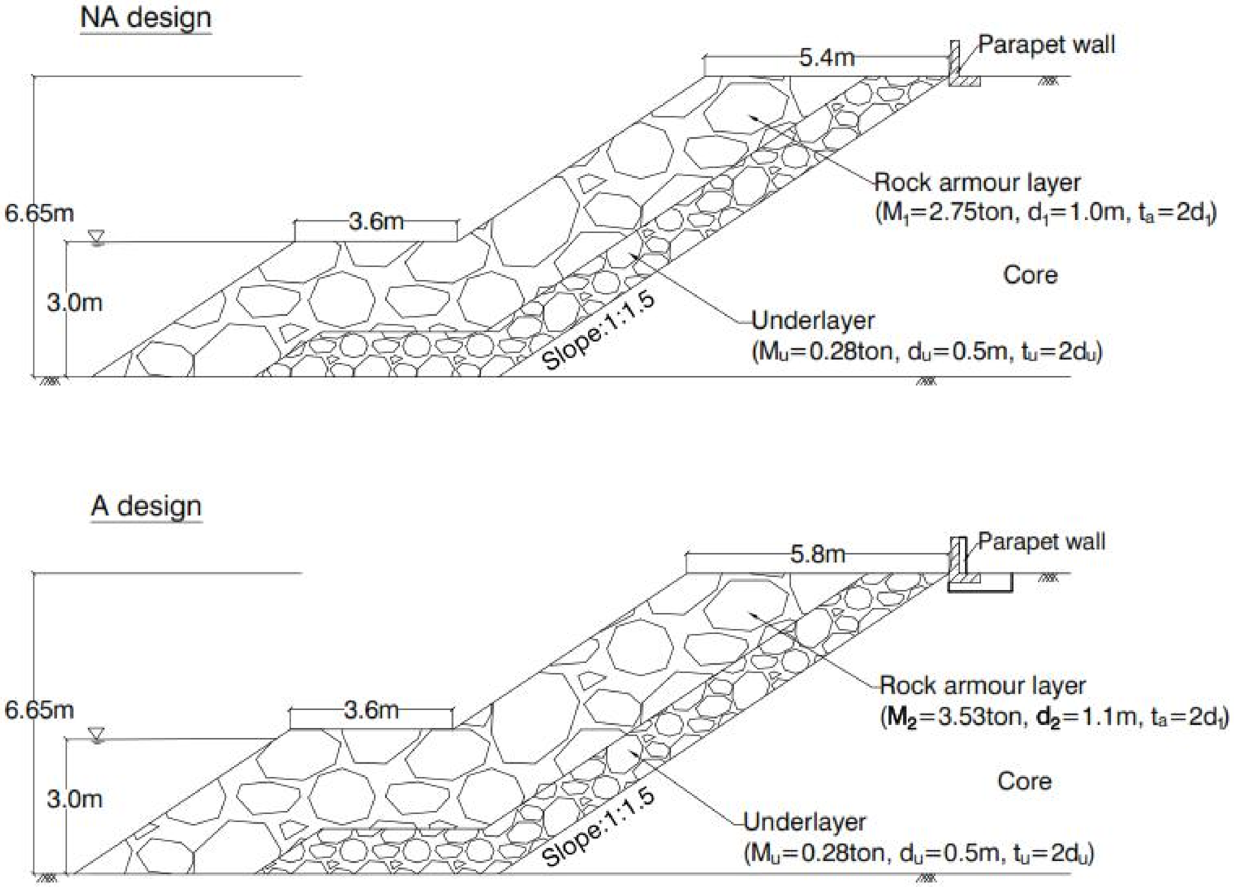
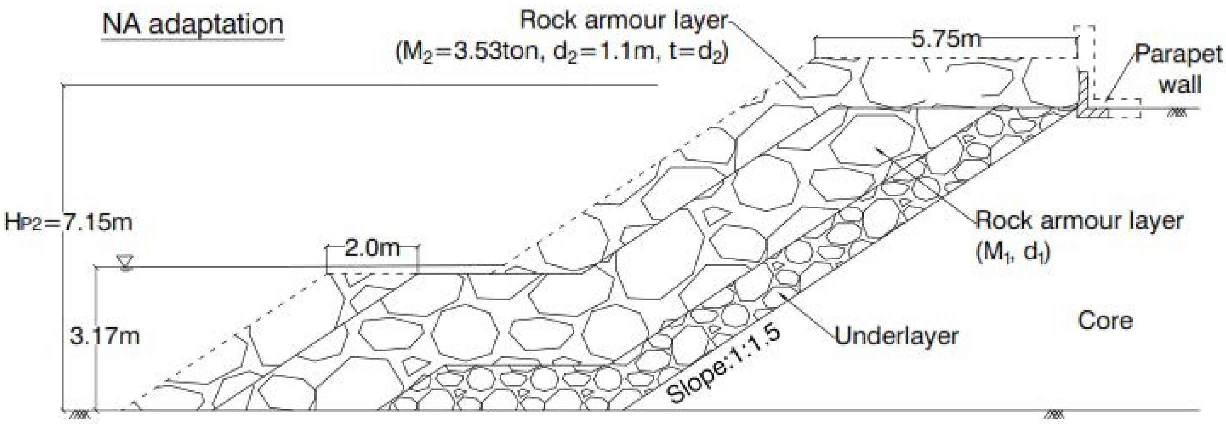


Figure D1. Case example: Rock seawalls cross sections – A vs. NA initial designs (bold notes/lines display designed-in adaptability features).



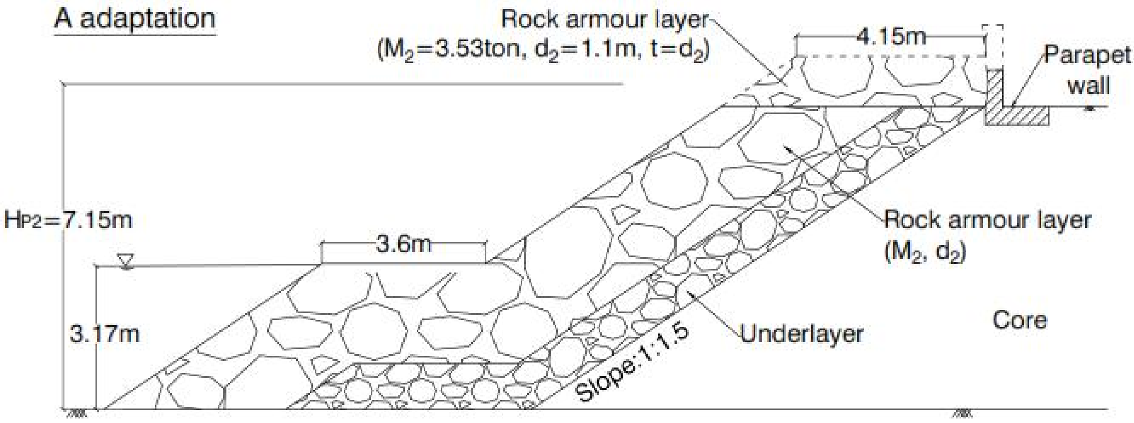


Figure D2. Case example: Rock seawall cross section – A vs. NA future adaptations (displayed by dashed lines).

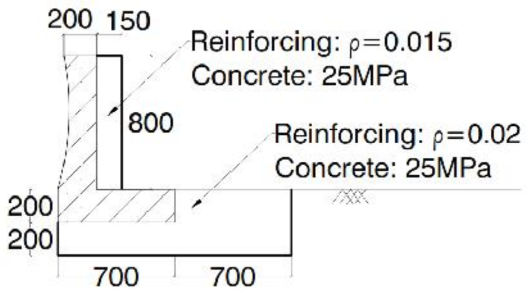


Figure D3. Case example: Parapet wall cross section – A vs. NA initial designs (bold lines display designed-in adaptability features).

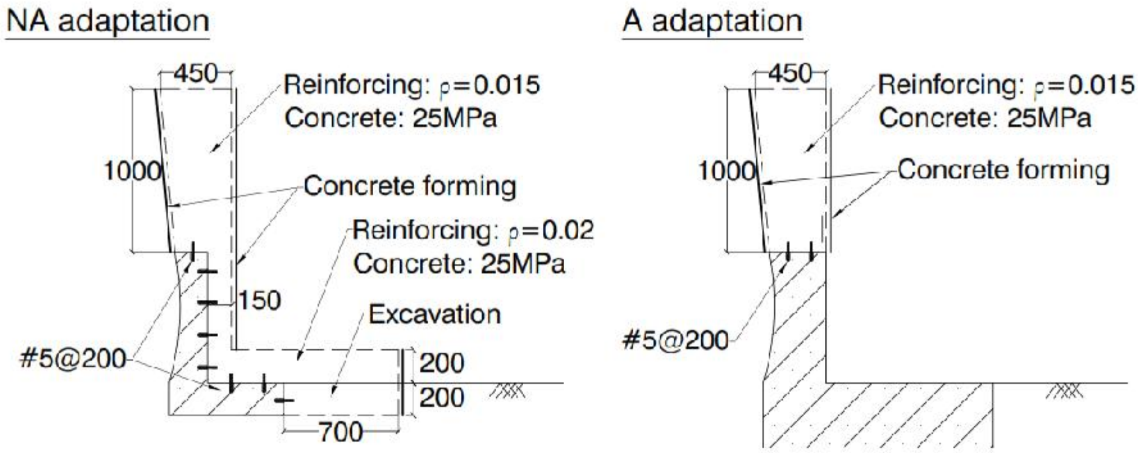


Figure D4. Case example: Parapet wall cross section – A vs. NA future adaptations (displayed by dashed lines).

Appendix E. Case example – residential housing designs

Figure E1. Typical timber-framed house in Sydney.

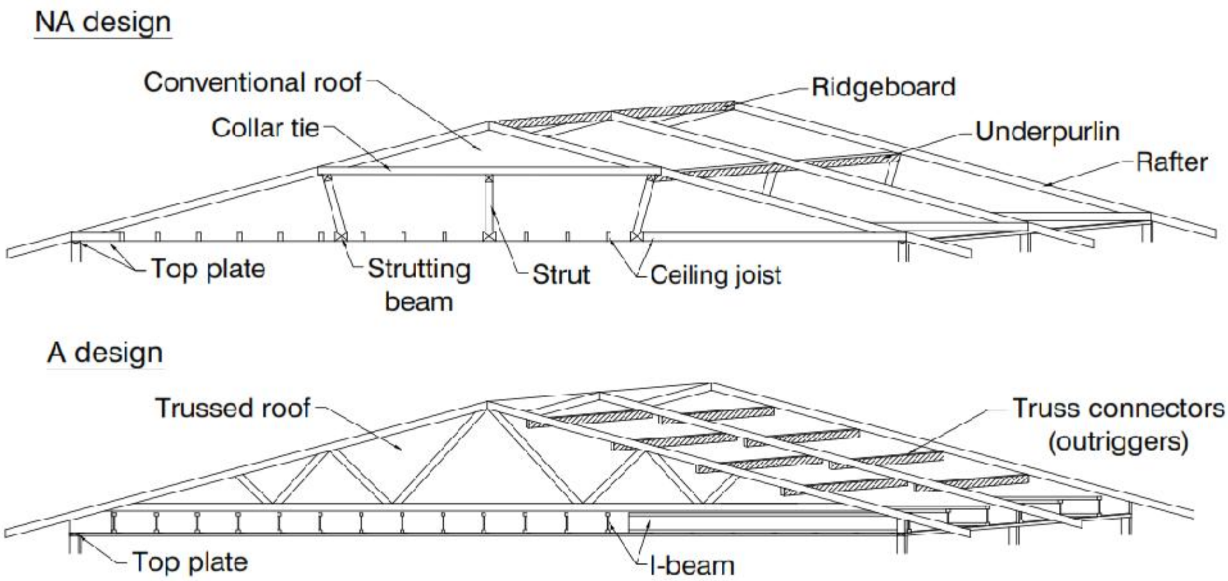


Figure E2. Case example: Residential housing – A vs. NA initial designs.

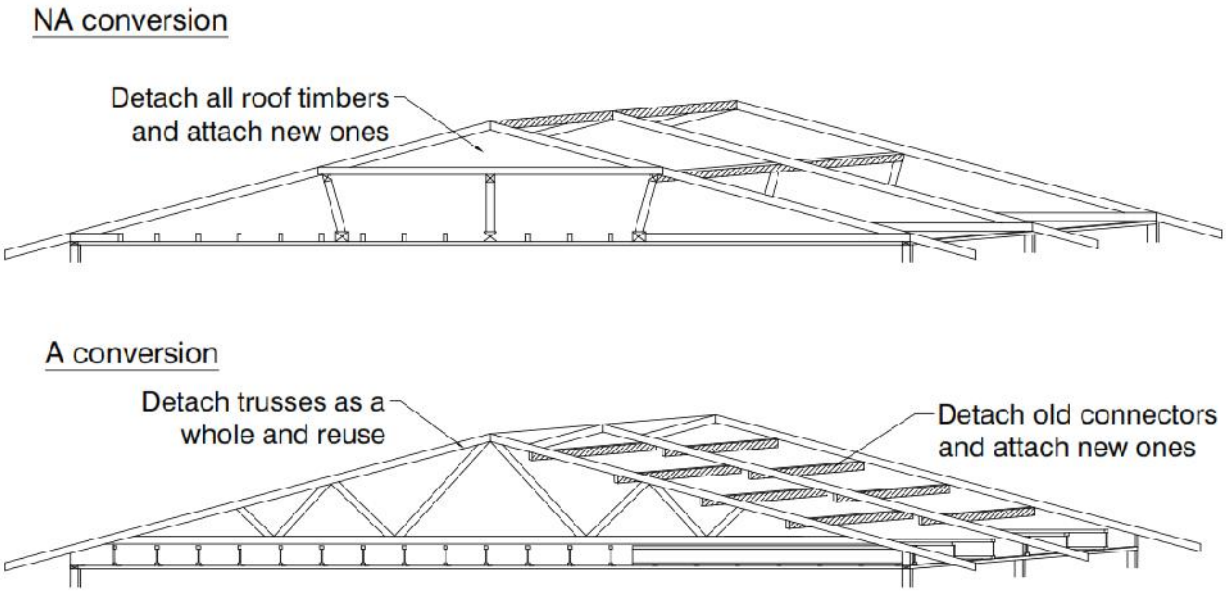


Figure E3. Case example: Residential housing – A vs. NA future conversions (differences in roofing).

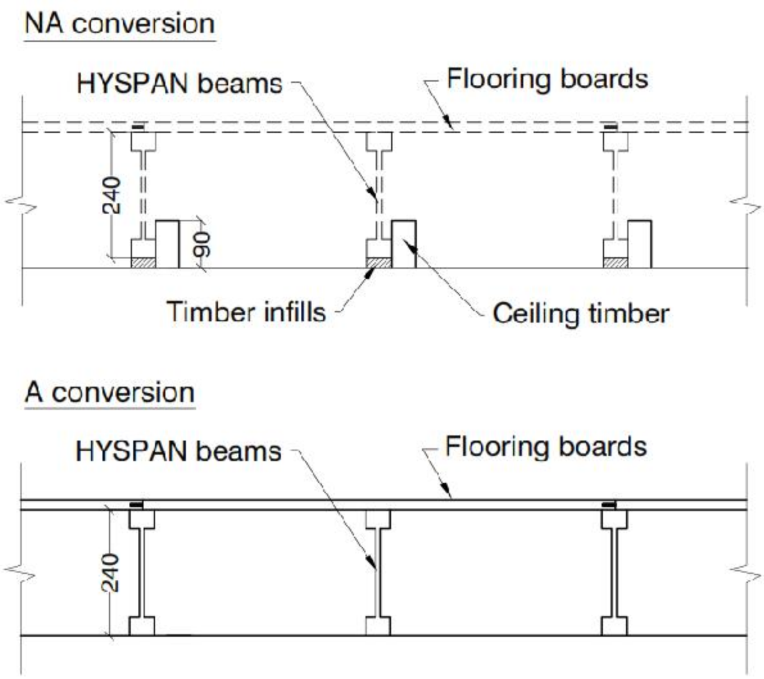


Figure E4. Case example: Residential housing – A vs. NA future conversions (differences in upper storey flooring).

Appendix F. Case example – open plan building designs

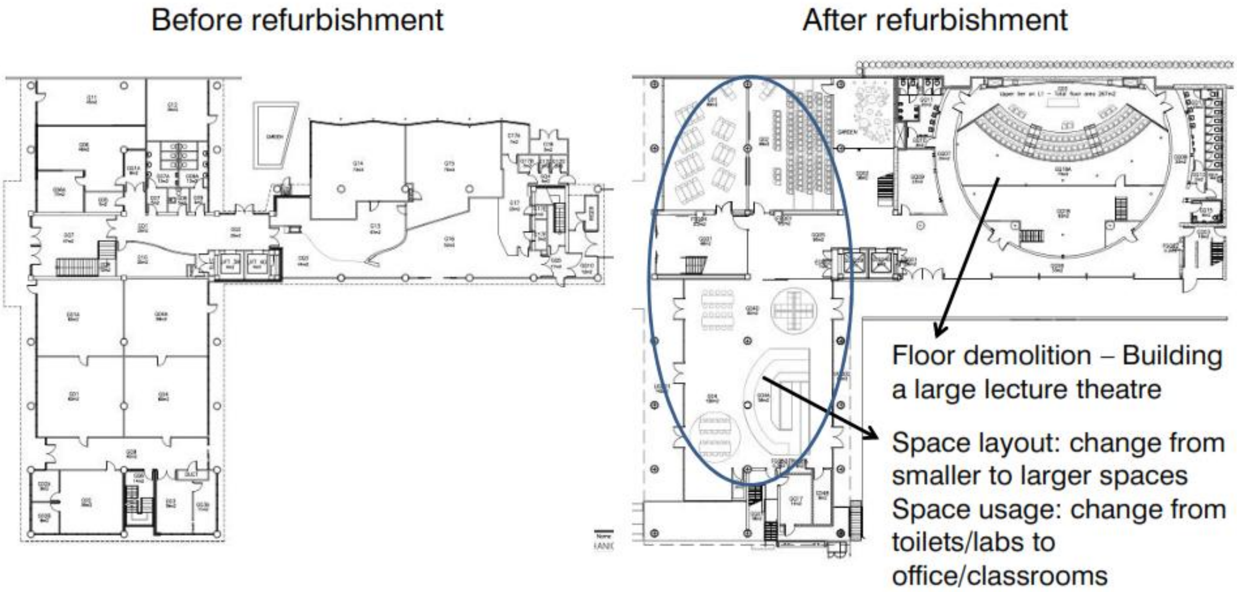


Figure F1. Mechanical engineering building refurbishment, UNSW – ground floor plan.

Figure F2. Mechanical engineering building refurbishment, UNSW – first floor plan.

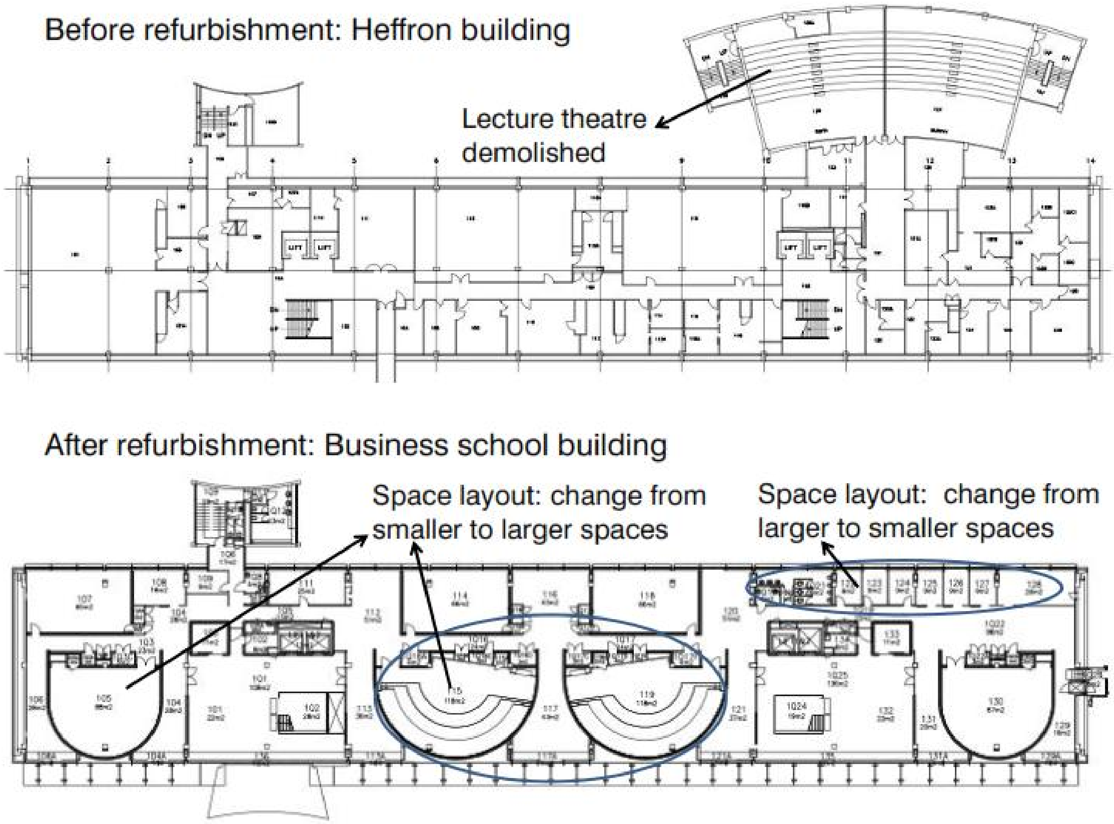
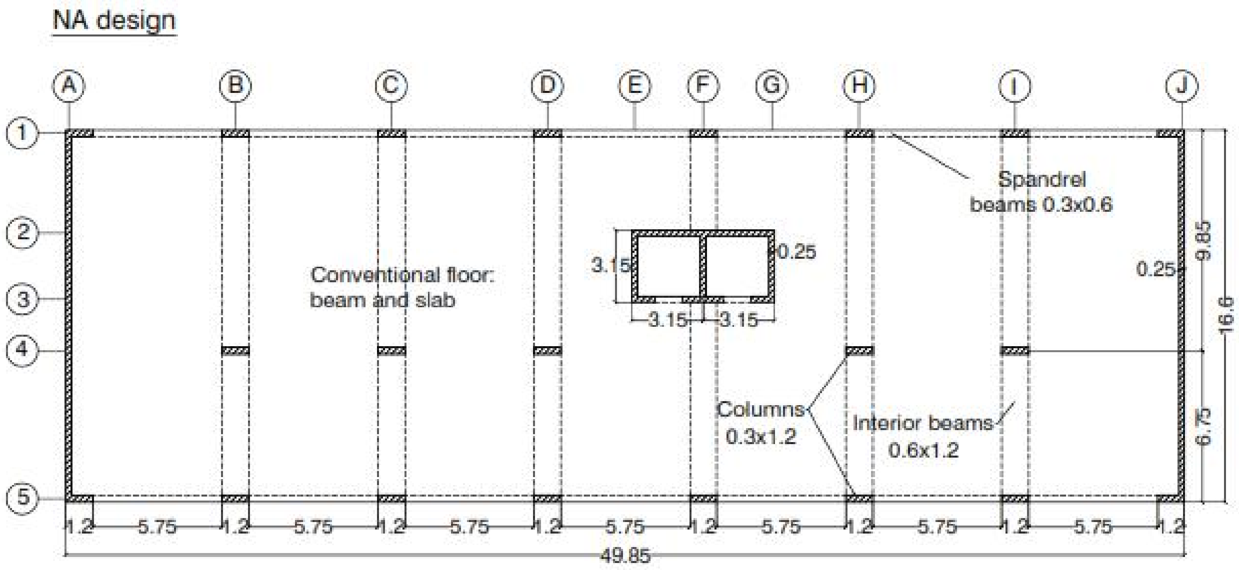


Figure F3. Business school building refurbishment, UNSW – first floor plan.



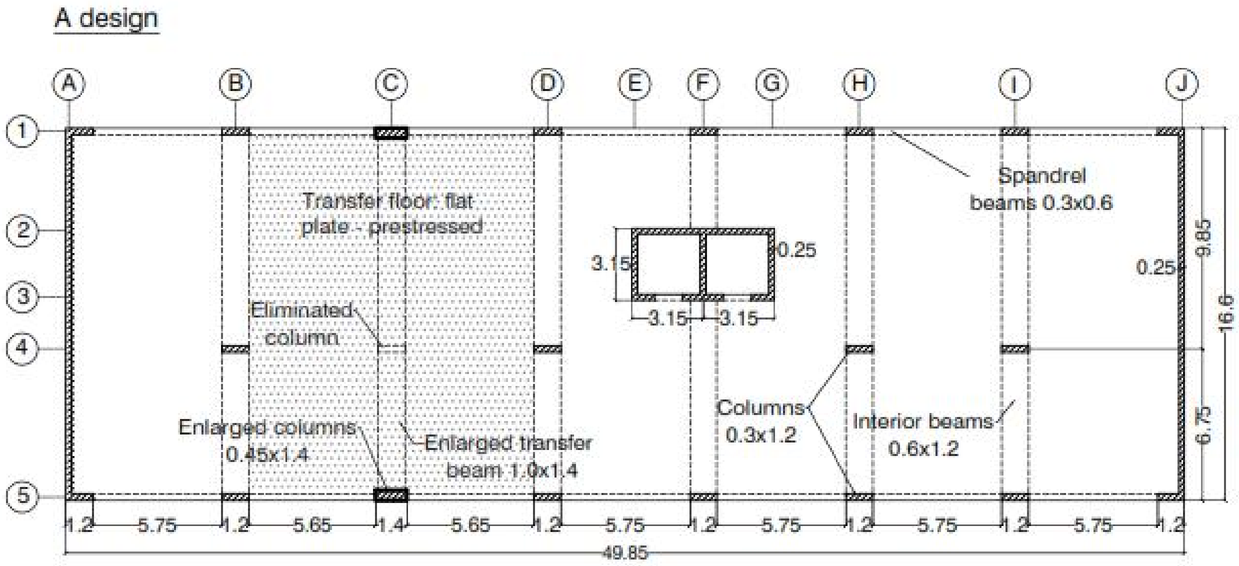


Figure F4. Case example: Civil Engineering Building, UNSW – ground floor structural plan: A vs. NA initial designs.

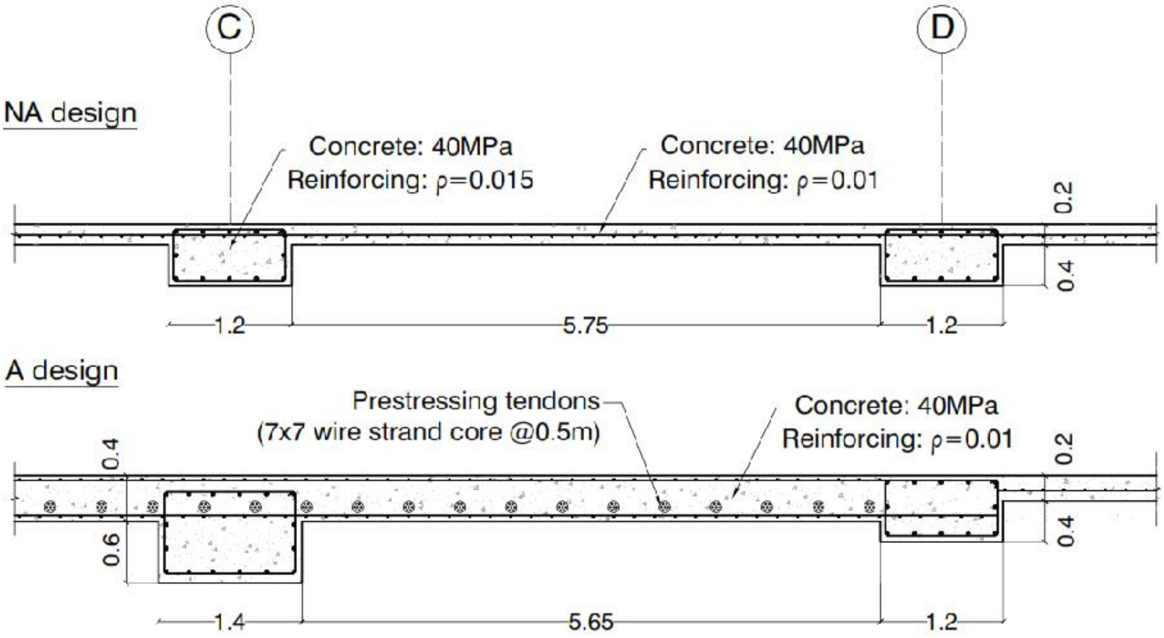


Figure F5. Case example: Civil Engineering Building, UNSW – ground floor section: A vs. NA initial designs.

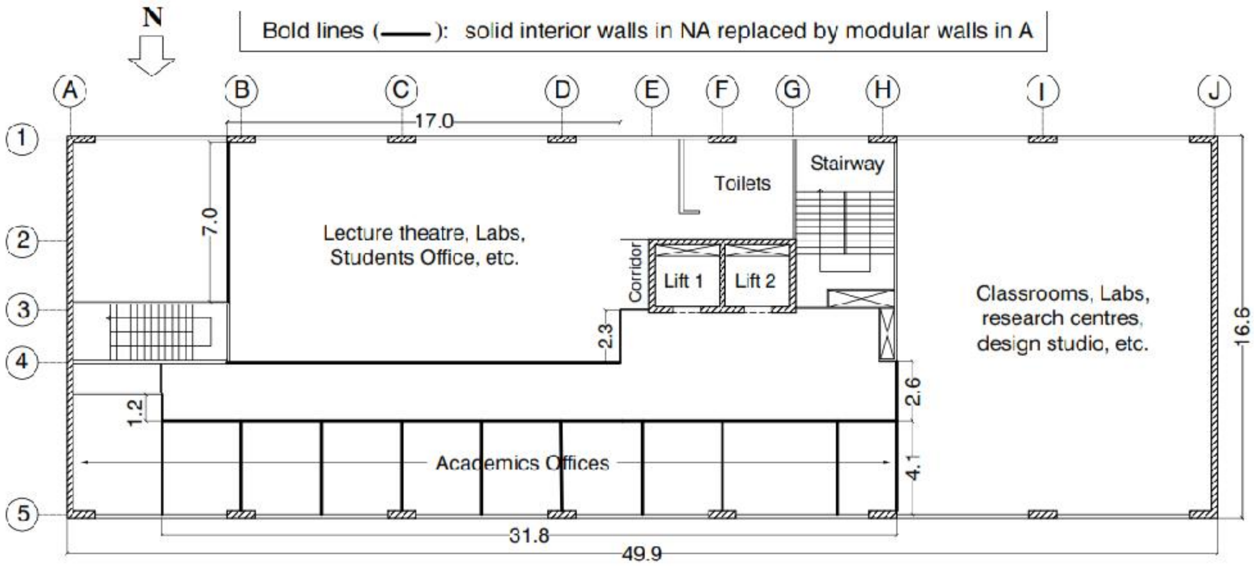


Figure F6. Case example: Civil Engineering Building, UNSW – typical floor plan: A vs. NA initial designs.

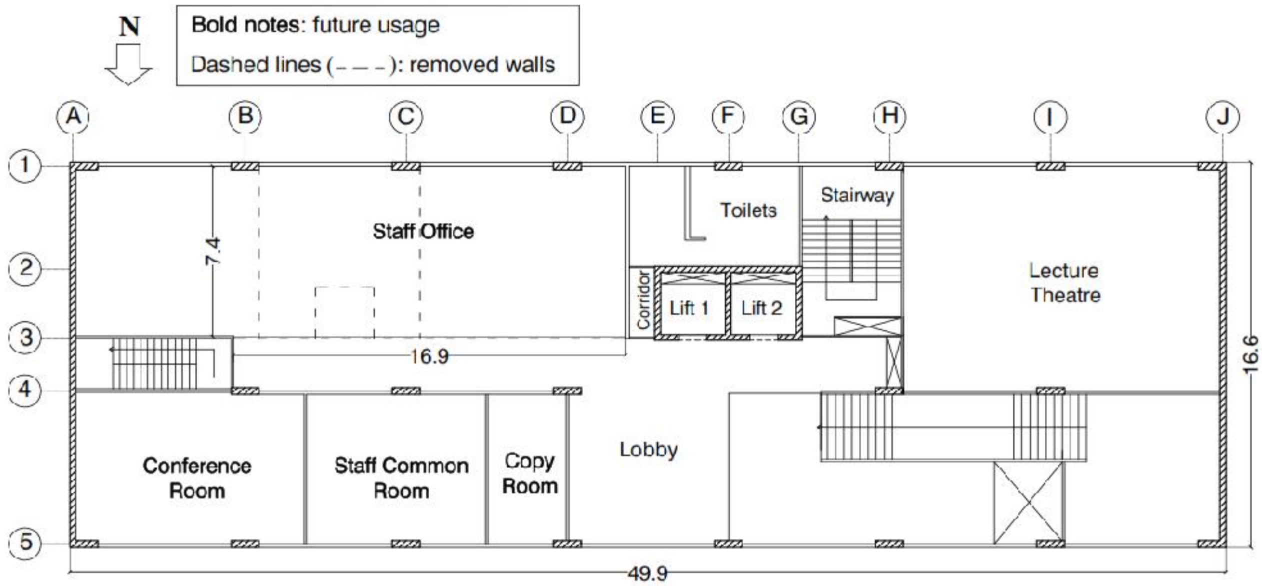


Figure F7. Case example: Civil Engineering Building, UNSW – ground floor plan: future refurbishments for both A and NA.

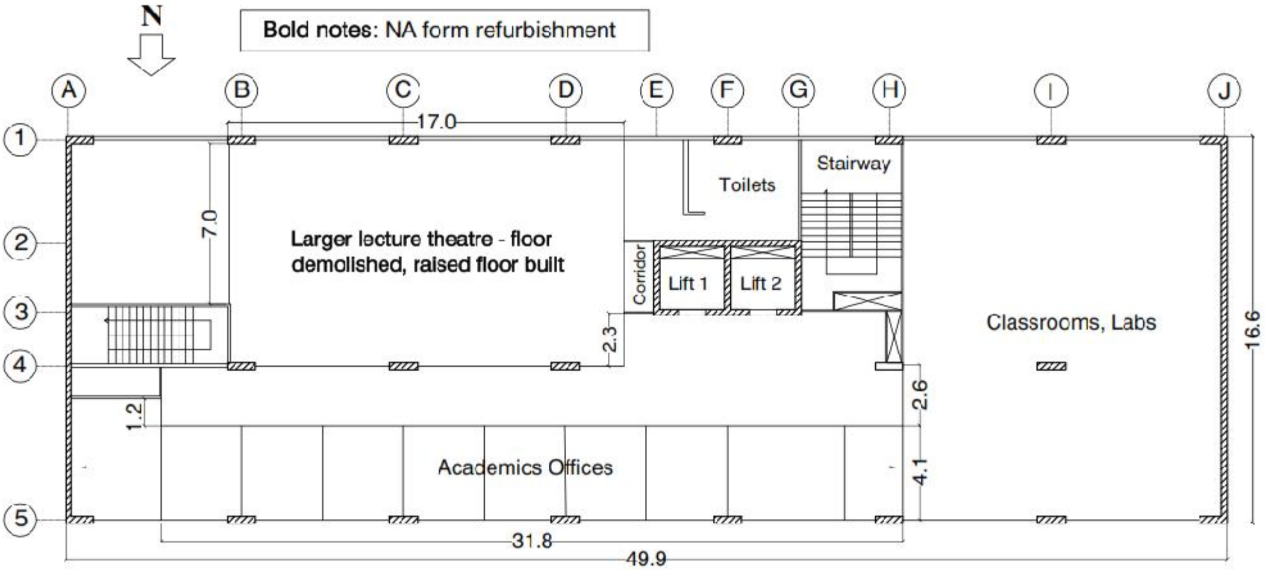


Figure F8. Case example: Civil Engineering Building, UNSW – 2nd floor plan: NA form future refurbishment.

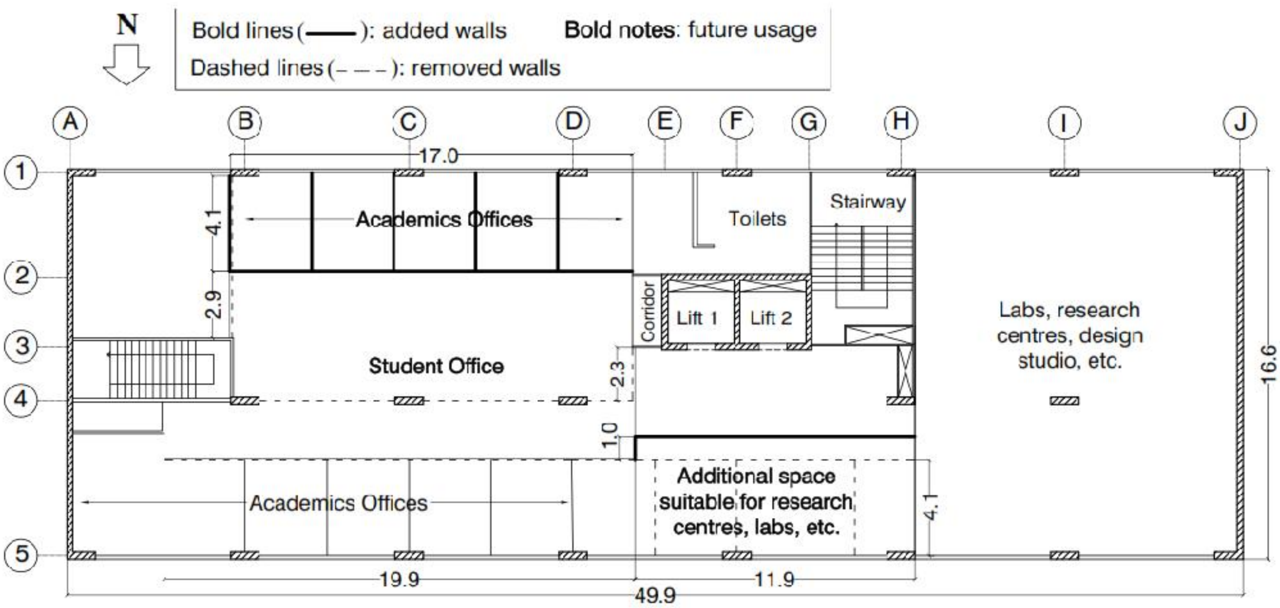


Figure F9. Case example: Civil Engineering Building, UNSW – upper floors typical plan: future refurbishments for both A and NA.

Appendix G. List of advisors and details of their background and experience

Advisor's name	Company	Background – field of expertise	Years of experience
A/Prof Ron Cox	UNSW – Water Research Laboratory	Coastal and ocean engineering, Coastal management, Climate change impact, risk assessment and adaptation	Over 30
Prof Ian Turner	UNSW – Water Research Laboratory	Coastal structures and coastal protection, coastal change and impacts of climate variability	Over 30
Dr Hamid Vali Pour Goudarzi	UNSW	Structural engineering, made of steel, concrete and timber	Over 20
Mr Ali Arashi	Shell Construction Group	Civil/Geotechnical engineer, Project manager, Licensed builder (MIEAust)	Over 15
Mr Roy Edwards	Heyden Frame and Truss	Construction and project management	Over 30
Mr Tim Bradley	Taylor Construction	Site manager – construction and refurbishment	Over 15
Mr Mahdi Babaee	Taylor Thomson Whitting	Senior structural engineer	Over 10
Mr Hamid Babakhani	Gozineh Consulting Engineers	Head of engineering supervision – construction and project management	Over 30
Mr Kevin Dashti	Kanebridge Construction	Site Manager – construction and project management	Over 20

Table G1. List of advisors consulted about constructability issues and estimation.