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Valuing Sustainability of Adaptable Infrastructure Using ROA-SEC: A Hybrid Approach

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ABSTRACT

Infrastructure providing fundamental services for societies may become obsolete under changing environments such as climate or demographics changes, creating the need for adaptability. Designing infrastructure for adaptability may affect life cycle costs as well as environmental and social issues such as resources consumption, waste production or disruption to services provided. Sustainability valuation of adaptable infrastructure is thus required. The Real Options Analysis (ROA) is widely used to evaluate financial viability of investing in adaptable infrastructure. But, the environmental and social aspects have been barely noticed and incorporated. Hence, a valuation method is required to properly address all aspects of sustainability. This paper bridges the gap and advances the literature by presenting a methodology for designed-in adaptability valuation, considering all the sustainability aspects. To this end, a hybrid approach is suggested through integration of Social and Environmental Costing (SEC) with ROA, providing a single measure for sustainability of adaptable infrastructure. In this approach, the outputs of Life Cycle Assessment (LCA) tools are monetized using SEC methods; and then incorporated in the ROA that is built on the probabilistic Discounted Cash Flow (DCF) analysis, suitable for engineering applications. The application of the proposed approach is illustrated on a case example involving seawalls under changing climate effects. For the case example, including sustainability issues in the analysis improved the viability of designing in adaptability. This conclusion cannot be generalized and each situation requires an individual analysis. However, the proposed approach and methodology will be the same in all the situations.

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1. Introduction

Infrastructure providing fundamental services for societies may become obsolete under changing environments such as climate or demographics changes. Infrastructure adaptability or flexibility is suggested as a key solution when design requirements change over time (Conrad and Raucher, 2013; Scholtes, 2007; Slaughter, 2001; Taneja et al. 2012). Given that infrastructure is intended for long term operation, it will be adapted to changes someway in future. Thus, developers are caught in a dilemma to whether or not design infrastructure for adaptability. This implies the notions of *non-designed-in (or fortuitous)* adaptation versus *designed-in (or in-built)* adaptation (Carmichael and Taheriattar, 2018) – where an option, a right but not an obligation, is embedded in design to accommodate uncertain changes (Wang and de Neufville, 2005). The latter, which is the focus of this paper and compared against the former, often requires or is perceived to require extra upfront cost and effort. While, possible fortuitous adaptation in future may lead to greater sustainability issues, such as enormous adaptation costs, resources consumption, or disruption to substantial services provided for the society.

Despite the literature acknowledges infrastructure adaptability to enhance sustainability through extended useful life (Moffatt and

Russell, 2001; Taneja et al. 2012; Wilkinson et al., 2009), it stops short in valuation of designed-in adaptability (Gosling et al., 2013; Schneider and Till, 2005; Slaughter, 2001). Real Options Analysis (ROA) is used to evaluate financial viability of investing in adaptable infrastructure (Carmichael et al., 2011; Copeland and Antikarov, 2001), but disregards social and environmental aspects. A few attempted considering sustainability issues in adaptability valuation using LCA tools (Carmichael and Taheriattar, 2018; Fawcett et al., 2014; Moffatt and Russell, 2001), while still have limitations in terms of incorporating uncertainty or interpreting the results (Fawcett et al., 2014).

Therefore, this paper aims to properly incorporate social and environmental issues and associated uncertainties into the sustainability analysis of adaptable infrastructure. Thus, the paper suggests integration of ROA with Social and Environmental Costing (SEC), providing a compatible extension to ROA application. The proposed approach also gives a single sustainability measure suitable for comparison and decision making purposes, as designed-in adaptability is compared against a base case of non-desigend-in adaptability. The study will be of interest to people within the construction industry as well as investors or corporates with social and environmental liabilities. Using this approach, they will be able to figure out whether and to what extent incorporating specific adaptability in any design and construction is viable, from sustainability viewpoint.

The paper firstly presents a literature review on infrastructure adaptability and sustainability and associated valuation approaches. The proposed approach is then introduced, followed by a discussion on commonly used SEC techniques. Finally, the proposed approach on adaptability valuation is demonstrated on an Australian case example (involving seawalls under changing climate effects), with arguments on the sustainability value of the incorporated adaptability. The analysis is done from public and investor viewpoints to reflect different views and show the capability of the proposed approach as well. The paper's methodology, but not necessarily the designs and assumptions used in the case example, can be applied to other situations.

2. Background

With responding to changes imposed on infrstarture, there exist two strategies of mitigation and/or adaptation. With climate change for example, the infrastructure may be designed and constructed in a way to reduce greenhous gas emissions mitigating the climate change and/or in a way to adapt to the impacts of the changing environment (Smit and Pilifosova, 2001). The adaptation strategy is the focus of this paper. Adaptability (the ability to adapt) causes the infrastructure to remain in operation by responding to future changes; thus enhances sustainability (Conrad and Raucher, 2013; Gosling et al., 2013; Scholtes, 2007; Taneja et al. 2012; Wilkinson et al., 2009). Schneider and Till (2005) state that *'sense tells us that adaptability is more beneficial in the long term because obsolescence is limited'* (Schneider and Till, 2005, p.162). The advantage of adaptation and having adaptability in general (versus no adaptability) has already been supported in the literature by quantitative assessments (Gosling et al., 2013; Moffatt and Russel, 2001). However, this should not be confused with the designed-in adaptability in particular (versus non-designed-in adaptability), which may or may not be worthwhile.

2.1 Designed-in Adaptability Valuation

Designed-in adaptability refers to an embedded ability to adapt, where the infrastructure is designed for adaptability to accommodate future changes while knowledge on the changes is unclear at the time of design (Slaughter, 2001; Gosling et al., 2013). Wang and de Neufville (2005) introduce designed-in adaptability as the ability developed by changing the technical design. Engel and Browning (2008) look at designed-in adaptability as the application of options theory in engineering design. Carmichael (2014) also talks of designed-in or deliberate adaptability allowing for future possible changes to infrastructure in response to future uncertain circumstances.

Given that designed-in adaptability provides infrastructure with an option (a right but not an obligation) to adapt to changed circumstances, ROA is required for valuation (Carmichael et al., 2011; Copeland and Antikarov, 2001). ROA based on financial options analysis such as Black-Scholes equations and simulations have been used (Copeland and Antikarov, 2001; Kodukula and Papudesu, 2006). However, such methods are complex and not suitable for valuation of real assets (Howell et al., 2001; Kodukula and Papudesa, 2006; Lewis et al., 2008). As such, there has been a reluctance among practitioners to adopt ROA (Block, 2007; Van Putten and MacMillan, 2004) due to i) inconsistency of the valuation models with Discounted Cash Flow (DCF) analysis which is commonly used in practice (Barton and Lawryshyn, 2011), and ii) lack of understanding of ROA, where incorrectly perceived as a substitute but not a supplement to conventional methods (Block, 2007; Kodukula and Papudesu, 2006). As a result, consistent versions of ROA have been developed using spreadsheet calculations (Carmichael et al., 2011; de Neufville and Scholtes, 2011).

It has been suggested to build ROA on traditional DCF calculations (Barton and Lawryshyn, 2011; Carmichael and Balatbat, 2009; de Neufville et al., 2006; Van Putten and MacMillan, 2004). de Neufville et al. (2006) introduce a computer-based spreadsheet model for estimating real options value using Monte Carlo simulation. However, the model still has shortcomings, namely i) taking into account the downside potential of investment where the option is not exercised (Howell et al., 2001), ii) the need for allocating probability distributions to analysis inputs, and iii) providing little insight into the calculations (Carmichael et al., 2011; Wang and de Neufville, 2005).

Carmichael and Balatbat (2009) suggest utilizing probabilistic DCF analysis with the second order moment approach to estimate real options value. The approach requires characterizing cash flows with their moments and fits a distribution to total present worth for valuation. This method only looks at upside potential of investment and is more appealing to engineers.

Such efforts made to adjust ROA for financial valuation of infrastructre adaptability, but the social and environmental aspects barely noticed. A few studies attempted incoporating social and environmental issues in adaptability valuation, but using inadequate approaches. For example, Fawcett et al. (2014) evaluate costs and environmental impacts of flexible infrastructure, using Monte Carlo simulation with abovementioned limitations, while ignoring the social aspect. Carmichael and Taheriattar (2018) suggest LCA approach combined with ROA to reveal the potential for enhancing financial viability of adaptable infrastructure by inclusion of both social and environmental issues. However, the uncertainty of social and environmental intangibles is not incorporated in Carmichael and Taheriattar (2018), the uncertainty of social and environmental intangibles is not incorporated. Hence, this paper aims to fill the literature gap by presenting an approach that integrates all sustainability aspects and captures the uncertainty to value designed-in adaptability infrastructure. To this end, the existing sustainability assessment techniques are first reviewed to clarify the proposed approach.

2.2 Sustainability Assessment Techniques

With sustainability comprising of financial, social and environmental criteria, a multi-objective situation arises for sustainability assessment. There exist assessment techniques combining social, environmental and financial measures, which vary in ways of dealing with sustainability issues, namely measurables and non-measurables (Dompere, 1995). Measurables can directly be measured and expressed quantitatively, typically using LCA tools (ISO, 2006; Lehmann et al., 2013). The measurables can be expressed using monetary and non-monetary terms e.g. carbon emissions in ton CO2-e. Non-measurables are those with inherent subjectivity, unable to directly be measured in numbers, and typically expressed using linguistic terms e.g. low, moderate, high. A summary of the techniques follows.

Fuzzy-based technique links non-measurables' linguistic expressions to fuzzy set membership (Tan et al., 2011). Fuzzy ratings of sustainability issues can be weighted and summed to create an overall fuzzy rating (Siew et al., 2016). The approach offers advantages in terms of dealing with subjectivity; however, it has issues with regard to the definition of fuzzy ratings and weightings as well as the integration of outcome with measurables.

Multi-Attribute Decision Making (MADM) techniques such as TOPSIS or SAW (see for example, Tzeng and Huang, 2011) combine measurables and non-measurables. In this technique, the alternatives are scored based on pre-defined scales for measured quantities or linguistic expressions; the scores are then normalized and weighted to calculate the alternatives' fitness. Sustainability reporting tools are a particular example of this technique with already normalized and weighted scoring model (Rogmans and Ghunaim, 2016). Such techniques may be criticized because definition of scales, allocation of scores and weightings are subjective and difficult to reach a consensus on.

Social and Environmental Costing (SEC) technique combines sustainability criteria through monetizing social and environmental impacts or liabilities, based on 'polluter pays principle' (de Beer and Friend, 2006; Steen, 2005). The idea of using life-cycle costing in conjunction with LCA previously supported in the literature (Dascalu et al., 2010; de Beer and Friend, 2006; Parker, 2000; Steen, 2005) and followed by a code of practice for environmental life-cycle costing (Swarr et al., 2011). According to EPA (1995), social and environmental issues directly or indirectly incur costs on individuals, organizations and society. SEC attempts to extend market boundaries to non-market objects (Dompere, 1995; Lohmann, 2009; Mirasgedis et al., 2000), such that renews the conventional appraisal by inclusion of social and environmental externalities for correct investment decisions (Dascalu et al., 2010). Some examples include converting emissions or pollution to dollars using carbon credits or pollution rights traded in the market (Godoy and Saes, 2016; Lohmann, 2009). SEC eliminates the need for impact categories and weighting of inventory data (Swarr et al., 2011); however, choice of suitable indexes and monetization methods might be challenging (de Beer and Friend, 2006; Dompere, 1995). The SEC technique is employed in this paper, since it matches ROA with financial basis. SEC has the capability of merging the concepts of sustainability and investment in adaptability by presenting a measure that is to be paid by investors (Dascalu et al., 2010). The single measure is also desirable for comparison and decision-making, which is the purpose of this paper.

2.3 SEC Methods

Social and environmental issues are costed in different ways, categorized based on the 'strategies to deal with sustainability issues', namely prevention, toleration and restoration (Dascalu et al., 2010; Parker, 2000). Such categories are associated with costing only and should not be confused with the 'strategies to deal with changes imposed on infrastructure', namely mitigation and adaptation. The categorization is intended to organize, but not to limit, the possible costing methods. A selective overview of commonly used SEC methods follows.

Prevention Costing Approach

Policy tools – taxes, subsidies, penalties and fees or charges on environmental loadings (Dascalu et al., 2010; Godoy and Saes, 2016; Parker, 2000) e.g. permission fees for waste disposal (Parker, 2000), penalties on excessive wastewater discharges or noise/water pollution offences (de Beer and Friend, 2006). *Insurance value* – premium paid in advance in proportion to potential damages to individuals, materials and biodiversity (de Beer and Friend, 2006; Leopold and Leonard, 1987). *Pollution/hazard control cost* – expenditures on control measures preventing damages due to pollution or safety incidents e.g. building noise barriers or using loading platforms (Wang et al., 2019). *Disturbance prevention value* – reward/penalty assigned to early/late completion of a project (Gilchrist and Allouche, 2005).

Toleration Costing Approach

Health/safety cost – direct costs of using health services i.e. charges for using hospital treatment facilities (Song, 2018).
Loss of productivity/contribution – lost earnings due to disturbance to operation e.g. reduction in machinery's production or loss of human capital i.e. due to health and safety issues or lower worker

employment (Dinwiddy and Teal, 1992; Leopold and Leonard, 1987; Sah and Stiglitz, 1985). *Delay cost* – losses due to people's delays caused by construction works e.g. lost earnings plus cost of extra fuel consumption due to traffic disruption (Gilchrist and Allouche, 2005).

Restoration Costing Approach

Remediation cost – cost of remedial process of unwanted construction by-products i.e. removal and treatment of waste materials or pollutions in the form of air emissions or soil and water contamination (de Beer and Friend, 2006; Parker, 2000). *Replacement cost* – cost of minimizing inconvenience due to construction, through replacing affected facilities with similar alternatives, either temporarily or permanently (Gilchrist and Allouche, 2005).

Suitable methods should be identified for each specific issue and situation. Target community should also be specified for a rational costing of sustainability issues; people may emphasize the issues which are affected by or pay for (Dompere, 1995; Steen, 2005). The outcomes of SEC methods can be used for valuation of adaptable infrastructure using ROA-SEC approach which is proposed in the following.

3. ROA-SEC: A Proposed Approach

3.1 Outline

ROA using probabilistic DCF analysis with second order moment approach is here proposed to be adapted for sustainability assessment. A hybrid approach is suggested such that ROA is integrated with SEC, using LCA outputs. Figure 1 displays the ROA-SEC scope within the whole picture of sustainability assessment approaches reviewed in the literature. The ROA-SEC is used to decide whether to design infrastructure for adaptability or not. To this end, designed-in adaptation (denoted A) is compared with a base case of non-designed-in adaptation (denoted NA):

- A. Where adaptability features are 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 is designed and built without adaptability features in mind, while future adaptation may still be fortuitously possible.

The alternatives are examined over the infrastructure service life. Financial cash flows estimated using conventional methods together with social and environmental costs generate inputs of the ROA-SEC model which follows.

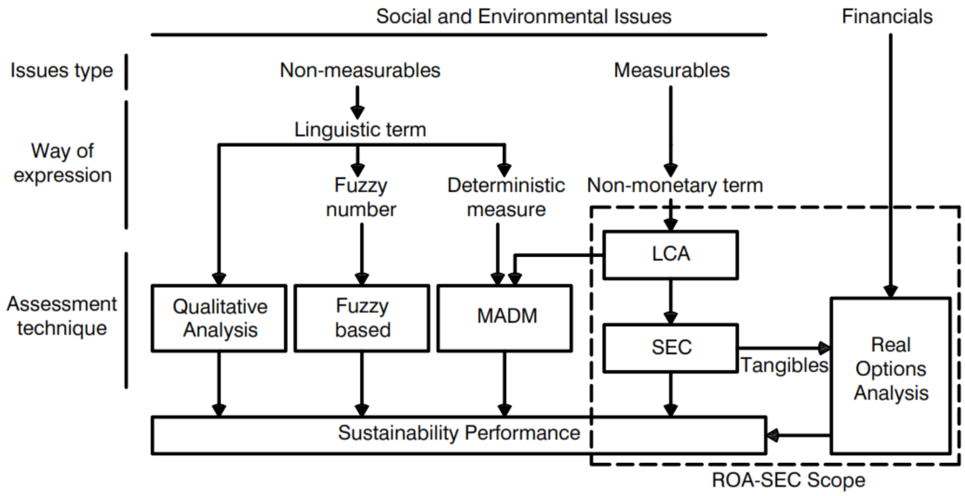

Figure 1 ROA-SEC scope – sustainability valuation of designed-in adaptability

3.2 Formulation

The options analysis follows Carmichael et al. (2011), which is capable of considering all the cash flows over the infrastructure service life. However, only monetary flows at time of adaptation, T, are considered in this paper. The time T is allowed to vary, to show the relationship between time of adapting and adaptability value. Expected values, E[ ], and variances, Var[ ], of all costs for both A and NA at T are estimated. Here, optimistic (a), most likely (b) and pessimistic (c) values are estimated as is done in the planning technique PERT. This leads to: expected value or mean = (a + 4b + c)/6, and variance = $[(c-a)/6]^2$. Because estimates for A and NA are based on similar assumptions, a strong correlation (approximately one) between the estimates would be assumed. For each adaptation form, the monetary flows of social and environmental issues are assumed to be perfectly correlated to financial flows, as they are all proportional to quantity take-offs. Should this not be the case, the formulation can be adjusted.

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

$$X_T = (NA_{T,F} - A_{T,F}) + \sum_i (NA_{T,SE_i} - A_{T,SE_i})$$

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, the expected value E[X_T] and variance Var[X_T] become

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

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

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

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

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

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

Adaptability value = ΦM

where Φ = P[PW] > 0, 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.

This adaptability value is then compared with the total cost of building in adaptability at time 0 (including monetized intangibles). Viability is established for designed-in adaptability when the adaptability value exceeds this initial cost.

3.3 Incorporating Intangibles Uncertainty

Shadow prices and subsequent SEC outputs are highly uncertain (de Beer and Friend, 2006; Mirasgedis et al., 2000, Steen, 2005). The uncertainty of intangibles' costs should be incorporated into the valuation model (Clarkson and Deyes, 2002). Given that sustainability issues may be costed using a single or multiple methods, it is suggested here to deal with the uncertainty using either of the following two propositions.

Prop.1. In case the intangible cost, Y, is estimated using a single method because of limited data availability or general agreement on reliability of the method, the three-point estimates of optimistic (d), most-likely (e) and pessimistic (f) are utilized. As done for financial estimates, the expected value, E[Y], and variance, Var[Y], of intangible cost then become

$$E[Y] = (e + 4d + f)/6$$

$$Var[Y] = [(f - e)/6]^2$$

Prop.2. In case there exist multiple methods for estimation, the uncertainty of the intangible cost associated with method j, y_j, j = 1, 2, …, n, is similarly captured using the three-point estimates, which give the method's expected value, E[y_j], and variance, Var[y_j]. There might be quite large differences between the methods' estimates. Each method is given a normalized weight, w_j, which basically reflects the existing view on reliability of the method. The reliability weight can be specified in different ways. It is here assumed to be inversely proportional to the variance; hence a method with smaller variance in estimates is anticipated to be more reliable (Strutz, 2016; Taylor, 1997). The reliability weights then become

$$w_j = \frac{1/Var[y_j]}{\sum_{j=1}^{n} 1/Var[y_j]}$$

Given that SEC methods are typically different in terms of the logic of monetization, the estimates obtained using various methods are anticipated to be uncorrelated. For this situation, the expected value, E[Y], and variance, Var[Y], of the intangible cost become

$$E[Y] = \sum_{j=1}^{n} w_j \times E[y_j]$$

$$Var[Y] = \sum_{j=1}^{n} w_j^2 \times Var[y_j]$$

The ROA-SEC approach incorporating intangibles uncertainty is demonstrated on a case example in the following.

4. Case Example – Rock Seawalls

Seawalls in Australia are conventionally designed to accommodate water depth at the toe and breaking waves load (NCCOE, 2012). With sea level rise, the idea of designing seawalls for adaptability comes in mind. The case example here involves upgrading a 100-metre long section of rock seawall (A form) with incorporated designed-in adaptability features, namely 1) use of bigger rocks, sufficient for greater wave heights, and 2) parapet wall of bigger foundation, capable of being heightened when sea level rise exceeds the design level. The features allow the A form to be adapted with minor effort; however, the NA form will require placing a layer of bigger rocks and rebuild the parapet wall for adaptation. Figure 2 highlights the rock seawall adaptability and adaptations (bold lines indicate designed-in adaptability features and dashed lines indicate future adaptation measures).

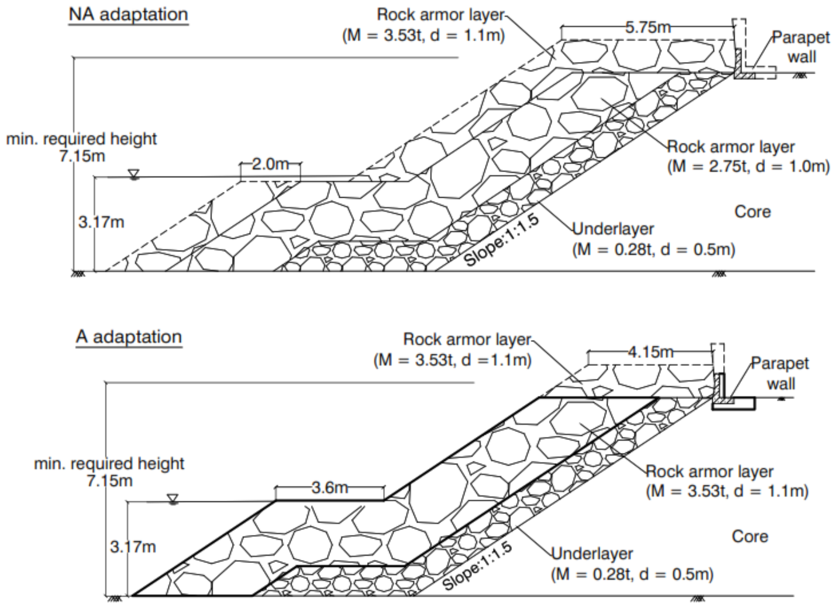

Figure 2 Rock seawall adaptability and adaptations – A vs. NA designs

It is assumed that the two forms of adaptation only differ at time 0 (initial design) and time T (time of adaptation). The different designs lead to differences in quantity take-offs as illustrated in Table 1. The initial cost of incorporating adaptability in design is estimated to be $57.7k (detail of financial cost estimating is omitted here for space reasons). The quantity take-offs are then used to calculate the differences in sustainability issues (A form minus NA form) as given in Table 2.

Table 1 Rock seawall adaptations – differences in quantity take-offs between A and NA forms

Time	A: Designed-in form	NA: Non-designed-in form
k = 0	• Extra mass of bigger rocks = 544 t	
	Parapet wall foundation of bigger size: • Extra amount of concrete = 50 m^3 • Extra amount of reinforcement = 5.9 t	
k = T	• Added rocks = 880 t	• Added rocks = 3296 t
	Parapet wall enlargement: • Concrete = 40 m^3 • Formwork = 200 m^2 • Concrete drilling = 500 no. • Reinforcement = 4.7 t	Parapet wall enlargement: • Concrete = 90 m^3 • Formwork = 300 m^2 • Concrete drilling = 1500 no. • Reinforcement = 10.6 t

Table 2 Summary of differences (A – NA) in environmental and social inventory flows

Sustainability issue	At k = 0	At k = T	Combined, k = 0 and T
Environmental			
Materials consumption (t)	664	-2,536	-1,872
Energy use (GJ)	185.2	-447.5	-262.3
Emissions (ton CO2-e)	20.2	-32.1	-11.9
Solid wastes (t)	29.3	-122.9	-93.6
Water pollution (kg)	35	-160	-125
Social			
Worker employment (h)	213	-855	-642
Safety incidents (number of injuries)	0.0070	-0.0282	-0.0212
Heath damage – noise exposure (h)	626	-12,408	-11,782
Inconvenience – traffic disruption (veh.h)	155	-686	-531

Negative values indicate that the NA form leads to greater sustainability issues compared to the A form

The extra upfront cost and sustainability issues for the A form are traded off against those of the NA form at adaptation time. Further detail on quantification of sustainability issues using LCA is relaxed and only the integration of SEC with ROA is focused here.

4.1 Analysis: Outline

The analysis is done from two different viewpoints: 1) *public viewpoint,* from which monetization of all the issues is attempted, reflecting the public awareness about sustainability (Parker, 2000), and 2) *investor viewpoint,* which only looks at the intangibles that are perceived by the author to be priced in the market within the decision timeframe (Swarr et al., 2011). For example, investors may be under no obligation to pay for not creating jobs or decreasing neighbors' productivity. Also, the environmental issues of materials consumption and energy use are excluded for both viewpoints because of lack of data on associated shadow prices. Note that the paper emphasizes on the methodology; others may look at different intangibles to reflect the investor or public viewpoints, but the method will remain the same. Table 3 illustrates the identified issues, the adopted SEC methods, and the way of incorporating associated uncertainty as discussed earlier in Section 3.3.

Table 3 Case example: sustainability issues and adopted SEC methods

Sustainability issue	SEC methods	Incorporating uncertainty by
Materials consumption	-	-
Energy use	-	-
Emissions*	Carbon tax*, Damage cost	Prop. 2
Solid wastes production*	Waste treatment cost*	Prop. 1
Water pollution	Remediation cost	Prop. 1
Worker employment	Contribution to society, Comfort value	Prop. 2
Safety incidents*	Insurance value*, Loss of contribution*	Prop. 2
Heath damage	Loss of productivity	Prop. 1
Inconvenience*	Delay cost, Replacement cost*	Prop. 2

Investor viewpoint analysis only looks at *

4.2 Shadow Price Estimates

Unit price of the sustainability issues is given here, considering likely changes. However, it is unclear as to how the price of some issues such as waste production, water pollution or inconvenience will change. Present-time estimate is used for such issues, assuming no significant change over the time.

Emissions

Carbon tax. Carbon tax scheme in Australia was in action with a fixed rate of about $25 per ton of carbon (Australian Government, 2011). Although it was repealed in 2014, it is likely to be re-established (Steen, 2005). The unit cost is estimated to reach $150-$500 by 2050, averaged at $260 per ton of carbon (Ackerman and Stanton, 2012).

Damage cost. The economic impacts and social damage costs are predicted to be enormous even with rapid reduction in emissions, ranging between $50 and $1500 (Ackerman and Stanton, 2012), with an average of $530 per ton of carbon in 2050 (Clarkson and Deyes, 2002).

Solid Waste Production

Waste treatment cost. A landfill gate fee of $120-180/ton of waste is charged in Sydney, which is significantly higher than waste recycling or reuse fee; hence people would not choose disposal (Hyder Consulting, 2011). The fee charged for reprocessing of concrete waste is $0-11/ton (Hyder Consulting, 2011). Steel and rock wastes are typically reused, in landscaping for example, with no salvage value. However, cost of collection and transport (approximated to be $50±20/ton) is included in reuse and recycling fees.

Water pollution

Remediation cost. Sediments remediation can be done by dredging, capping or in-place treatment. The former is commonly used for sediments of low chemical concentrations (Rosengard et al., 2010). The unit cost of hydraulic dredging and landfill disposal is approximately $220/$m^3$ of sediment (Mohan et al., 2011). This may however range between $15 and $3300 per m^3 of sediment depending on the type of particles and dredging process (Rosengard et al., 2010).

Worker employment

Contribution to society. The value of employment can be characterized by worker's contribution to economy less cost of employment creation (Dinwiddy and Teal, 1992; Sah and Stiglitz, 1985). Worker's contribution is estimated to be $75 per hour worked (Pye, 2012), with projected growth rate of 1.5±0.1% per annum (Commonwealth of Australia, 2015). Employment cost equals worker's earnings that is about $40 per hour plus an extra 40% to account for superannuation, employer taxes and workers' compensation (ABS, 2019). The earnings are projected to grow at an annual rate of 1.4±0.1% (Commonwealth of Australia, 2015).

Comfort value. The employment value can be seen as the money which maintains people's welfare at level they would enjoy without job; this equals minimum wage they would accept minus unemployment compensation (Londero and Cervini, 2003). Minimum wage is assumed to be 56% of average earnings estimated earlier (Commonwealth of Australia, 2014). So-called 'Newstart Allowance' paid to an unemployed person is $6.5 per equivalent hour worked (Department of Human Services, 2019). The government's spending on the allowance is projected to decline, reaching $5.5±0.5/h in 2050 (Commonwealth of Australia, 2015).

Safety incidents

Insurance value. Social liabilities for safety incidents can be costed using insurance premium paid for employed workers (de Beer and Friend, 2006; Leopold and Leonard, 1987). The insurance premium is estimated to be 3.1% of wages – the wage rate of $40/h for construction workers gives a premium of $1.25/h (ABS, 2019), which is assumed to grow at an annual rate of 1.4±0.1% (Commonwealth of Australia, 2015).
Loss of contribution. Social damages due to injury can be costed using the lost earnings plus the uninsured costs of treatment. Assuming 33 injuries per million working hours and average recovery time of 34 h per work-related injury (Safe Work Australia, 2012), gives 0.11% loss of working hours due to injury. Average earnings of $40/h (ABS, 2019) leads to lost earnings of $0.05/h. Uninsured cost of treatment is assumed to be a fifth of insurance value estimated above (Leopold and Leonard, 1987), giving $0.25/h. These lead to a total unit cost of $0.3/h for safety incidents, which is assumed to follow wages growth at an annual rate of 1.4±0.1%.

Health

Loss of productivity. Depending on people's sensitivity to noise and type of task they do, the reduction in productivity may be between 1.5% and 40% for noise levels just above 80 dB (Safe Work Australia, 2010). Average earnings of $30/h leads to lost earnings of $0.5-12.0 per exposure hour due to reduced productivity. This is also assumed to follow wages growth rate.

Inconvenience

Delay cost. Inconvenience of traffic disruption to commuting people can be costed using lost earnings due to delay (Gilchrist and Allouche, 2005). As given above, average earnings of $30/h is assumed, with an annual growth rate of 1.4±0.1%.
Replacement cost. The inconvenience can also be monetized using the cost of making a detour, as a replacement for blocked access road (Gilchrist and Allouche, 2005). This comprises the rental cost of traffic signs, $4-8 per day, and traffic barriers, $20-40 per day (quoted from Coateshire). Thus, the replacement cost would range between $24 and $48 per day.

Table 4 summarizes the estimates of unit prices and reliability weights for all the intangibles. The lower reliability weights indicate larger variances in the estimates of the associated SEC method. Apparently, these methods have lower influence on the costing outputs.

Table 4 Case example: unit price estimates and reliability weights

Sustainability issue	**SEC methods**	**Units price**			**Reliability weight**
		o	**m**	**p**	
Emissions* ($/ton CO2-e)	Carbon tax*	150	260	500	0.94
	Damage cost	50	530	1500	0.06
Solid wastes production* ($/t)	Waste treatment cost*				
Rocks	*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
Heath (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

Investor viewpoint analysis only looks at *
o: optimistic / m: most-likely / p: pessimistic

4.3 Results and Discussion

Having the differences in social and environmental inventory flows and using the shadow price estimates, the monetary flows can be calculated. Table 5 illustrates the differences in the monetary flows associated with sustainability issues between the A and NA forms, at times 0 and T. Since there is no uncertainty associated with present-time estimating, the deterministic dollar values (with no variances) are given at time 0. While, probabilistic estimates (with expected values, E[ ], and variances, Var[ ]) are made for future time T. Also, the worker employment benefits are illustrated using negative values, since the positive values represent the sustainability issues/costs.

Table 5 Case example: differences in monetary flows between A and NA forms, at times 0 and T

Sustainability issue and SEC method	At k = 0		At k = T					
	A-NA		A			NA		
	Quantity	$ value	Quantity	$ value		Quantity	$ value	
				E[ ]	Var[ ]		E[ ]	Var[ ]
Emissions (t CO2-e)								
*Carbon tax**	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 wastes production (t)								
*Rocks (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	32	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
Worker 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
Heath (noise exposure, 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	228	13	468	2.7e3	44	1,584	9.0e4

Investor viewpoint analysis only looks at *

Having the moments and reliability weights associated with different SEC methods, the resultant moments are obtained for each intangible using the formulation given in Section 3.3. Table 6 summarizes the expected values and variances of intangibles' costs, estimated from public and investor viewpoints. From the public viewpoint, health, emissions and worker employment with the largest expected values and variances have the greatest effect on the analysis outputs. The health and emissions issues work in favor of the A form, while the worker employment (with negative expected value) is reversing the decision in favor of the NA form. However, the large variance for worker employment still works in favor of the A form, since it leads to a larger variance of the total present worth. From investor viewpoint, emissions with the largest expected value and variance have the most significant impact on the outcomes.

Table 6 Case example: moments of intangibles' costs for A and NA forms at k = T, from public and investor 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 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

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

$$E[NA_{T,SE}] = \$169.6k,\ Var[NA_T] = (\$65.5k)^2$$
$$E[A_{T,SE}] = \$52.5k,\ Var[A_T] = (\$18.8k)^2$$

And investor viewpoint gives the following:

$$E[NA_{T,SE}] = \$25.1k,\ Var[NA_T] = (\$5.9k)^2$$
$$E[A_{T,SE}] = \$8.4k,\ Var[A_T] = (\$1.5k)^2$$

Estimates of financial cash flows give the following moments:

$$E[NA_{T,F}] = \$297.9k,\ Var[NA_{T,F}] = (\$24.8k)^2$$
$$E[A_{T,F}] = \$102.8k,\ Var[A_{T,F}] = (\$8.6k)^2$$

Combining the moments of social, environmental and 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 adaptability value. Figures 3 and 4 show the change in adaptability value with r and T, and compare the results of only-financial analysis with those of sustainability analyses from public and investor (or council) viewpoints. The initial cost of building in adaptability is estimated to be $57.7k; inclusion of monetized social/environmental issues slightly increases this figure to $60.0k for both sustainability analyses.

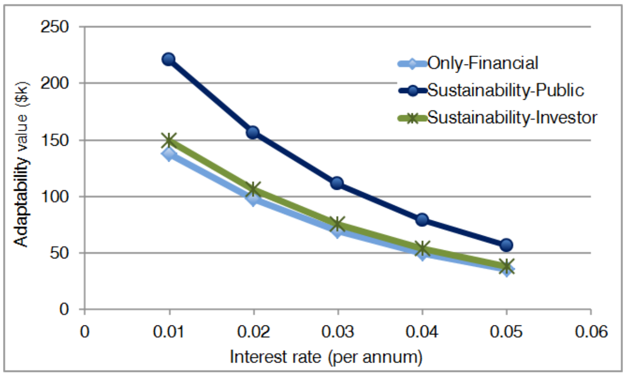

Figure 3 Case example – change in adaptability value with interest rate, T = 35 years

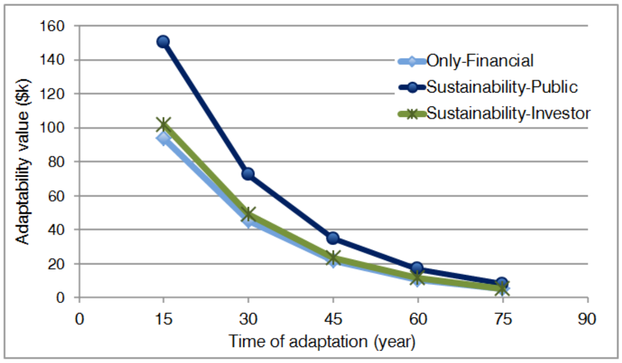

Figure 4 Case example – change in adaptability value with time of adaptation T, r = 5% p.a.

It is seen, from both viewpoints, that building in adaptability is more viable for lower r and lower T. Compared to only-financial analysis, the sustainability analysis from public viewpoint significantly improves the viability of seawalls adaptability. The improvement is manifested in maintaining viability for longer adaptation times (changed from just below 30 years to above 35 years) or greater interest rates (changed from 3.5% p.a. to 5% p.a.). This is mainly due to incorporating health, emissions, and worker employment issues in the analysis. However from investor viewpoint, neither the initial cost nor the adaptability value changes considerably by inclusion of social and environmental costs. Hence, there is not much potential for encouraging the councils in investing in seawalls adaptability; even though, such potential may be developed in future should pricing regulations be set in the market for intangibles such as worker employment, health issues and inconvenience due to traffic disruption.

The analysis attempted to capture the increasing sustainability imperatives and uncertainties over the time; however, the future changes in unit price of some sustainability issues such as waste production or water pollution were unclear and excluded. Much larger uncertainties could be assumed leading to greater adaptability values. Also, inclusion of environmental costs associated with resource depletion, namely materials consumption and energy use, could further improve the viability of the specific designed-in adaptability in the case example. Including such sustainability intangibles in the analysis requires developing monetization methods. Future studies can be targeted towards addressing the above issues.

5. Conclusion

The paper presented an approach for incorporating sustainability in ROA to value designed-in adaptability of infrastructure. This was realized by integration of social and environmental costing with an options analysis that is suitable for engineering applications. The paper suggested looking at sustainability from public and investor viewpoints to examine the potential for encouraging investment in adaptability. The method was demonstrated on a seawall case example under changing climate effects. It was shown, for the assumptions considered, that inclusion of sustainability issues improves the viability of designing in adaptability. However, no general conclusion can be drawn on the viability of designed-in adaptable infrastructure, and each situation requires an individual analysis. Designing in adaptability will be more sustainable in some situations, but not necessarily in all situations. The methodology will be the same for all situations, but the assumptions about design and estimation may change.

ROA used in the literature for financial valuation of investing in adaptable infrastructure; social and environmental aspects not addressed unless using inadequate methods. The paper advances current literature by incorporating sustainability into ROA; this specifies whether and to what extent inclusion of sustainability issues may improve the viability of designed-in adaptability.

The paper's valuation approach resulting in a quantitative measure for sustainability of adaptable infrastructure is original. The outcomes will be useful to construction industry practitioners, investors and corporates with social or environmental liabilities, contemplating measuring sustainability for decision making on building in adaptability.

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