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Life-cycle Cost Analysis of Deteriorating Civil Infrastructures Incorporating Social Sustainability

Abstract

As one of the three pillars of sustainability, social sustainability has rarely been considered in the design and decision-making process of civil infrastructures. This paper applies social costs in structural design, assessment, and management process to represent the social dimensions of structural sustainability. The social impacts of civil infrastructures are classified into two categories: personal-level impacts, including physical conditions, psychological conditions and personal economic conditions; and social-level impacts, comprising human settlements, social-economic development and social resources. The social impacts are transferred into social costs in this paper, and detailed computational equations are presented with an emphasis on civil infrastructures. A deteriorating bridge is used to illustrate the calculation of various components of social costs, and a social-cost incorporated life-cycle cost analysis (LCCA) is performed based on the proposed deterioration model, maintenance plans and accident information.

Keywords: Social impacts; Social costs; Civil infrastructures; Life-cycle cost analysis; Bridges; Sustainability.

1. Introduction

The sustainability development of civil infrastructures depends on the environmental, economic and social performances, which are known as the three pillars of sustainability[1]. Studies have been widely carried out on the environmental and economic dimensions of engineering structures, while the evolution of social sustainability assessment has been relatively hysteretic[2]. The deterioration and improper design of structures and infrastructures can cast vast negative impacts on human society, such as fatalities and injuries, pain and suffering, property damage and social-economic losses, among others. Numerous structural accidents that caused tremendous social consequences have been witnessed around the world in history, such as the failure of the poorly maintained Val di Stave Dam in 1985 of Italy that killed 268 people, destroyed 63 buildings and demolished 8 bridges[3]; the collapse of Hotel New World of Singapore[4] in 1986 owing to serious design errors that caused the death of 33 people; and the structural failure of Sampoong Department Store[5] of South Korea in 1995 resulted from substandard materials and improper design that led to 502 deaths, 937 injuries and approximately 216 million US$ of property damage. Civil infrastructures play a vital role in public daily lives and in social development by providing various structural functions. And it is precisely because of this vital position, the failure of structures and infrastructures can have enormous adverse impacts on the society.

Despite the potentially huge social impacts of civil infrastructure projects, efforts have been mainly paid on the determination of social impact assessment (SIA) framework and indicators [6][7][8][9], while social sustainability and social impacts have rarely been involved in practical design and decision-making process of structures. Social impact generally includes all the social and cultural consequences to human populations of any public or private actions that alter the ways in which people live, work, play, relate to one another, organize to meet their needs, and generally cope as members of society[10]. In simple terms, social impacts are the changes to the society resulted from policies, incidents and other social changes. And the social sustainability of civil infrastructures is to reduce the harmful social impacts of engineering activities and construction works through proper life-cycle design and management of structures, so as to improve the quality of human life, to seek fair distributions of social resources within the society, and to ensure intergenerational equity[6]. Some representative social impact categories are presented in Table 1.

Table 1. Social impact categories in existing body of knowledge

Authors	Social impact categories
Taylor et al., 1990[11]	Lifestyles; Attitudes; Beliefs and values; Social organization.
Juslèn, 1995[12]	'Standard' social impacts (noise, pollution, et al.); Psychosocial impacts; Anticipatory fear; Impacts of carrying out the assessment; Impacts on state and private services; impacts on mobility.
Interorganizational Committee on Guidelines and Principles, 1995[13]	Population characteristics; Community and institutional structures; Political and social resources; Individual and family changes; Community resources.
Vanclay, 2002[14]	People's way of life; Culture; Community; Political system; Environment; Health and well-being; Personal and property rights; Fears and aspirations.
Lockie et al., 2008[15]	Health and social well-being; Liveability; Economic impacts and material well-being; Cultural impacts; Family and Community Impacts; Institutional, legal, political and equity impacts; Gender relations.

To merge social impacts that have different sources, forms and consequences, and to consider the overall social sustainability of infrastructures, monetary evaluation can be applied to generate the social costs related to various social impacts. Social costs of engineering structures are the external costs produced by engineering activities that are undertaken by the public rather than by the project participants[16], which represent the overall impact on the social welfare of engineering activities such as construction, maintenance, repair and rehabilitations[17][18][19]. Social costs of transport sector[20], construction accidents[21], road crashes[22] and construction projects[23][24][25] have been studied in previous studies, as summarized in Table 2. Although social cost is rarely used in the bidding or budget estimate of construction projects, it is usually considered as a part of the indirect cost within the life-cycle cost (LCC) model[26]. Including social costs into the classical LCC model can facilitate more comprehensive life-cycle cost analysis (LCCA) or cost-benefit analysis (CBA) of structures. However, in practical application, the most frequently-used social costs of engineering structures were limited to time loss, fatality, vehicle operating costs and traffic crash costs [27][28][29], which are far from complete.

The main novelty of this paper is the classification and quantification of life-cycle social costs related to the deterioration and maintenance of civil infrastructures, and the application of social cost-incorporated LCCA. The social impacts are classified into personal-level and social-level categories, and the computational formulae for associated social costs are proposed. The social costs are incorporated into the LCCA of a deteriorating bridge as an illustrative example, so as to determine the maintenance plan that have better economic efficiency and social sustainability.

Table 2. Social cost categories in existing body of knowledge

Sources	Objectives	Social cost categories
Maibach et al.[20]	Transport sector	Congestion and scarcity costs; accident costs; air pollution costs; noise costs; costs of climate change; other external costs.
Tang et al.[21]	Construction accidents	Day losses of victims; permanent disability costs; fatality costs; loss from injured worker; hospitalization and medical expenses; solicitor fees; equipment or plant loss; damaged material or finished work; idle machinery/equipment; loss of victim's relatives.
Wijnen et al. [22]	Road crashes	Medical costs; production loss; human costs; property damage; administrative costs.
Çelik et al. [23]; Gilchrist et al.[24]	Construction projects	Loss of parking space; additional fuel consumption; travel delay; increased traffic accident rate; accelerated deterioration of roads; road rage; loss of income; productivity reduction; loss of tax revenues; property damage; treating compromised physical/mental health; reduced quality of life; restoration cost.
Matthews et al. [25]	Utility construction projects	Traffic delays; vehicle operating costs; pedestrian delays; parking losses; noise pollution; dirt pollution; air pollution; pavement restoration costs.

2. Social Impact Categories and Social Costs of Infrastructures

The life-cycle social impacts of civil infrastructures are divided into personal-level and social-level impacts, as shown in Figure 1. The personal-level impacts are associated with the losses of individuals that can be quantified by per capita parameters, such as average personal wage, GDP per capita and implied cost of averting a fatality (ICAF). While social-level impacts are related to larger groups such as communities, administrative districts, nations and even national alliances. These kinds of social losses should be determined by macroeconomic information. Hence, the personal-level impacts herein include the physical, psychological and personal economic conditions of the people affected, such as constructors and users of infrastructures; and the social-level impacts consist of the changes of human settlements, social-economic conditions and social resources. The social impacts and associated social costs will be discussed in detail in following sections.

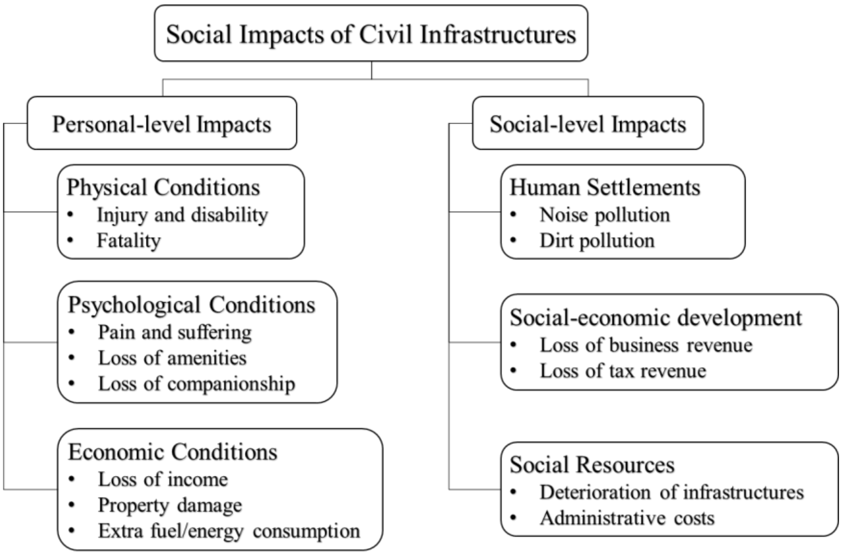

Figure 1. Social impacts related to civil infrastructures

2.1 Personal-level Impacts

2.1.1 Physical Conditions

Physical impacts refer to the negative effects of engineering activities on the physical health and well-being of people, which can be quantified by the social costs of injuries/disabilities and fatalities. The medical expenses for injuries are usually counted as financial costs [21], while the losses of working ability and efficiency due to injury and disability are social losses. The social costs of injury and disability can be computed by Equation (1) [21].

$$SC_{da} = 365 \cdot c_v \cdot (T_{retire} - T_{injured}) \cdot p_{da} \tag{1}$$

where c_v is the daily wage of the injured person (US$/day); T_{retire} is the retire age; $T_{injured}$ is the injury age; and p_{da} is the doctor certified percentage of disability (%).

The social costs of fatal cases are related to the death toll and the economic value of human lives. There are various methods to estimate the economic value of human lives, such as the forgone earnings due to death[21][30], the value of a statistical life (VOSL, the money people willing to pay for risk reduction)[22], the implied cost of averting a fatality (ICAF, the money society willing to pay for saving lives based on its ethical principles and economic capabilities) [31], among others. However, these values are merely used for economic evaluations, and do not represent the true value of human lives, as the true value of human lives is infinite and beyond measure, irrespective of age, sex, race and social position, etc. [31] To avoid ethical controversy, the term 'cost to save lives' is usually preferred over 'economic value of human lives'. Hence, ICAF is used herein to estimate the social costs derived from fatalities, as Equation (2) shows.

$$SC_{ft} = FT \cdot ICAF \tag{2}$$

where FT represents fatalities. The ICAF(US$ per fatality) of several countries investigated by Rackwitz[31] are presented in Table 3.

Table 3. ICAF of several countries [31]

Country	ICFA (US$, 2016)*
USA	3.24×10^6
Germany	2.82×10^6
France	2.68×10^6
UK	2.26×10^6
China	3.67×10^5

*The currencies are converted to US$ 2016 using GDP deflators.[32]

The social costs of overall physical impacts SC_{PHY} can be expressed as:

$$SC_{PHY} = SC_{da} + SC_{ft} \tag{3}$$

2.1.2 Psychological Conditions

Structural failure and accidents of civil infrastructures can have significant impacts on the psychological conditions of related populations. This kind of losses are usually beyond the coverage of personal insurance, and were mostly neglected in previous studies. The risk-value method is used in several studies[20][33] to estimate the social costs of pain, grief and suffering caused by accidents, where the risk-values for fatalities, severe injuries and slight injuries are recommended to be 100%, 13% and 1% of VOSL, respectively. Hence, the social costs of psychological impacts can be computed by Equation (4) [33].

$$SC_{PSY} = (FT + 0.13 \cdot N_{severe} + 0.01 \cdot N_{slight}) \cdot VOSL \tag{4}$$

where N_{severe} is the number of severe injuries; N_{slight} is the number of slight injuries; and $VOSL$ is the value of statistical life of a country(US$), as presented in Table 4[22][33][34].

Table 4. VOSL of several countries

Country	VOSL (US$, 2016)*
USA[22]	8.48×10^6
Germany[33]	3.02×10^6
France[33]	2.83×10^6
UK[33]	2.96×10^6
China[34]	2.46×10^5

*The currencies are converted to US$ 2016 using GDP deflators.[32]

2.1.3 Economic Conditions

Personal economic conditions are also under the effects of the life-cycle performance and engineering activities of civil infrastructures. The maintenance, repair and failure of infrastructures can induce function loss and reduced serviceability, and the associated social costs in terms of personal economic losses herein include the loss of income, property damage and extra fuel/energy consumption.

2.1.3.1 *Loss of income*

Structure users' income loss is usually caused by time loss or travel delay resulted from structural maintenance and repair, which can be calculated by:

$$SC_{il1} = \Delta T \cdot c_w \tag{5}$$

where ΔT is the time loss due to engineering activities like maintenance and repair (h); and c_w is the hourly wage of infrastructure users (US$/h).

While for injury cases resulted from construction accidents or road accidents, the income loss of victims and relatives is related to the recovery time, as presented in Equation (6) [21].

$$SC_{il2} = (c_v + c_{re}) \cdot d_l \tag{6}$$

where c_{re} is the daily wage of the relatives of victims (US$/day); and d_l is the day loss (recovery time) due to injury (days).

The co-workers' loss of income is also considered herein when they take time to deal with accidents, as shown in Equation (7) [21].

$$SC_{il3} = c_{co} \cdot t_l \tag{7}$$

where c_{co} is the hourly wage of the co-workers of victims (US$/h); and t_l is the time loss of co-workers in dealing with the accidents and assisting the injured persons (h).

The overall loss of income SC_{il} related to deteriorating infrastructures can be computed as

$$SC_{il} = SC_{il1} + SC_{il2} + SC_{il3} \tag{8}$$

2.1.3.2 *Property damages*

The property damages are mainly induced by deteriorating structural conditions, construction accidents and road accidents. For instance, the property damages associated with poor road surface condition include the depreciation of vehicles [20] and the damages to fragile cargos; while accident-related property damages include the damage to equipment, materials, finished works [21], and vehicles

[22], among others. The social costs of these damages can be estimated based on the costs of restoration or replacement [24], as shown in Equation (9).

$$SC_{pd} = \sum C_R \tag{9}$$

where and C_R is the replacement/restoration cost of damaged property (US$).

2.1.3.3 *Extra fuel/energy consumption*

The extra fuel/energy consumption related to deteriorating civil infrastructures, especially transport infrastructures, are usually resulted from detour, frequent stops and speed changes. The social costs of detour can be computed by Equation (10) [59][35].

$$SC_{fc1} = \left[c_{r,car} \left(1 - \frac{TT_p}{100} \right) + c_{r,truck} \frac{TT_p}{100} \right] D_l A d_t \tag{10}$$

where $c_{r,car}$ and $c_{r,truck}$ are the operation cost of cars and trucks, respectively (US$/km); TT_p is the percentage of trucks in average daily traffic (%); D_l is the detour length (km); A is the average daily traffic (ADT); and d_t is the duration of the engineering activities that lead to the detour (days).

With respect to frequent stops and speed changes, Zaniewski et al.[36] set up the fuel consumption models for constant speeds, accelerations and decelerations of various types of vehicles. In general, the social costs of frequent speed changes can be expressed by Equation (11).

$$SC_{fc2} = V_F C_F \tag{11}$$

where V_F is the extra fuel consumption due to speed changes and frequent stops (liters); and C_F is the unit cost of fuel (US$/liter).

The total social costs related to extra fuel/energy consumption SC_{fc} can be calculated as

$$SC_{fc} = SC_{fc1} + SC_{fc2} \tag{12}$$

, and the social costs in terms of overall personal economic losses SC_{PE} is:

$$SC_{PE} = SC_{il} + SC_{pd} + SC_{fc} \tag{13}$$

2.2 Social-level Impacts

2.2.1 Human Settlements

Whether a community is suitable for living largely depends on its human settlement environment. The most obvious impacts of engineering activities on human settlements are the noise and dirt pollution. Noise pollution is usually associated with the operation of construction equipment and the alteration of traffic flows. It casts negative impacts on people's physical and mental health, disturbs people's work and sleep, and reduces the value of the houses exposed to noises. The social cost of noise pollution herein is determined based on the depreciation of housing values, as shown in Equation (14) [25].

$$SC_{np} = (N_C - N_N) \cdot NDI \cdot APV \cdot N_H \tag{14}$$

where N_C and N_N are the noise levels with and without construction activities, respectively (dB); NDI is the noise depreciation index of housing value; APV is the average property value of the investigated area (US$); and N_H is the number of houses affected by noises.

Earthwork-related engineering structures can cause dirt and dust pollutions, resulting in extra cleaning fees and reduced quality of life. The social cost of dust pollution can be calculated by Equation (15) [25] considering additional cleaning fees.

$$SC_{dp} = t_{clean} c_{clean} (d_t/7) \tag{15}$$

where t_{clean} is the additional cleaning time per week to control dirt pollution (h/week); and c_{clean} is the hourly wage for cleaning (US$/h).

The overall social cost for human settlements SC_{HS} can be expressed by Equation (16).

$$SC_{HS} = SC_{np} + SC_{dp} \tag{16}$$

2.2.2 Social-economic Development

Infrastructures are the fundamental facilities and systems that are necessary for a society's economy to function, hence the deterioration and failure of civil infrastructures will hinder the economic development of affected areas. The associated social-economic impacts include loss of business revenue and tax revenue [23][24]. Customers usually prefer commercial areas that are not affected by construction works. Hence, the businesses of restaurants, shopping malls, entertainment venues and gas stations are most likely to be affected by engineering activities, as well as those requiring just-in-time deliveries. The computational method of the loss of business revenue proposed by Matthews et al. [25] is presented as $SC_{br} = \alpha R_m D_m$

(17)

where α is the business impact factor; D_m is the duration of engineering activities in month (month); and R_m is the monthly business revenue (US$/month).

Due to the decrease of personal income and business revenue, government is also faced with loss of tax revenue. Flat tax rates are used here to simplify the computation of tax revenue losses, as indicated in Equation (18).

$$SC_{tx} = r_{tp} SC_{il} + r_{tb} SC_{br} \tag{18}$$

where r_{tp} is the tax rate of personal income; and r_{tb} is the tax rate for business revenue.

The overall social costs concerning social-economic development SC_{SE} can be expressed as:

$$SC_{SE} = SC_{br} + SC_{tx} \tag{19}$$

2.2.3 Social Resources

Social resources[37][38] are the facilities and services provided by the society that can be accessed and used in social actions to satisfy people's various social needs, and to maintain and improve people's chances of survival as they interact with the external environment. The reduced value of deteriorating civil infrastructure is one type of social resource losses, and the associated social costs can be determined based on the initial construction cost and the time-variant reliability level of infrastructures:

$$SC_{dt} = C_0 \frac{\beta_0 - \beta_t}{\beta_0} \tag{20}$$

where C_0 is the initial construction cost of infrastructures (US$); β_t is reliability index at time t; and β_0 is the initial reliability index.

Administrative costs herein refer to the costs of the general services provided by administrative departments (e.g., police forces, fire services, the courts and insurance departments) [21][22] and other social organizations (e.g., traffic departments and construction departments) [21]. Administrative costs are especially outstanding in construction accidents, road accidents and structure failure incidents. Tang et al.[39][40] indicated that the average administrative cost of construction accidents in Hong Kong is around 5% of the total social costs. The administrative costs of road crashes are estimated to be around 3%-8% of total crash costs in developing countries during 1998 to 2000[41]. Ismail et al.[42] estimated that the average administrative costs of fatal accident, serious accident, slight accident and property-damage-only accident are 0.2%, 4%, 14%, and 10% of total resources costs (including lost productivity, medical treatment costs and property damage costs), respectively[42]. Based on the abovementioned estimations and experiences, the administrative costs herein are considered 5% of the total social costs related to accidents, which can be calculated by Equation (21).

$$SC_{ad} = 0.05\,(SC_{PHY} + SC_{PSY} + SC_{il2} + SC_{il3} + SC_{pd}) \tag{21}$$

The social costs induced by loss of social resources can be expressed as:

$$SC_{SR} = SC_{dt} + SC_{ad} \tag{22}$$

The life-cycle total social cost C_S of deteriorating civil infrastructures is the sum of the abovementioned cost components, as shown in Equation (23).

$$C_S = SC_{PHY} + SC_{PSY} + SC_{PE} + SC_{HS} + SC_{SE} + SC_{SR} \tag{23}$$

3. Social Cost-included Life-cycle Cost Model

Life-cycle cost (LCC) of engineering structures is the sum of all costs incurred within the structural lifespan, including the costs of design, construction, inspection, maintenance, repair and failure, as shown in Equation (24)[43].

$$LCC = C_T + C_{PM} + C_{INS} + C_{REP} + C_F + C_D \tag{24}$$

where C_T is the initial cost, including the cost of design and construction; C_{PM} is the cost of routine preventive maintenance; C_{INS} is the expected cost of inspections; C_{REP} is the cost of repair; C_F is the failure cost; and C_D is the demolition cost. The cost of design and construction are usually referred as initial costs, and the rest as future costs [43]. Studies[44] concluded that although design stage accounts for only 5%~7% of the total LCC, the decisions made at this stage can determine the allocation of 70%~80% of the construction cost and future costs. In other words, initial structural designs and plans can significantly affect the future costs.

The LCC can also be divided into direct costs and indirect costs. Direct costs are the costs of materials, transportation, labors and equipment that are directly undertaken by project participants. While indirect costs encompass the economic losses induced by adverse environmental and social impacts[26], i.e. environmental costs and social costs. Indirect costs are born by parties excluding project participants, such as structure users, the public and the society. This paper places major attention on the life-cycle social costs of bridge structures, and the indirect costs associate with harmful environmental impacts are not considered herein. The LCC of bridge structure can be written as the summation of direct costs and social costs as Equation (25) presents.

$$LCC = C_{DIR} + C_S \tag{25}$$

where C_{DIR} is the direct costs; and C_S is the social costs.

The social cost-included LCC model in Equation (25) will be used in the LCCA to evaluate the life-cycle economic and social performance of a deteriorating bridge structure. The baseline to determine social impacts is defined as the undamaged state of the bridge herein, and the social impacts are generated because of the change from undamaged state to deteriorated state. Specifically, the maintenance activities and probable accidents due to bridge deterioration are considered as the incentives of social costs. Detailed LCCA is performed in the following sections.

4. Case Study: Life-cycle Cost Analysis Incorporating Social Costs

4.1 Basic Information and Assumptions

To perform social cost-included LCCA, a reinforced concrete highway bridge that connects Island J with the mainland is taken as an example, as shown in Figure 2. The bridge length is L = 2000m, and width is W = 24m. The designed service life is T = 75 years. The bridge supports a four-lane highway with a designed speed of 80km/h. The thickness of bridge deck is 200mm. Three layers of reinforcement meshes with a mutual distance of 50mm are embedded 50mm deep in the deck. The layout of bridge superstructure is depicted in Figure 3. A conservative estimation of the construction cost of bridge deck is C_0=33,411,640 US$, i.e. around 696US$/m^2 [45] (including 12000m^3 of concrete, 4310t of steel reinforcements and corrosion preventive coating; in 2016 US$). Initial reliability index of bridge deck is $\beta_0 = 4.2$, and target reliability index is $\beta_{target} = 3.7$[46].

Figure 2. Highway bridge for case study

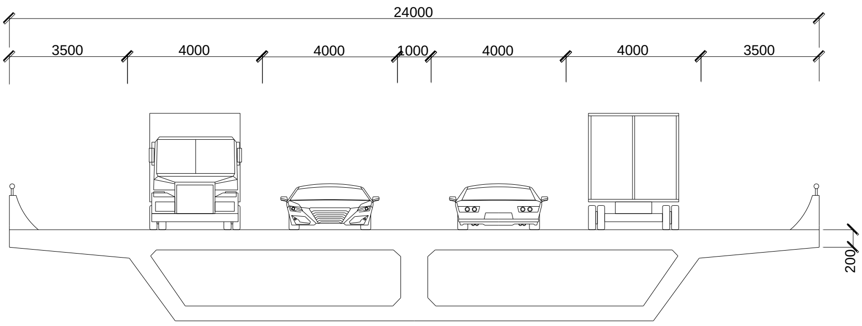

Figure 3. Layout of bridge superstructure

4.2 Deterioration Model and Maintenance Plans

The reinforced concrete bridge deck is under the corrosion effect of marine atmosphere and deicing salt. Water repellent surface impregnation with silane (WRSIS) is applied to concrete surface as corrosion preventive coating. Based on the service life prediction approach used by Wang et al.[47], the bridge deck built with C30 concrete and WRSIS coating, with surface chloride concentration of 2.14%, critical chloride concentration of 0.20% and a chloride diffusion coefficient of 2.0×10^{-6} mm^2/s will go through top mesh corrosion at the 17th year and surface cracking at the 22th year. Based on Jin et al.[48] and Vidal et al.[49], the middle reinforcement mesh is estimated to start corrosion at the 28th year.

The corrosion of middle reinforcement mesh implies that the entire deck has been contaminated by chloride ions, and all the reinforcements within the deck have been corroded. It also signifies the replacement of entire bridge deck[50]. Hence, the deck reliability is assumed to reach the target level when middle mesh corrosion happens.

The reliability degradation process of the bridge deck is simplified to a hypothetic four-stage polyline, including protection stage, propagation stage, corrosion and cracking stage and deterioration stage, as shown in Figure 4. The bridge deck is protected by WRSIS coating in the first 10 years, where $\beta = \beta_0$. Chloride ions accumulate within the concrete and result in top mesh corrosion in the next 7 years, where $\alpha_1 = 0.01$ and $\triangle\beta_1 = 0.07$. The bridge deck experiences cracking and more aggressive corrosion during the 17th-22nd year, where $\alpha_2 = 0.038$ and $\triangle\beta_2 = 0.19$. When the middle mesh starts to corrode at the 28th year, the reliability index is assumed to reach the target level, where $\alpha_3 = 0.04$ and $\triangle\beta_3 = 0.24$.

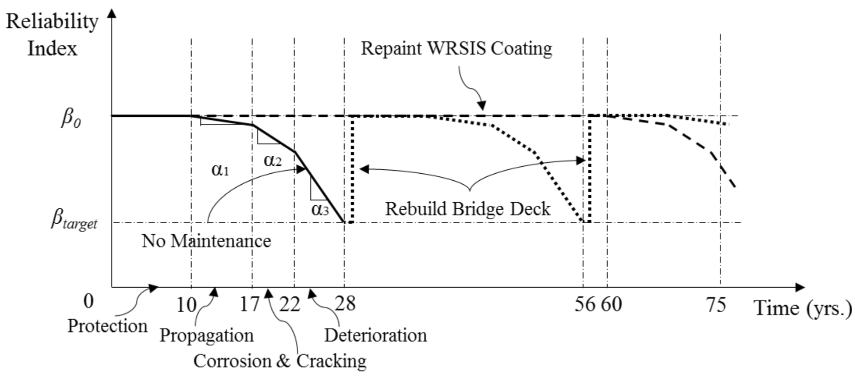

Figure 4. Hypothetic reliability deterioration model of bridge deck

In consideration of the deteriorating condition of the bridge deck, two maintenance strategies are available: (1) repaint WRSIS coating to delay deterioration, i.e. remove old coatings, clean residuals and apply new coatings every 10 years (6 times in total and stops after the 60th year); and (2) rebuild deck, i.e. tear down the damaged deck and rebuild a new deck every 28 years [50] (2 times in total). Repainting WRSIS coating can stop structural deterioration for 10 years, while rebuilding the deck can restore the structural reliability level to initial value. The effects of two maintenance strategies are illustrated in Figure 4.

The direct cost for repainting WRSIS coating is around 22 US$/m^2, including the cost of sandblasting[51] and painting [47]. The duration of repainting the entire bridge deck is assumed to be 4 months with 1/4 of the lanes closed. The direct cost to rebuild the deck is 984 US$/m^2 [52](in 2016 US$). Rebuilding the entire bridge deck is assumed to take 12 months with entire bridge closed. The life-cycle direct costs of two maintenance plans with a monetary discount rate of 2% are presented in Figure 5. The life-cycle direct cost of repainting coating is 36.76 million US$, and that of rebuilding deck is 75.82 million US$.

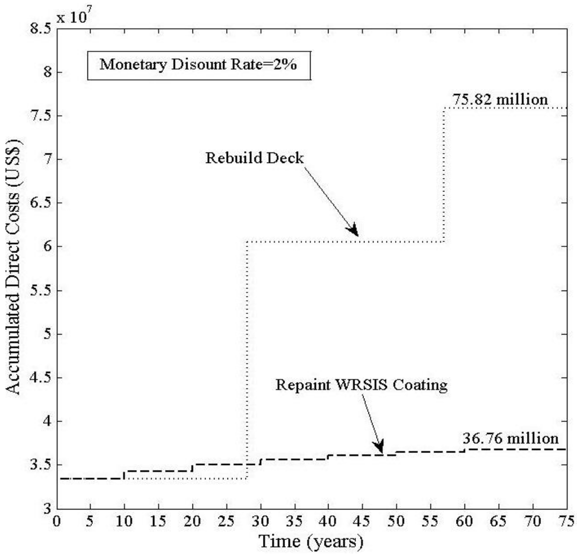

Figure 5. Life-cycle direct costs of two maintenance plans

4.3 Accident Information and Assumptions

The characteristics of road accidents are estimated based on history data. 2015 Traffic Safety Facts[53] reported that the road accident rate in the USA was 126.4 per 100 million vehicle kilometers traveled. Total people killed and injured in road accidents were 35092 and 2443000, respectively [53]. Among all injured people, around 7.4% suffered permanent disability [53]. The most fatalities and injuries happened in the age range of 25-54. With respect to work zone crashes[54], the additional accident rate was 1.94 per 100 million vehicle kilometers traveled. Work zone fatalities were estimated to be 2% of all roadway fatalities nationally [54]. The total economic loss of 5419000 traffic crashes in 2010 was 242 billion US$ [53], making average economic loss of each accident around 49530 US$ (in 2016 US$).

Based on the road accident data, around 32 road crashes are likely to happen on the bridge annually, with 0.18 fatalities, 11.5 injuries and 1 permanent disability. When the bridge is under maintenance, the additional road accident related to work zones is estimated to be 0.041 per month (30 days). Fatalities and injuries of work zone accidents are assumed to be proportional to those of road accidents, so the monthly fatalities, injuries and permanent disability due to work zone accidents are 0.0003, 0.019 and 0.0017, respectively. Accident-related data are summarized in Table 5. Note that road accidents depend on various factors, and the figures in Table 5 are statistical data used for demonstration only.

Table 5. Accident-related data applied in the case study

Type of accidents	Total accident	Victims (persons)		
		Fatalities	Injuries	Permanent disability
Normal Road Crashes [a]	32 /year	0.18	11.5	1
Work Zone Crashes [b]	0.04 /month	0.0003	0.019	0.0017
Detour Route Crashes [c]	128 /year	0.72	46	4

[a]. Normal road crashes refer to the accidents happen on the bridge without maintenances or other construction activities;[b]. Work zone crashes refer to the additional accidents happen on the bridge resulted from maintenances or other construction activities; and[c]. Detour route crashes refer to the accidents happen on the detour route when the bridge is closed for rebuilding.

The average injured age of victims is assumed to be 40 years old, average disability level is assumed to be 20%, and the average hourly wage of victims, relatives and co-workers are assumed to be 42 US$/h[55]. The average day loss of victims and relatives due to accident injury is assumed to be 7 days. For work zone crashes, each victim is assumed to need the assistance of two co-workers, and the time loss of co-workers is assumed to be 4 hours.

4.4 Social Cost-incorporated LCCA of Deteriorated Bridge

The social costs related to the two types of maintenance strategies are calculated based on the formulae proposed in Section 2 and the inputs provided in Table 7. Models concerning fatalities, income loss, extra fuel consumption and business impact factor that are specific for the case study are presented as indicated in Equation (26) to (28).

With respect to fatal cases, Zhu et al.[56] and Sabtino et al.[57] computed the fatalities based on the probability of bridge failure, traffic conditions and bridge length, as shown in Equation (26).

$$FT(t) = P_f(t)\left(\frac{L}{f_d}+1\right)\left[O_r\left(1-\frac{TT_p}{100}\right)+\frac{TT_p}{100}\right] \tag{26}$$

where $P_f(t)$ is the failure probability of the deteriorating bridge at time t; L is the length of the bridge (m); f_d is the safe following distance during driving (m); and O_r is the occupancy rate for non-truck vehicles. The fatalities related to the deteriorating bridge state (Equation 26) and road accidents (Table 5) are both considered in the calculation of social costs.

The bridge users' loss of income owing to congestion and/or detour can be computed by Equation (27)[58][59].

$$SC_{il1} = \left[c_{w,car}O_r\left(1-\frac{TT_p}{100}\right)+c_{w,truck}\frac{TT_p}{100}\right]\triangle T\cdot A\cdot d_t \tag{27}$$

where $c_{w,car}$ and $c_{w,truck}$ are the hourly wage of car drivers and truck drivers, respectively (US$/h).

Affected by maintenance work zones on the bridge, the traffic flow are forced to change speed or stop frequently. A speed changing zone of 2km as presented in Figure 6 is assumed when maintenance activities are taking place on the bridge. The extra fuel consumption to drive through this area is calculated based on the models of Zaniewski et al.[36], as presented in Table 6, and the social costs associated with extra fuel consumption is calculated by Equation (11).

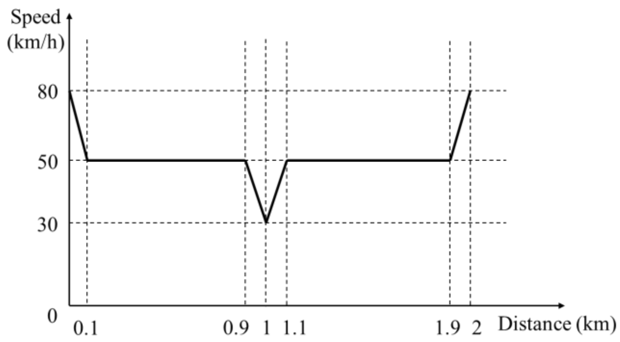

Figure 6. Hypothetic speed changing process within a 2km-distance

Table 6. Additional fuel consumption for the speed changing process

Row No.	Speed changing process	Fuel consumption (liters)			
		Small car	Medium car	Large car	2-axle truck
1	80 km/h to 50 km/h within 100m	0.04246	0.07306	0.08404	0.16422
2	50km/h for 800m*	0.10611	0.11890	0.13093	0.43139
3	50km/h to 30km/h within 100m	0.06858	0.11874	0.13615	0.25545
4	30km/h to 50km/h within 100m	0.01458	0.02399	0.03199	0.11188
5	50km/h for 800m*	0.10611	0.11890	0.13093	0.43139
6	50 km/h to 80 km/h within 100m	0.01458	0.02399	0.03199	0.09498
7	Total fuel	0.35242	0.47758	0.54603	1.48931
8	80km/h for 2000m*	0.17697	0.31704	0.36859	1.14362
9	Additional fuel**	0.17545	0.16054	0.17744	0.34569

*row 2, 5 and 8 are calculated based on Appendix C of Zaniewski et al., 1982[36];**row 9= row 7 – row 8, representing the extra fuel consumption of the speed changing process compared to driving at a constant speed of 80km/h.

The business impact factor α largely depends on the bridge's position in local transport network and supply-marketing channels, its traffic capacity, as well as the travel time through the bridge. The business impact factor of deteriorating bridge structures is computed as

$$\alpha = \frac{\Delta T}{\Delta T_{closed}} \cdot \frac{L}{L_{total}} \cdot \frac{A}{A_{total}} \tag{28}$$

where $\triangle T$ is the extra travel time due to congestion or detour (h); $\triangle T_{closed}$ is the extra travel time when the bridge is totally closed (h); L is the length of the bridge (km); L_{total} is the length of all available routes that connect the investigated areas (km); A is the average daily traffic volume of the bridge; and A_{total} is the total daily traffic volume between investigated areas. $\Delta T = 0$ means that the daily traffic on the bridge is not affected by bridge deterioration, which makes the impact factor $\alpha = 0$; while $\Delta T = \Delta T_{close}$ means that the bridge totally loses its traffic capacity, and the impact factor α is determined by the traffic volume and length of other available routes.

The inputs related to the case study are summarized in Table 7.

Table 7. Inputs and assumptions applied in case study

Parameters	Description	Unit	Values	References
A	average daily traffic (ADT) of the bridge	10^3	35	Assumption
A_{total}	average total daily traffic from Island J to mainland	10^3	115	
APV [a]	average property value	10^6 US$	0.8	[60]
C_0	initial construction cost of bridge deck	10^6 US$	32.36	[45]
C_F	unit cost of fuels	US$/liter	0.64	[61]
C_R [b]	property damage cost of each accident	US$	49530	[53]
c_v, c_{re} [c]	average daily wage of victims and relatives	US$/day	336	[55]
c_{co} [c]	average hourly wage of co-workers	US$/h	42	
c_{clean} [c]	average hourly wage for cleaning	US$/h	42	
$c_{r,car}$	operation cost for cars	US$/km	0.07	[47]
$c_{r,truck}$	operation cost for trucks	US$/km	0.014	
GDP_{ind} [d]	gross domestic production of selected industries	10^9 US$	39.89	[62][63]
R_m [d]	monthly business revenue	10^9 US$	3.32	
d_l	average day loss of victims due to injury	days	7	Assumption
D_l	detour length	km	8	
L	length of the bridge	km	2	
n_a	average assistance needed for each victim	persons	2	
N_N	normal noise level	dB	65	[64]
N_C	construction noise level	dB	85	
N_H	number of houses affected by noise	-	180	Assumption
NDI_{12}	noise depreciation index for 1-year project	%	0.2	[25]
NDI_4	noise depreciation index for 4-month project	%	0.06	
p_{da}	average percentage of disability of injuries	%	20	Assumption
f_d	safe following distance during driving	m	55	[52]
O_r	occupancy rate for non-truck vehicles	persons	1.56	
TT_p	the percentage of truck in ADT	%	4	
$T_{injured}$	average injured age of victims	years	40	Assumption
T_{retire}	retire age	years	65	[21]
t_l	average time loss of co-workers	hours	4	Assumption
$t_{clean\text{-}rc}$	weekly extra cleaning time for repainting coating	hours	1	
$t_{clean\text{-}rd}$	weekly extra cleaning time for rebuilding deck	hours	6	
r_{tp} [e]	personal tax rate	%	4.5	
r_{tb} [e]	business tax rate	%	8	

ICAF [f]	implied cost of averting a fatality	10^6 US$	3.24	[31]
VOSL [f]	value of a statistical life	10^6 US$	8.48	[22][33][34]
β_0	initial reliability index	-	4.2	[46]
β_{target}	target reliability index	-	3.7	

[a]. average property value is estimated based on the 2018 average housing price of San Francisco Bay Area, CA, USA, which is around 0.8 million US$ per house;

[b]. the property damage of each accident is roughly estimated using the economic loss data of accidents in 2010, which is around 49530 US$ (in 2016 US$);

[c]. personal wage is determined based on the average hourly earnings of all employees in San Jose-Sunnyvale-Santa Clara, CA region, which is around 42 US$/h.

[d]. business revenue in case study is estimated referring to the 2016 gross production of retail trade, wholesale trade and entertainment and food services of the San Jose-Sunnyvale-Santa Clara metropolitan area, CA, USA, which is 39.89 billion US$. The monthly business revenue is 1/12 of the annual business revenue, i.e., 3.32 billion US$;

[e]. flat tax rates are assumed and applied in case study;

f. *ICAF* and *VOSL* of USA are used in case study.

The social cost components of each maintenance action are calculated and presented in Table 8. Figure 7 illustrates the proportions of different social cost components. The life-cycle accumulated social cost components of two maintenance strategies are presented in Table 9 and Figure 8 to 9.

Table 8. Social cost components of each maintenance action (US$)

Cost components	Repaint WRSIS coating		Rebuild deck		LCC_D/LCC_C [e]
	One-time cost [a]	LCC_C (r = 2%)	One-time cost [b]	LCC_D (r = 2%)	
SC_{PHY}	18,784	66,981	4,460,882	4,104,925	61.28
SC_{PSY}	13,941	71,714	10,858,016	10,004,616	139.51
SC_{PE} [c]	12,299,176	39,043,638	60,026,678	54,280,966	1.39
SC_{HS}	1,944,720	6,173,691	6,493,140	5,871,621	0.95
SC_{SE} [d]	660,303,327	2,096,193,055	2,630,189,326	2,378,429,392	1.13
SC_{SR}	2,054	6,992,889	7,470,418	48,584,444	6.95
C_S	674,582,002	2,148,541,968	2,719,498,459	2,501,275,964	1.16
C_{DIR}	1,056,000	36,764,008	47,232,000	75,817,093	2.06
$C_{DIR} + C_S$	675,638,002	2,185,305,976	2,766,730,459	2,577,093,057	1.18

a. social costs at the 10^{th} year for repainting WRSIS coating;

b. social costs at the 28^{th} year for deck rebuilding;

c. extra travel time for repainting WRSIS coating is derived from the speed changing process described in Figure 6, and $\triangle T_1$=0.045 h; extra travel time for rebuilding deck resulted from detour is $\triangle T_2$=0.060 h;

d. business revenue impact factor is α=0.046 for repainting WRSIS coating, and α=0.061 for rebuilding deck.

e. subscript '*D*' represents values of rebuilding bridge deck strategy, and subscript '*C*' represents values of repainting WRSIS coating strategy. Same below.

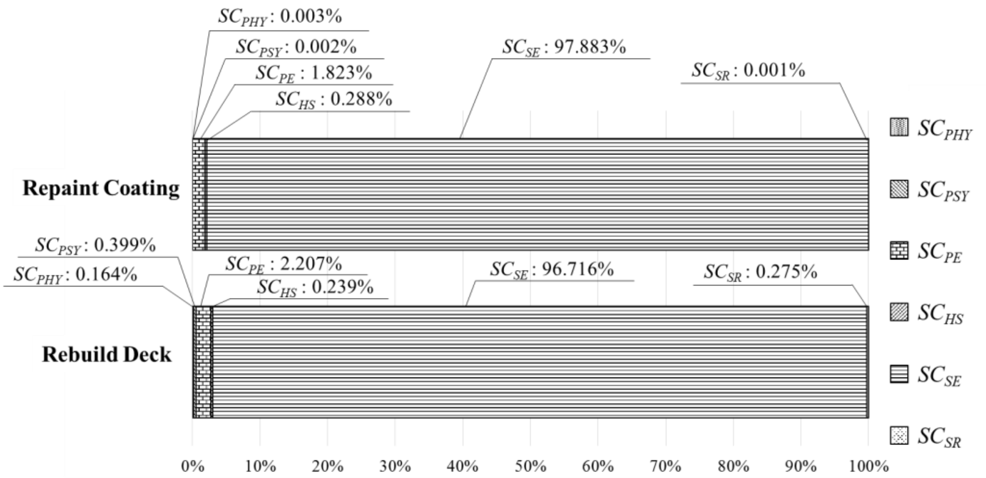

Figure 7. Proportions of various social cost components of two maintenance approaches

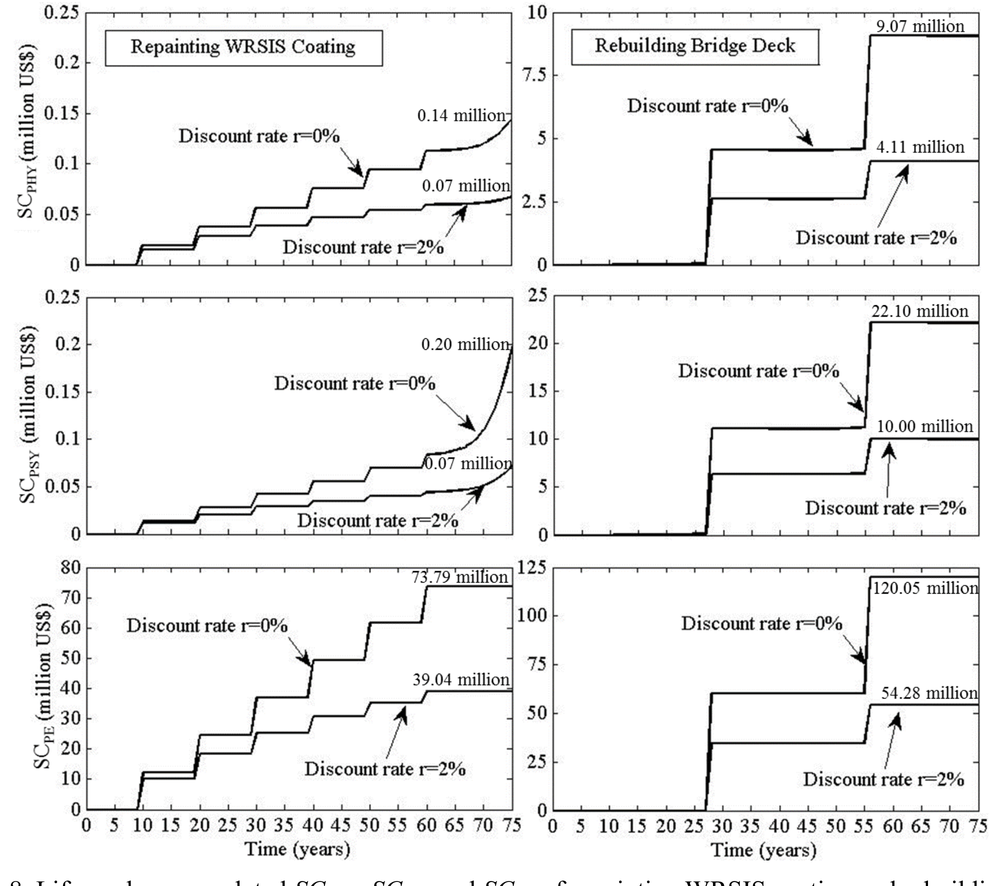

Figure 8. Life-cycle accumulated SC_{PHY}, SC_{PSY} and SC_{PE} of repainting WRSIS coating and rebuilding deck

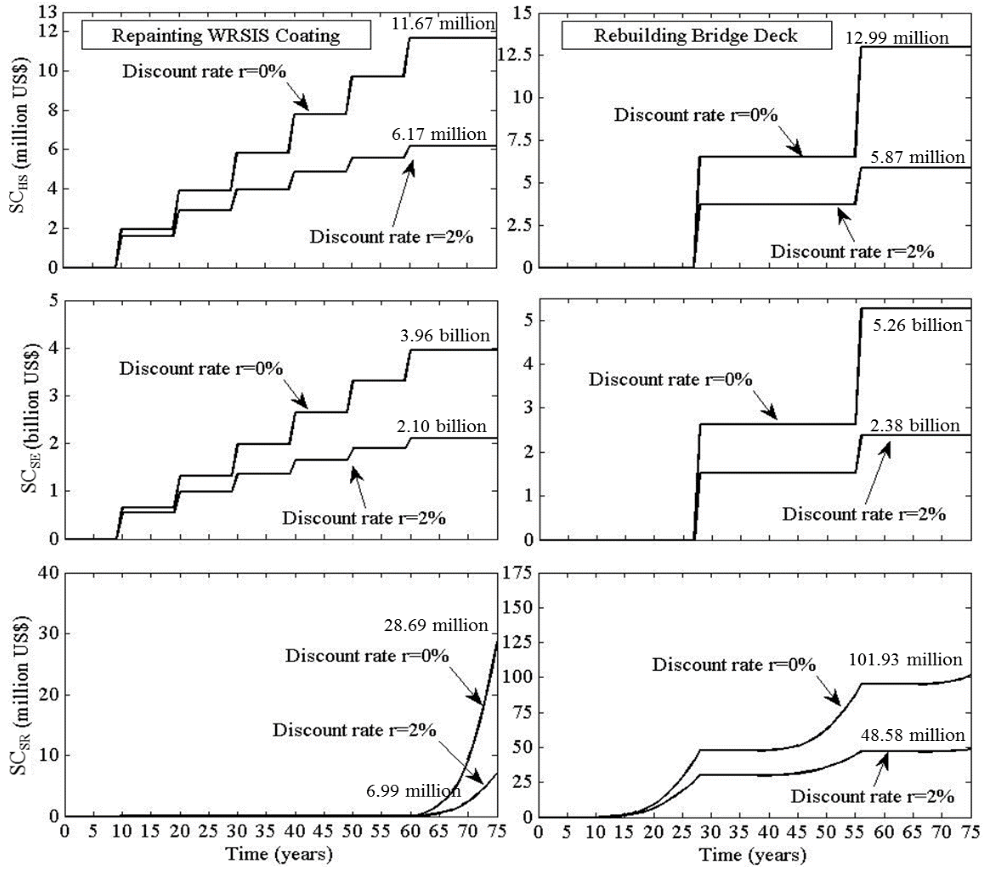

Figure 9. Life-cycle accumulated SC_{HS}, SC_{SE} and SC_{SR} of repainting WRSIS coating and rebuilding deck

As indicated in Figure 7, the social costs associated with social-economic development SC_{SE} and personal economic conditions SC_{PE} are the biggest two parts within the total social costs, with proportions of approximately 97.2% and 2.0%, respectively. It means that the social cost C_S of the deteriorating bridge is most sensitive to SC_{SE}. The loss of business revenue SC_{br} accounts for around 92.6% of the SC_{SE}, hence the business impact factor α and business revenue R_m are of vital significance in the analysis. Another relatively sensitive indicator is the loss of personal income SC_{il}, which is also a common indicator shared by SC_{SE} and SC_{PE}. The proportion of SC_{il} is 82.8%~99.9% within SC_{PE}, and 1.86%~1.89% within SC_{SE}, indicating that the hourly wages of affected people can also have considerable effect on the total C_S. Other four social cost components are relatively small, totally provides around 1% within the social costs.

Table 8 indicates that all the social cost components of rebuilding deck are bigger than those of repainting coating. The C_{DIR} and C_S of rebuilding bridge deck are considerably higher than repainting deck coating, being 45 times and 4 times those of repainting coating, respectively. In general, repainting WRSIS coating is a more economic and social sustainable maintenance measure.

Table 8 also shows that the ratios of life-cycle SC_{PE}, SC_{HS} and SC_{SE} between rebuilding deck and repainting coating are around 0.95 to 1.4, which are relatively stable and close to the ratio of life-cycle C_S. But the ratios of life-cycle SC_{PHY}, SC_{PSY} and SC_{SR} are much larger and changeable, varying from 6.9 to 139.5. The life-cycle SC_{PHY}, SC_{PSY} and SC_{SR} are related to the probability of failure P_f(t) of structures, hence these costs are changing and increasing all the time even when no maintenance action is in performance, as can be witnessed in Figure 8 and 9. In addition, more deteriorated life-cycle performance can induce more construction and road accidents, as well as more depreciated structural value, so the ratios of life-cycle SC_{PHY}, SC_{PSY} and SC_{SR} also imply that the overall structural performance of repainting coating is better than that of rebuilding deck.

The life-cycle C_{DIR} accounts for approximately 1.7%~2.9% within the total LCC, while the life-cycle C_S accounts for around 97.1%~98.3%. As analyzed earlier, the social costs are largely controlled by SC_{SE} and SC_{PE}, and the LCC is dominated by social costs. When the social cost-incorporated LCC is used in structural optimization or decision making process, weight factors are recommended to modify the proportions of social cost components, and to adjust the ratio between social costs and direct costs. The determination of weight factors depends on the preferences and attitudes of decision makers.

The life-cycle C_S and LCC of two maintenance strategies are presented in Figure 10. The maintenance strategy including rebuilding bridge deck shows higher life-cycle C_S and LCC than repainting deck coating, that is because rebuilding bridge deck is associated with larger engineering quantity and longer construction time, involves more manpower and material resources, and is more disruptive to people's routines and social development. Hence, governments and administrative departments should encourage more durable and stronger structure design, more preventive maintenance strategies, as well as more measures and techniques to reduce social impacts, so as to avoid the huge economic costs and improve the social sustainability of construction industry.

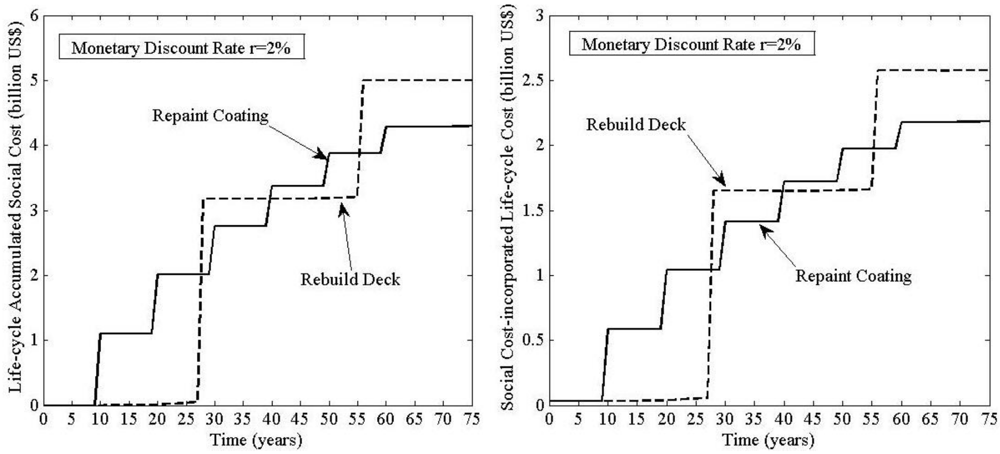

Figure 10. Accumulated social costs and social cost-incorporated life-cycle costs of two maintenance strategies

5.1 Discount Rate of Social Costs

The monetary discount rate is used to reflect the time value of money in LCCA and cost-benefit analyses (CBA). Future costs are normally discounted to present value using a certain discount rate. The value of social costs, just like other costs occur during the life-cycle of engineering structures, is also affected by time. The economic losses resulting from fatalities and disabilities account for a significant part of the overall social costs. One of the questions raised is the discounting of social costs including economic values of human lives, such as ICAF and VOSL. The debates over this question have mainly focused on whether it is ethical or moral to discount the value of human lives. The objectors argue that the discounted future cost of saving lives is less than the life-saving cost now, which means that the lives saved in the future is less important than those saved at present[65]. This is obviously unacceptable, since human lives are equally valuable regardless of time and places. While the supporters claim that the value of human lives should be discounted just as any other benefits or costs so as to avoid inconsistency in LCCA or CBA[31][65].

The discount rate for social costs is set to be the same with other costs in this paper. The authors believe that the intrinsic values of human lives cannot be converted into money, since human lives are priceless. All we can do is to estimate the money people or society willing to pay to reduce risks and save lives according to the ethical standards and economic strength of the society. Hence, the economic values of human lives such as ICAF and VOSL are just indicators created based on census and GDP of a place, so that the impacts of human life losses can be easily included in economic analyses. These figures do not represent the true value of human lives. When the future social costs associated with fatalities are discounted into presented value, it is the value of money that are affected by time rather than the value of human lives.

6. Conclusions

This paper investigates the social impacts and associated social costs of deteriorating civil infrastructures. The social impacts of civil infrastructures are divided into two categories: personal-level and social-level impacts. The computational formulae for associated social costs are presented in this paper. A deteriorating bridge deck is used as illustrative example to perform social cost-included life-cycle cost analysis. The following conclusions are reached for this study:

- Social-economic loss SC_{SE} contributes the biggest part to the overall social cost, indicating that the total social cost C_S is highly sensitive to the business revenue R_m and business impact factor α. The personal economic loss SC_{PE} is the second biggest part in C_S. The personal income loss SC_{il}

is a common indicator shared by SC_{SE} and SC_{PE}, which makes it also a relatively sensitive indicator.

- Within social cost-incorporated LCC of this study, the life-cycle direct cost only accounts for around 1.7%~2.9%, and the life-cycle C_S takes the dominant position of 97.1%~98.3%. Social impacts and social costs of deteriorating infrastructures are non-negligible, and the social cost-included LCC model can evaluate the comprehensive performance of economic efficiency and social sustainability of structures.
- The direct cost C_{DIR} and social cost C_S of rebuilding bridge deck are considerably higher than those of repainting WRSIS coating. The maintenance strategy including rebuilding bridge deck has larger engineering quantity and longer construction time, requires more labors and materials, and causes more disturbance to public routines and social development. Thus, repainting coating is a more economic efficient and social sustainable bridge maintenance measure.
- Social costs are affected by numerous uncertainties, such as structure types and projects, places and time, quantification and measurement approaches, computational methods, assumptions and coverage of social cost inventories. For specific structures and projects, the evaluation of social costs should be adjusted based on actual situation.

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