MODELING AND ANALYSES OF THE RETIREMENT OF DETERIORATED STRUCTURES

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ABSTRACT

With the increasing stock of aging structures, the strategy to model and analyse the retirement of deteriorated structures is becoming a challenging research field. As the converse of construction of new projects, the retirement of constructed facilities puts forward some new management and economics themes as well as environmental issues or adds some new contents even though the same issues are faced in construction. This research aims to model and analyse the maintenance and demolition activities of constructed facilities from economic and environmental perspectives. Both cost and carbon dioxide of maintenance and demolition activities are formulated based on those of construction activities and applied to an empirical study on deteriorated bridges. Further modelling and analysis is investigated to elaborate the demolition stage of a structure. The developed modelling and analysis methodology may enable the decision maker to determine the retirement strategy for a deteriorated structure.

Keywords: analysis, demolition, deteriorated structure, economics, environment, maintenance, modelling, retirement

1. INTRODUCTION

It has been widely recognised that the lifecycle approach can play an important role in project management by considering all lifecycle stages at the same time [1]. However, people initially concentrated on the design and construction stages, and then incorporated the planning activities. It might be since 1980s that maintenance has been taken into serious consideration, and maintenance attracted much emphasis from 1990s [2]. A previous publication argued in concise language that there was an infrastructure crisis in USA due to a lack of inadequate maintenance of existing facilities [3]. However, publishing the book did not draw society’s attention immediately to the crisis, and the scope of the problem became clear in the following years while a large number of bridges in USA collapsed partially or completely [4]. The lessons learned from the failures and disasters led to better understanding of the importance of the proper maintenance. Therefore, till 1996, it could be concluded that most of the national governments, and local authorities in the developed world had switched their minds from new infrastructure projects requiring large capital investment to the maintenance of the existing stocks [5].

The emphasis on the demolition stage was highly due to the increasing environmental pressure, particularly in waste disposal. The demolition of building structures produces enormous amounts of materials that in most regions result in significant waste streams. For example, in Australia, the construction and demolition of existing facilities is responsible for some 30-40% of the country's solid waste streams which total about 14 million tonnes annually according to the
Australian Bureau of Statistics [6]. In recent years, there have been various attempts to improve landfill disposal technologies as well as to set up advanced recycling technologies. As further improvements in processing are technically limited, future efforts will have to concentrate on improving the demolition method from destruction to deconstruction.

The goal of this research is to model and analyse the maintenance and demolition activities of constructed facilities from economic and environmental perspectives. The research scope presented in this paper is as follows. In the following section, both cost and carbon dioxide (CO₂) of maintenance and demolition activities are formulated based on them of construction activities. Based on the developed formulations, an empirical study is carried out to model and analyse the deteriorated bridges in Section 3. Further modelling and analysis is investigated to elaborate the demolition stage of a structure in Section 4. The final section summarises the main findings in this research.

2. METHODOLOGIES OF ECONOMIC AND ENVIRONMENTAL ANALYSES

In this research, bridges are used as examples in the empirical study to model and analyse the economic and environmental effects of maintenance and demolition activities in the ratios to those of construction activities. The maintenance requirements and specific techniques of a bridge or its components are determined according to the periodic inspection and the further testing in detail if necessary. Based on the existing bridge inspection manual and the hearing with the practical bridge engineers [2], eight types of bridge components need more maintenance, which are the pavement, deck, painting, expansion joint, support, girders, guard fence, and pier (abutment), because of the structural deterioration due to the service and material aging. Among these eight components, however, the girder, guard fence and pier are usually damaged by some unpredicted events such as the earthquake and traffic accidents, and therefore it is difficult to determine the maintenance needs and the maintenance period of such a bridge component. In this research, only five bridge components are considered for the lifecycle evaluation, namely the pavement, deck, painting, expansion joint, and support. The maintenance periods (service lives) of these components are assumed to be 5~20, 15~30, 5~15, 5~20, and 20~30 years respectively by referring the hearing with the practical engineers and previous publications [7]. Several bridge replacement methodologies exist, such as closing the traffic while replacing, constructing a temporary bridge instead of the existing bridge under the replacement, and closing a part of the bridge and keeping the other part for the service. The selection of such a replacement method is dependent on the bridge type, the site condition, the traffic condition and so on. To determine the environmental impact and cost due to the replacement activity, the consumptions of materials and machinery of each replacement operation are essential. However, such data have not been summarized well so as to be able to be utilized for the further calculation. Therefore, the environmental impact and cost from the replacement stage in this research are assumed to be constants without considering the possible change due to the different method.

2.1 Cost Formulation for Maintenance and Demolition Activities

Lifecyle cost is the total cost accrued during the life of a bridge. Various types of costs are incurred by the owning agencies and users during the service life of a bridge. User cost incurred due to the closure of a bridge for various reasons such as the maintenance and rehabilitation activities is a significant part of the lifecycle cost. However, in this research only the agency costs of bridges are considered for the lifecycle cost analysis. Mainly three types of costs are included in the lifecycle cost: construction cost, maintenance cost and demolition cost. The total lifecycle cost can be evaluated as:

\[
LCC = \sum_{i=1}^{T_a} \sum_{j=1}^{N} (C_C(i,j) + C_M(i,j) + C_D(i,j)) \times (1+r)^{-i}
\]

Where, \(LCC\) is the total lifecycle cost of a bridge for a given analysis period of \(T_a\); \(C_C(i,j)\) is the construction cost of the bridge component \(j\) at the year \(i\); \(C_M(i,j)\) is the maintenance cost of the bridge component \(j\) at the year \(i\); \(C_D(i,j)\) is the demolition cost of the bridge component \(j\) at the year \(i\); and \(r\) is the average annual discount rate during the analysis period. These costs are represented in units without consideration of the currency of a country.

Several difficulties exist in predicting lifecycle cost with required accuracy. The construction and demolition costs can be estimated with fair degree of accuracy with several assumptions on the construction and demolition with help of manuals and databases. Since bridges last for several decades with various maintenance activities, the maintenance cost always becomes a significant part of the lifecycle cost. Estimation of maintenance cost needs proper understanding of maintenance strategies and historical databases of maintenance costs. However, such data are seldom available for the civil infrastructures, and the maintenance cost is normally assumed in the lifecycle cost calculations, for example [8]. The major maintenance activities and their frequencies in this study are adopted from previous literatures and interview with practicing bridge engineers [2, 7]. In such a condition of lack of data about lifecycle performances and effectiveness of maintenance strategies, it is very difficult to carry out the prediction of lifecycle cost accurately. Despite the difficulty in calculating the value of lifecycle cost accurately, lifecycle cost analysis can be useful in comparing several alternatives following the consistent method of evaluation. Further, if the lifecycle data will be
 gathered continuously, the present methodology can be improved to find more accurate value of the lifecycle cost in the future. Since the analysis period is relatively long, the selection of the discount rate is another difficult issue in the lifecycle cost analysis. To be at the conservative side, a discount rate of 2% is sued in this research.

### 2.2 Environmental Impact Formulation for Maintenance and Demolition Activities

The bridge lifecycle consumes the natural resources and energy in the form of construction materials and equipment. The construction materials used during the construction and maintenance can be accumulated to find the global environmental impact from bridges. The demolition stage also uses a lot of equipment for demolition activities and construction materials for temporary structures. The environmental impact of vehicles passing on the bridge is not incorporated into the lifecycle of the bridge in this study. The total lifecycle global environmental impact, indicated by the emissions of carbon dioxide, from the bridge lifecycle can be given by the following equation:

\[
LEI = \sum_{i=1}^{T} \sum_{j=1}^{N} (I_C(i, j) + I_M(i, j) + I_D(i, j))
\]

where \(LEI\) = total lifecycle environmental impact; \(I_C(i,j)\) is the environmental impact from the construction of the bridge component \(j\) at the year \(i\); \(I_M(i, j)\) is the environmental impact from the maintenance of the bridge component \(j\) at the year \(i\); and \(I_D(n)\) is the environmental impact from the demolition of the bridge component \(j\) at the year \(i\).

The volume and weight of materials are calculated for a bridge lifecycle based on the design manuals and the interview with bridge engineers. Similarly, the time length of construction equipment used in various construction, maintenance and demolition activities are found by the databases depicting past experiences and interview. The CO\(_2\) emissions from per unit volume or weight are taken from the previous studies by Japan Society of Civil Engineers (JSCE) [9] and Public Works Research Institute (PWRI) [10]. The PWRI values are obtained from input-output tables. The JSCE values are calculated with lifecycle assessment (LCA) method in which all processes are accounted for making a product. This LCA method is supplemented by input-output analysis. Since JSCE values are relatively new and are cross-checked with both LCA and the input-output analysis, the JSCE values are used in this research to calculate the lifecycle environmental impact of bridges. However, the unit CO\(_2\) emissions of some construction materials that are not included in JSCE analysis are calculated according to the PWRI values.

### 3. NUMERICAL EXAMPLES

#### 3.1 Empirical Data

In order to identify the environmental impact characteristics in the construction, maintenance and replacement stages obtained from the developed system and to discover the possible revised approaches, a case study is carried out. Two typical superstructure types are considered in this case study, which are the steel simple non-composite I girder bridge and the PC simple pre-tensioned T girder bridge. The span arrangement for both bridges compared are of three spans with 33m+34m+33m. It is assumed that the bridge is located in Nagoya. The basic data are shown in Table 1.

<table>
<thead>
<tr>
<th>Superstructure type</th>
<th>Type 1: Steel simple non-composite I girder bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge length</td>
<td>100m</td>
</tr>
<tr>
<td>Bridge width</td>
<td>17m</td>
</tr>
<tr>
<td>Spans</td>
<td>33m, 34m, 33m</td>
</tr>
<tr>
<td>Heights</td>
<td>1.9m, 2m, 1.9m</td>
</tr>
<tr>
<td>Number of main girders</td>
<td>9</td>
</tr>
<tr>
<td>Substructure type</td>
<td>Inverted T pier (abutment)</td>
</tr>
<tr>
<td>Foundation type</td>
<td>Reverse pile</td>
</tr>
</tbody>
</table>

Table 1. Bridge data for the case study

#### 3.2 Comparison of CO\(_2\) Emission and Cost

Further comparison study on the CO\(_2\) emissions and costs consumption from each lifecycle stage has been performed by considering three cases of deteriorating speeds (rapid, medium and slow) of each major bridge component as shown in Table 2. The basic data of bridges as same as shown above in Table 1. For the purpose of comparison, it is assumed that all bridge components have the same deteriorating speed. The unit in this table is year and the service life of a bridge is considered as 60 years old.
### Table 2. Deteriorating speed of bridge components (year)

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deteriorating speed</td>
<td>Slow</td>
<td>Medium</td>
<td>Rapid</td>
</tr>
<tr>
<td>Pavement maintenance</td>
<td>20</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Re-painting</td>
<td>20</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Deck maintenance</td>
<td>25</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Deck replacement</td>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Expansion joint replacement</td>
<td>20</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Support replacement</td>
<td>30</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>

Figures 1 and 2 represent the CO$_2$ emission and costs consumption from the three lifecycle stages of both a steel simple non-composite I girder bridge and a PC simple pre-tensioned T girder bridge, respectively. It can be concluded that a PC bridge contributes more CO$_2$ emissions than a steel bridge in each of three cases although its cost is relatively less.

#### 3.3 Effects of Recycled Materials

It has been widely noticed that recycling of construction materials is one efficient method for reducing the environmental impact as well as reducing the construction cost. As a majority of landfills is being of limited capacity and the construction waste holds a high portion of the solid waste, recycling will also be able to reduce the load to these landfills. The steel used in the superstructure can be recycled most efficiently with a ratio of more than 95% [10]. Steel can usually be recycled by melting it in the electric arc furnace. This recycled steel can be used instead of virgin iron extracted from mines, which results in about 60% energy saving, and consequently, reduction in environmental impact (PWRI 1994). On the other hand, concrete can be recycled as aggregate for new concrete, as material for road base course, and so on [11]. The environmental impact of concrete produced with recycled aggregate will be about 86% compared with conventional concrete [10].
As a high material quality is normally required to gain the confidence in safety for the construction of a large civil infrastructure such as bridges, in the present practice, the recycled materials are not used in structures although the recycled materials such as steels in most cases can meet the requirement of the structural and functional capacities. However, with the development of recycling technology and the increasing burden onto the global and local environment, it is expected that more recycled materials will be used in the near future. Figures 3 and 4 present the effects of recycling onto the lifecycle environmental impact and cost respectively, in which concrete and steel are two recycling materials. As shown in these figures, the use of recycled materials can decrease the environmental impact and cost to 10-20% and 2-5% respectively. Particularly the recycling of the steel of a bridge can result in higher percentages of decreases of environmental impact and cost compared to the recycling of the concrete. In addition, steel can be considered superior to concrete from the environmental point of view because steel can be recycled as steel, while concrete can be recycled only as aggregates. This means more limestone and other natural resources are still depleted even concrete is fully recycled.

![Graph showing CO₂ emission comparison between new and recycled materials for steel and PC bridges](image1)

**Fig 3. Effect of Recycling on Environmental Impact.**

![Graph showing lifecycle cost comparison between new and recycled materials for steel and PC bridges](image2)

**Fig 4. Effect of Recycling on Lifecycle Cost.**

### 4. DEMOLITION OF DETERIORATED STRUCTURES

#### 4.1 Demolition Economics

The abovementioned small number of demolition companies also implies low economic benefits of demolition projects. Current demolition cost factors retard the boom of demolition business [12]. These factors consist of the present low acceptance of recycled and reused components and materials, high labour costs, low tipping fees of demolition waste and so on. The salvaged materials market is currently struggling due to a secure economic climate, where the average home handyman, enterprise manager and urban developer will source new material from a hardware store rather than even considering second-hand materials.

The general consensus is that further education on environmental protection is required to drastically change this behaviour in society. The economics of demolition performance also drives demolition waste disposal decision-making. Any change in hauling costs, tipping fees and virgin material prices may induce the adoption of substitutive demolition and disposal methods.
4.2 Demolition Options

Buildings account for one quarter of the world’s wood harvest and two-thirds of its material and energy flows [13]. From the viewpoint of natural resource reservation, the construction and demolition industries can use materials much more sustainable than they are doing now. Construction materials extracted from natural resources are sent to landfills after only one or two usages. As any natural resource is within limits after which irreversible or serious depletion and damage can occur, the resource extraction activities have to be undertaken with a view to the carrying capacity of the relevant ecosystem to absorb its varied effects [14]. To be more conscious of natural resources and more innovative in building demolition, there is a desperate need to find new ways of using no longer occupied or unwanted buildings. An example is that in 2001 the Architectural Institute of Japan launched a design competition to extend the service life of a building to one hundred years, over three times the existing design life of thirty years [15]. Although the currently widely-used machine demolition may be a quick, cheap and easy solution to remove buildings, other options under a systematic approach now more than ever need to be explored for the purpose of minimising construction and demolition waste. Figure 5 represents the construction-demolition chain from the raw materials extracted from the earth to landfill after one or more usages through construction and demolition activities. Building demolition alternatives decide the proportions of materials going back to construction through each of the loops from top to bottom as shown by the dashed lines.

![Decision-making Process on Building Demolition](image)

Fig 5. Decision-making Process on Building Demolition.

An ideal solution for an abandoned constructed facility, which cannot be used as it is from a structural or functional standpoint, is to refurbish or relocate it. In this case the life of a building is extended, and the majority of a building is retained. For many years, renovation and rehabilitation of buildings in Australia has been developed under requirements for building heritage preservation. An example is the Geelong Waterfront Campus of Deakin University, in which the whole building originally built in the 19th century underwent extensive redesign and refurbishment in the 1990s. Relocation has widely been applied on residential houses, particularly with post and beam, weatherboard cladding and timber frame. In the Victorian region of Australia, more than one thousand buildings are relocated each year [16]. Worldwide, successful relocation has occurred for bridges, churches, odeums and stations, and other structures. After refurbishment or relocation, as shown in Figure 5, a building may be on service again with the original or a modified function. In addition, buildings that are optimally designed with environmentally sustainable materials and with deconstruction in mind are of extreme value for reducing waste although most buildings currently being refurbished or totally demolished are not of this nature. Deconstruction is the first consideration from an ecological viewpoint if demolition has to be carried out. By deconstructing the building, the reuse of materials would provide the next best result following refurbishment or relocation in terms of waste minimization. Destruction, which represents machine-based dismantling, may still allow a major portion of the material to be recycled and reprocessed into building elements. The last process in order of preference is the disposal of the demolished waste to landfill, which should only occur after all other options have been fully explored and investigated.

This optimal decision-making process on alternative approaches implies maximisation of resources conservation by preventing demolition waste in the first place, such as by extending the building’s life or optimal design of the building for reuse. Minimum waste oriented demolition processes also provide a systematic approach to reduce landfill pressure from the construction industry. The economic performance of each demolition method may be analysed and compared. Based on a real case study, research was carried out to depict both the economic advantages and disadvantages of three demolition strategies, which are machine demolition, machine demolition for recycling and deconstruction [12]. The base case for comparison was traditional machine-based demolition. The main cost factors considered were labour costs, materials benefits, plant costs, environmental costs, and administrative costs. Through the empirical study, it is found that machine demolition has the highest project costs and deconstruction is the most economical with the most
profit, although machine demolition for recycling (as used in practice) is slightly lower than deconstruction in terms of financial return. This previous study may be extended to define and model all demolition and alternative scenarios with an emphasis on refurbishment and relocation. Each scenario may further be evaluated holistically using a combination of multiple criteria such as financial return, functional performance, energy usage, and environment impact criteria.

4.3 Value of Demolition Materials

Building materials, identical to other commodities, have their associated economic value. During its own lifecycle, building material alters its economic value following the transformation that the material goes through. Moreover, the transformations of building materials are generally the consequences of human activities, and sometimes natural routine movements. The human activities, according to their nature of economic influence on the building materials, can be classified as value adding, value declining and non-value related activities. Generally, a piece of building material goes through a pool of value related or non value related human activities till its retirement, from the chemical compounds in a mineral plant or other virgin nature resources to wastes disposed to landfills. As a result, the financial value of the piece of building material, taking different form, shapes or situations of existence, increases or shrinks regarding to the undertaken human activities. At one point, the economic value reaches its peak, which presents the most degree of usefulness of the piece of building material to the user or client. While as the least financial value of the building material occurs in the start and the end of its lifecycle. The economic value of a piece of building material is determined by the overall effects of value adding activities and value-consuming activities it experiences. Apparently, the value is dynamic during the material lifecycle and various activities.

Three sequential stages are denoted to building material lifecycle, namely pre-construction, construction and post-construction periods. Most value adding activities are performed in the first two stages. Other activities in the third stage such as renovation and maintenance also promote the value of building materials. Through these activities, the value of a piece of building material accumulates to a highest level, while activities in last stage of building material lifecycle consume the value within the building material and turn it back to zero. The activities such as building use and demolition, normally over a relatively long period compared with activities in first two stages of building material lifecycle, are major components of the last life stage before disposal. It should also been noticed that non value related activities, such as material marketing, transportation, and inventory, also play a significant role in realising and facilitating value adding activities. However, for the reason that these activities do not directly create value for the building materials, they should be avoided, or simplified, to speed up the value adding process and minimise wastes. For example, inventories are tightly controlled or eliminated in the manufacturing process, which is the central philosophy of Just-in-time [17]. Similarly, transportations are minimised and material marketing is facilitated and automated using logistic management and information technology [18]. Consequently, less human and monetary resources are spent on non value-adding activities during the building material lifecycle. However, the quality of these activities should be maintained to ensure the next human activity is able to carry on.

At the end of the building material lifecycle, a number of building materials are dismantled and sent to landfill. It might indicate that the economic value of the building material is dropped to zero. However, the end of a building’s life does not necessarily lead to the end of the building materials’ lives. Especially, in current situation of urban development, redevelopment and restructuring, large portion of erected building structures are demolished with spatial or functional rather than structural or material quality problems. For such a reason, at the point of demolition, a building, as an aggregation of building materials, is still functional. Therefore, either the whole building or the embodied building materials contain financial value that should not be neglected. While the building materials that come out from a building demolition project are dumped into landfill, their value is too dumped and wasted. However, building reservation, building material R&R help to reserve the value within the building materials and extend their lives. Furthermore, the value of the building materials may reach another peak while participating another construction project and serving in another building structure. Apparently, the success of such transformation largely depends on many other factors such as secondary material markets, local, national and international demands, information availability, R&R facilities, and amount of labour and costs involved.

From the observation of value curve of a piece of building material during its lifecycle, it is possible to improve its value by several ways. That is, the ratio of performance and costs of the piece of building material can be enhanced, mainly in managerial aspects. For building materials, a better performance denotes a longer serving life and usefulness. It is possible to boost the value of the piece of building material through first two stages of building material lifecycle. The ever-developing technologies enable better quality of both building materials and the building structure. As a result, at the same declining rate, building materials with better value and quality last longer. Secondly, the declining rate of value of building materials can be slow down through better maintenance and necessary refurbishment. These activities either slow down the speed of value shrinking or promote the value to another higher level. Finally, but most importantly, while a building life comes to an end, building material R&R should be performed. After being reprocessed and reused in other projects, the value of building materials experience through the first and second stages of lifecycle again and is promoted to the second peak value. While the quality maintains in a reasonable level, further
reuse or recycling could also be possible. The value curve of those building materials can be illustrated in waves shown in Figure 6.

![Fig 6. Lifecycle Value Chart of Materials.](image)

5. CONCLUSIONS

This paper has modelled and analysed the effects of maintenance and demolition activities on the economic and environmental perspectives of constructed facilities. Both cost and carbon dioxide of maintenance and demolition activities have been formulated according to the amounts of construction activities. Using the developed formulations, an empirical study has been carried out to investigate the deteriorated bridges. Research was also carried to elaborate the demolition activities of a structure. The developed modelling and analysis methodologies could be expected for determining the economic lives and retirement strategies of deteriorated structures.

6. REFERENCES

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