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# Efficiency Assessment of Road Project Delivery Models by Grey System Theory

Shih-Ching Lo
Chung Hua University
Hsinchu 300
Taiwan
Email: sclo@chu.edu.tw

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## ABSTRACT

*In this study, four road project delivery models are analyzed by the grey relational analysis (GRA). The four models are design-bid-build (DBB), design-build (DB), construction management (CM) and design-build-maintenance (DBM). Evaluating road project delivery models is difficult because the projects differ from road to road, state to state and country to country. Thus, the evaluation data of project delivery systems are poor and lacking. Therefore, grey relational analysis and grey entropy weighting method are considered to compare the efficiency of the four road project delivery models. Grey system theory is a multidisciplinary and generic theory dealing with systems characterized by poor information and/or for which information is lacking. According to the result, DBM is the best model. DBB is the worst one and DB is better than CM. The results may provide public sectors to employ an adequate model so as to proceed with road construction project.*

***Keywords:*** *Road Project Delivery, Design-Bid-Build, Design-Build, Construction Management, Design-Build-Maintenance, Grey Relational Evaluation, Grey Entropy Weighting.*

## INTRODUCTION

Historically governments and municipalities or cities have been responsible for designing, constructing and managing infrastructure assets. In both developed and developing countries, infrastructure sectors of road construction become more difficult because public financing is becoming more and more constrained and deficient as people are ageing, which drives up health care and pension costs (Global trends: 2015). Introducing private capital and increase competition to road construction become an important issue. Traditionally, a project is divided to planning, design or construction contracts, and then private sectors bid for each part of the project. However, dividing projects up and procuring different kinds of services via separate contracts are inefficient. Therefore, innovative delivery methods are increasingly used in infrastructure projects (Koppinen and Lahdenperä, 2004a, 2004b, Molenaar et al., 1999, Pakkala, 2002). The purpose of this study is to compare the performance of the different project delivery models of road construction.

The road project delivery (RPD) methods included in this research are traditional Design-Bid-Build (DBB), Design-Build (DB), Construction Management (CM) and Design-Build-Maintain (DBM and its variants Design-Build-Operate-Maintain, Design-Build-Finance-Build-Operate, Build-Operate-Transfer, Build-Own-Operate-Transfer, etc.). The depth discussion of financing issues and assessment of the societal affects of different project delivery methods are beyond the scope of this study. Data collection is a difficult problem for evaluation of road project delivery methods because each project differs from state to state and from road region to road region. In addition, employing the cost/benefit analysis will face a serious problem; that is, deciding the weight of each benefit and cost indicator.

Grey system theory is an effective method for lacking information (Deng, 1982, 1988, 1989). Grey system theory has already been widely used in many fields since 1982. Grey system provides multidisciplinary approaches for analysis and abstract modeling of systems for which the information is limited, incomplete and characterized by random uncertainty. Grey system theory typically deals with external boundaries but internal uncertainty or vagueness, while conversely fuzzy mathematics deals with systems, objects or concepts having a well-defined internal characteristics but not well defined boundaries (Liu and Lin, 1998). As other theories, grey system theory gradually developed from requirements for new methods to solve certain problems. Main contributions to grey system theory came from: grey systems and control, grey relational analysis (GRA) and grey modeling (GM). Similarly like fuzzy control, grey control enriches the domain of systems and control in addition to conventional methods (Liu and Lin, 1998, Yuan, 2007). GRA is used for system analysis, in contrast to traditional statistical methods. Statistical methods require a probability distribution. In some real world cases, a probability distribution cannot be determined due to limited availability of data. The research object of grey system theory is the system with "little sample" and "poor information", which is partly known and is partly unknown to outsider. However, we can obtain some valuable information by developing the known information, and know how the system runs and how to control the system.

In this paper, the grey relational analysis method is used to evaluate different road project delivery methods. Two kinds of data are employed to evaluate the efficiency of the four models. The first set of data only considers the cost effect of the RPD models and the second set of data considers performance of cost and value generation of the RPD models. Therefore, the second set of data is suggested to assess the efficiency of RPD models. Among the four models, DBM is the best one and traditional DBB is the worst one. The remaining content is organized as follows. In Sec. 2, road project delivery models are introduced briefly. Grey evaluation model, which includes grey relational analysis and grey entropy weighting, is introduced in Sec. 3. Empirical study and discussion are presented in Sec. 4. Finally, conclusions are drawn in Sec. 5.

## ROAD PROJECT DELIVERY MODELS

To overcome the shortcomings of traditional procurement, the concept of public-private partnership (PPP) is proposed. PPP refers to contractual agreements formed between a public agency and private sector entity that allow for greater private sector participation in the delivery of transportation projects. According to the concept of PPP, the construction industry has developed a large number of different project delivery systems (Koppinen and Lahdenperä, 2004a, 2004b, Molenaar et al., 1999, Pakkala, 2002). Among PPP models, CM, DBB, DB and DBM are four commonly used methods. Each of them will be introduced as follows (Koppinen and Lahdenperä, 2004a, 2004b, Molenaar et al., 1999, Pakkala, 2002). Construction management (CM) is a project delivery method based on the owner's agreement with a qualified construction firm to provide leadership and perform administration and management for a defined scope of services. Design-bid-build (DBB) is the traditional project delivery approach that was used for most of the 20th century to procure public works. In the design-bid-build model, a designer prepares complete construction documents for the owner. The owner then receives bids from contractors based on the design documents and awards a construction contract to the lowest responsive, responsible bidder. The contractor builds the project, and upon completion, the owner assumes responsibility for the operation and maintenance of the project. The owner provides all financing. Design-build (DB) is a project delivery method that combines two, usually separate services into a single contract. With design-build procurements, owners execute a single, fixed-fee contract for both architectural/engineering services and construction. The design-build entity may be a single firm, a consortium, joint venture or other organization assembled for a particular project. The owner provides all financing. Design-build-maintain (DBM) combine a maintenance provision with DB model. The term is used here as a general term that covers all procurement methods that extend the contractors' responsibilities from pure design and construction to longer term maintenance liability, with or without other duties, such as operation and financing.

## GREY EVALUATION MODEL

The grey relational analysis is a kind of method by which the related degree of every factor in the system is analyzed. The basic idea of this method is to judge the related degree by dynamic developing situation of the system. In this study, the evaluation the road project delivery models is regarded as a grey multi-objectives decision-making problem and a grey relational evaluation model is set up. Firstly, a $m \times n$ matrix **X** is set up, where $m$ is the number of project delivery models, $n$ is the number of indicators (or criteria). Thus, the element $x_i(k)$ of **X** means the value of the $k$th indicator of the $i$th project delivery model.

Usually, it is difficult to compare different kinds of indictors because of the different dimension. Therefore, the standardized transformation to these indictors must be done. Three formulas can be used to do this as follows:

$$x_i(k) = [x_i(k) - \min x_i(k)] \,/\, [\max x_i(k) - \min x_i(k)], \qquad (1)$$

$$x_i(k) = [\max x_i(k) - x_i(k)] \,/\, [\max x_i(k) - \min x_i(k)], \qquad (2)$$

$$x_i(k) = | x_i(k) - x_{obj} | / [\max x_i(k) - \min x_i(k)], \tag{3}$$

where $x_{obj}$ is the objective value. Equation (1) is the transformation for the benefit-type indicator; Eq. (2) is the transformation for the cost-type indicator and Eq. (3) is the transformation for the optimization-type indicator. Next, the absolute difference of the compared series and the referential series should be determined by the following formula $\Delta x_i(k) = | x_o(k) - x_i(k) |$, where $x_o(k)$ is the element of referential series. Find the maximum and minimum of $\Delta x_i(k)$ and compute the grey relational coefficient $\gamma_o(k)$, which is defined by

$$\gamma_{oi}(k) = [ \min\Delta x_i(k) + \zeta\max\Delta x_i(k)] / [\Delta x_i(k) + \zeta\max\Delta x_i(k)], \tag{4}$$

where $\zeta$ is the distinguishing coefficient of the grey relation. In practical application, $\zeta = 0.5$. Finally, calculate the relational degree by

$$\Gamma_{oi}(k) = \Sigma_k[w(k) \times \gamma_{oi}(k)], \tag{5}$$

where $w(k)$ is the weight of the $k$th indicator and $\Sigma_k w(k) = 1$. The result of Eq. (5) can be used to measure the performance of road project delivery models. To determine the weight of each indicator is a problem. Three weighting profiles are compared in this study. The first one is equal weighting profile, which considers the importance of each indicator is equal. If the total number of criteria is $n$, then $w(k)$ is equal to $1/n$. The second one is nested weighting profile, which is determined by the hierarchy of the indicator. In this study, the indicators are categorized into two levels. Let $n_1$ be the number of categories of the first level and $n_{j2}$ be the number of indicators in the second level belongs to the $j$th category in the first level. If indicator $k$ belongs to $j$th category in the first level, then $w(k)$ is equal to $1/(n_1 \times n_{j2})$.

The third one is the grey entropy weighting method. The concept is derived from Shannon's entropy (Shannon, 1948), which quantifies uncertainty associated with a set of information or data. The grey entropy weighting method combines the concept of "least information theory" with the grey system theory (Deng, 1989) and the concept of Shannon's entropy. Because the grey entropy weighting method (Bezdek and Pal, 1992, Wen and Wu, 1996, 1998, ) determines the weight of each indicator by the uncertainty of its collected data, it is considered as an objective weighting profile. The grey entropy weighting method is described in brief as follows. Grey entropy weight of sequence $\boldsymbol{X}$ is defined by

$$e(k) = -\frac{\sum_{i=1}^{n} f_i(k) \ln x_i(k)}{\ln n}, \tag{6}$$

where $f_i(k) = x_i(k) \Big/ \sum_{i=1}^{n} x_i(k)$ is the weight of each element. To ensure Eq. (6) meaningful, let $\hat{x}_i(k) = \beta x_i(k) + (1-\beta)$, where $\beta$ is an arbitrary constant. Generally, $\beta$ is suggested to be 0.9. Thus, Eq. (6) is rewritten as

$$e(k) = -\frac{\sum_{i=1}^{n} \hat{f}_i(k) \ln \hat{x}_i(k)}{\ln n}, \tag{7}$$

where $\hat{f}_i(k) = \hat{x}_i(k) \Big/ \sum_{i=1}^{n} \hat{x}_i(k)$. Then the entropy weighting is given by

$$w(k) = \frac{1 - e(k)}{\sum_{k=1}^{m} 1 - e(k)}, \tag{8}$$

Next, the GRA with different weighting profiles is applied to analyze the four road project delivery models.

## EMPIRICAL STUDY

Before analyzing the models, the background about the studying case of road construction is introduced. A set of secondary data, which is collected and estimated by Koppinen and Lahdenperä (2004a and 2004b), is employed. Since one road construction would be only delivered by one model, it is impossible to compare the four project delivery models by the same case. Besides, there is no project that can represent the typical road delivery project. Each project is unique in one way or another. Therefore, Koppinen and Lahdenperä collected data by interviewing clients (government officials), contractors, designers and consultants in five countries, which are Finland, United Kingdoms, United States of America, Australia and New Zealand. The five countries are chosen because of their experiences of road project delivery methods. There are 66 interviewees, which were selected through expert referrals, industry journals and databases, local road administrators' Web pages, and referenced articles. Table 1 gives the number and their nationality. The questionnaire involved gathering general performance information instead of detailed, case-specific time, and cost. Interviewees were asked to give 'average' estimates based on numerous projects or to give estimates based on one or a few cases, whereby the impacts of potentially unique circumstances were eliminated. Then, a real Finnish DB project is considered as a base case. Its time and cost of each phase are derived from the interviews and literature review, which are listed in Table 2.

Table 1. The Number of Research Interviewees (Koppinen and Lahdenperä, 2004b).

| Country | Client | Contractor | Designer | Consultant | Total |
|---|---|---|---|---|---|
| Finland | 11 | 4 | 1 | 1 | 17 |
| UK | 5 | 2 | 0 | 1 | 8 |
| Australia | 12 | 4 | 1 | 4 | 21 |
| New Zealand | 1 | 1 | 1 | 2 | 5 |
| USA | 4 | 1 | 2 | 8 | 15 |
| Total | 33 | 12 | 5 | 16 | 66 |

Firstly, we assess the efficiency of the four models by the time and cost factors directly. According to the original data, CM has the best control of time, the design and construction cost of DB is the minimum, and the operation and maintain cost of DBM is the minimum. The evaluating indicators are classified into time and cost categories and each of the categories includes two indicators, which is shown in Table 2. Because the indicators in Table 2 are cost-type, Eq. (2) is considered to transform the original data. The minimal value of each indicator is considered as the element of the referential series; that is, (0.21, 4, 53122, 12568). The equal weight, nested weight and entropy weight are denoted by $w_1$, $w_2$ and $w_3$, respectively. The weights ($w_1$, $w_2$ and $w_3$) are given in Table 3 and the relational degree ($\Gamma_1$, $\Gamma_2$ and $\Gamma_3$) and the ranking of the four models are shown in Table 4. Because the indicators are classified into two categories and each category has two indicators, the profile of $w_1$ is equal to the profile of $w_2$. From Table 4, the ranking of the relational degrees is $\gamma_3 > \gamma_1 > \gamma_4 > \gamma_2$; that is, CM is the best model, DBB is the worst one. DB is better than DBM. The ranking of $\Gamma_1$, $\Gamma_2$ and $\Gamma_3$ are the same.

Table 2. Time and cost information used of the base case (Koppinen and Lahdenperä, 2004b).

| Time phase factor unit:[year] | Notation | DB | DBB | CM | DBM |
|---|---|---|---|---|---|
| Procurement | $C_1$ | 0.875 | 0.42 | 0.21 | 1.5 |
| Design and Constructi | $C_2$ | 4.3 | 5.2 | 4 | 4.6 |
| Total (time) | | 5.175 | 5.62 | 4.21 | 6.1 |
| Cost factor unit:[1000eı | | DB | DBB | CM | DBM |
| Design and Constructi | $C_3$ | 62,856 | 73,664 | 66,794 | 53,122 |
| Operation and Mainten: | $C_4$ | 12,569 | 17,777 | 19,067 | 16,824 |
| Total | | 75,425 | 91,441 | 85,861 | 69,946 |

Table 3. The Three Weighting Profile of the Time and Cost Indicators.

| Time phase factor unit (year) | Notation | $w_1$ | $w_2$ | $w_3$ |
|---|---|---|---|---|
| Procurement | $C_1$ | 0.25 | 0.25 | 0.278 |
| Design and Construction | $C_2$ | 0.25 | 0.25 | 0.270 |
| Cost factor unit (1000 euro) | | | | |
| Design and Construction | $C_3$ | 0.25 | 0.25 | 0.237 |
| Operation and Maintenance | $C_4$ | 0.25 | 0.25 | 0.215 |

Table 4. The Ranking of the Models Based on the Three Weighting Profiles.

| | $\Gamma_1$ | ranking | $\Gamma_2$ | ranking | $\Gamma_3$ | ranking |
|---|---|---|---|---|---|---|
| DB | 0.668 | 2 | 0.668 | 2 | 0.653 | 2 |
| DBB | 0.451 | 4 | 0.451 | 4 | 0.461 | 4 |
| CM | 0.691 | 1 | 0.691 | 1 | 0.721 | 1 |
| DBM | 0.567 | 3 | 0.567 | 3 | 0.558 | 3 |

Measuring the efficiency by the time and cost factors directly may lose some crucial information. Therefore, Koppinen and Lahdenperä (2004b) propose twelve indicators, which are classified into four main categories: economic efficiency, development potential, potential efficiency and influence of the future business environment. The four categories are introduced briefly as follows. Public owners are constantly challenged to find the right combinations of cost, time, quality and other value determinants. Economic efficiency is considered to measure cost and value comprehensively. Economic efficiency is determined by the ratio of value generation to cost performance. The more value the project delivery system creates at a certain cost, the more economically efficient way it is to procure roads. Development potential is employed to assess the future performance of the project delivery methods. Two components are included: the project delivery method's inherent ability to develop and the available means of improvement. Both the cost and value generation of the inherent ability and available means are assessed. Development potential of the project delivery means the difference in value for money between traditional and more innovative project delivery methods. Also, the cost and value generation of development potential are assessed. The last one is the influence of the future business environment, which includes the influences of controlling factors, input factors, output factors, mechanisms to success and operative factors. The description and weights of the items are listed in Table 5.

Table 5. Notation and Weighting Profiles of the Evaluating Indicators of Cost Performance and Value Generation.

| Description | | Notation | $w_1$ | $w_2$ | $w_3$ |
|---|---|---|---|---|---|
| Economic efficiency | Cost performance of current economic efficiency | $S_1$ | 0.083 | 0.25 | 0.129 |
| Development potential | Cost performance of inherent ability to develop | $S_2$ | 0.083 | 0.0625 | 0.070 |
| | Value generation of inherent ability to develop | $S_3$ | 0.083 | 0.0625 | 0.084 |
| | Cost performance of means of improvement | $S_4$ | 0.083 | 0.0625 | 0.083 |
| | Value generation of means of improvement | $S_5$ | 0.083 | 0.0625 | 0.082 |
| Potential efficiency | Cost performance of future potential | $S_6$ | 0.083 | 0.125 | 0.077 |
| | Value generation of future potential | $S_7$ | 0.083 | 0.125 | 0.081 |
| Influence of the future business environment | Future performance of controlling factors | $S_8$ | 0.083 | 0.05 | 0.025 |
| | Future performance of input factors | $S_9$ | 0.083 | 0.05 | 0.106 |
| | Future performance of output characteristics | $S_{10}$ | 0.083 | 0.05 | 0.096 |
| | Future performance of mechanisms for success | $S_{11}$ | 0.083 | 0.05 | 0.088 |
| | Future performance of operative factors | $S_{12}$ | 0.083 | 0.05 | 0.076 |

Also, three weighting profiles ($w_1$, $w_2$ and $w_3$) are compared. The original data of the indicators are shown in Table 6. The maximal value of each column is considered as the element of the referential series; that is, (1.6, 0.58, 0.92, 0.71, 0.62, 0.6, 0.7, 0.26, 1.33, 1.11, 0.71, 0.67). In this study, the indicators are benefit-type; therefore, Eq. (1) is employed to transform the original data. Finally, the relational degree and the order of two weighted profiles are given in Table 7.

Table 6. The Original Data of the Indicators (Koppinen and Lahdenperä, 2004b).

| | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ | $S_8$ | $S_9$ | $S_{10}$ | $S_{11}$ | $S_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DB | 1.29 | 0.49 | 0.61 | 0.71 | 0.62 | 0.6 | 0.61 | 0 | 0.88 | 0.67 | 0.71 | 0.17 |
| DBB | 1 | 0 | 0 | 0.21 | 0.31 | 0.11 | 0.15 | -0.07 | 0.44 | -0.22 | 0.44 | -0.17 |
| CM | 1.04 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | -0.04 | 0 | 0.44 | 0.04 | 0.5 |
| DBM | 1.6 | 0.58 | 0.92 | 0.57 | 0.48 | 0.58 | 0.7 | 0.26 | 1.33 | 1.11 | 0.53 | 0.67 |

According to Table 7, no matter which weighted profile is considered, the ranking of the four project delivery models is $y_4 > y_1 > y_3 > y_2$; that is, DBM is the best one and DBB is the worst one. DB model is better than CM model. The result is quite different from the result in Table 4. The major reason is that the twelve indicators focus not only the efficiency of cost but also the value generation. From Table 5, we can see the value generation and development potential are the major concern of the indicators. Therefore, DBM is considered the best.

Table 7. Ranking of the Relational Degrees Under Different Weighting Profiles.

| | $\Gamma_1$ | order | $\Gamma_2$ | order | $\Gamma_3$ | order |
|---|---|---|---|---|---|---|
| DB | 0.681 | 2 | 0.583 | 2 | 0.692 | 2 |
| DBB | 0.355 | 4 | 0.277 | 4 | 0.196 | 4 |
| CM | 0.360 | 3 | 0.284 | 3 | 0.275 | 3 |
| DBM | 0.835 | 1 | 0.681 | 1 | 0.725 | 1 |

In our preliminary study (Lo and Chao, 2007), several evaluation methods are employed to assess the performance of the four models, such as the data envelopment analysis (DEA) and cost/benefit analysis. The result of cost/benefit analysis depends on the setting of weight. In some weighted profiles, DBM is the best, whereas, DB is the best. DBB is always the worst one. Although the analysis of DEA does not need to set the weight, the results are diverse. DB, DBM and CM are at the frontier of the envelop curve. CM has the efficiency of construction time. DB is efficient in maintenance and DBM is efficiency in design and construction. A serious problem of applying DEA is the number of indicators is much more than the number of the alternatives that will induce multiple solution of the problem. In this study, the grey relational analysis is employed to evaluate the performance of road project delivery methods successfully. The procedure of analysis may be a good method to assess the road construction models.

## CONCLUSIONS AND PERSPECTIVES

In this study, four road delivery project models, which are CM, DB, DBB and DBM, are compared by the grey relational analysis with three weighting profiles. An empirical study is employed to determine the performance of the four models. Two kinds of data are employed and the results of ranking are quite different. If we only want to minimize the time and cost factors, CM is the best RPD model. If the cost performance, value generation and potential are considered, DBM is the best method. No matter which set of data is employed, the traditional method DBB is the worst. To assess the efficiency of RPD models, we suggest that the cost performance, value generation and potential should be considered at the same time. That is, DBM should be considered first. The conclusion could be a suggestion for initiating a road construction project. From the practical viewpoint, projects differ from each other. The project delivery methods are neither equal effect nor equal results under all project conditions. Any one of the resulting processes may be the most effective one only under certain conditions. It is still often appropriate to use DBB, when projects are relatively small, simple, have well-defined end results, and offer no opportunities to innovate or to generate revenue. In addition, if politics is likely to lead to substantial changes during the project, the DBB is advantageous. However, the usage of DBB is likely to decrease in the future, but it will remain one of the road project delivery alternatives. On the other hand, DBM may involve political issues and induce time delay in procurement phase. Therefore, if a construction project is initialized, delivery model has to be chosen carefully based on characteristics of the project.

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