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# MULTI-OBJECTIVE DECISION-MAKING TO SELECT MULTIPLE PROJECT DELIVERY METHODS FOR MULTI-PROJECT TRANSPORTATION SYSTEMS

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This paper focuses on providing a methodology to optimize the selection of multiple project delivery methods for multi-project transportation systems under uncertainty. In contrast to previous studies, this paper considers that owners sometimes divide transportation projects into sub-projects that are constrained by construction sequence. The owners' objectives are to minimize the total project cost and duration for the whole multi-project undertaking by selecting the most appropriate project delivery method for each sub-project. The complexity of this problem is the motivation for the development of a multi-objective decision making model that can help owners evaluate and choose the appropriate project delivery method for each sub-project. The model considers three fundamental project delivery methods, i.e., design–bid–build, design–build, and construction manager-as-general contractor. The project cost and duration of each sub-project when selecting different project delivery methods are estimated by experts employed and/or retained by the owner, and regarded as fuzzy variables. Furthermore, a fuzzy simulation-based multiple objective particle swarm optimization algorithm is developed to find feasible Pareto solutions. Results and analysis of a numerical example are presented to highlight the performance of the model.

*Keywords*: Fuzzy, Multi-project transportation system, Pareto solutions.

## 1 INTRODUCTION

The selection of project delivery methods may have significant impact on the project duration and cost (Gordon 1994). Contractual relations, contemporary laws and regulations, the owner's perception of risks, awarding mechanism and the method of payment all contribute to project delivery system selection (Ghavamifar and Touran 2008). Each of the three project delivery systems in this study have their own set of advantages and disadvantages. Design-bid-build (DBB) has the most history behind it, as it is the most used, both historically and currently. This makes owners and contractors confident of their ability to execute the contract. DBB also usually produces the lowest bid price of the three. The other two systems, design-build (D-B) and construction-manager-as-general-contractor (CM/GC), are known as "fast-tracked" delivery systems due to the fact that portions of the project may be under construction before other parts of the project are designed. D-B and CM/GC therefore offer a shorter duration than DBB. They also offer a higher degree of innovation in design and construction (Minchin et al. 2013). Innovation often results in lower actual costs than DBB. A disadvantage of fast-tracked systems, at least to the owner, is that the owner gives up some of the control that it enjoys in the DBB system. In short, the owner trades control for speed and innovation. CM/GC offers more control to the owner than D-B because of a direct contractual relationship with the designer, which gives the owner ultimate control of the design. CM/GC has the additional advantage of affording the parties the flexibility, long into the project, to allocate and re-allocate risk to the appropriate parties. This can further increase innovation and lower cost.

There have been numerous studies focusing on the selection of project delivery methods. According to Touran et al. (2009a), the relevant literature can be divided into two groups, (1) literature that compares project delivery methods on the basis of observed performance measurements collected from a group of projects, and (2) literature that provides a list of criteria and a framework for decision making. One of the best examples of the first kind of literature comes from Konchar and Sanvido (1998), in which a set of criteria is defined for a performance comparison of different delivery methods. Existing literature on the second group present a variety of selection tools for owners. Oyetunji and Anderson (2006), Touran et al. (2009b), Chen et al. (2011), Sillars (2009) and Mafakheri et al. (2007), among others, have developed decision models for selection of appropriate delivery methods for various types of projects. Now, there is a trend to simultaneously use multiple project delivery methods as described by Miller et al. (2000), which has never been studied for transportation construction. Mafakheri et al. (2007) described uncertain aspects of a construction project, such as cost and duration, by using fuzzy theory. As a result, this paper employed the fuzzy-theory method to deal with the uncertainty encountered in multi-project transportation systems.

## 2 PROBLEM STATEMENT

When encountering multi-project transportation systems, the problem becomes much more complex due to the usual limitations of time and cost, plus the precedence constraints between sub-projects.

### 2.1 Project Delivery in Multi-Project Transportation Systems

Transportation construction projects are usually large, horizontal public projects such as highways, airports, subways, dams, and railroads. Many such projects span multiple jurisdictions, which introduces the contract parties to sometimes substantial differences in statutes, regulations and procedures. Also, the whole concept of the fast-tracked delivery systems allows the contractor to build in areas where permits and right-of-way have been procured and utility lines relocated before those things have been accomplished in other areas of the project. Often in these circumstances, the best strategy for the owner is to divide the project into sub-projects. In this paper, this kind of large-scale transportation project is defined to be a multi-project transportation system.

### 2.2 Selection of Multiple Project Delivery Methods

The trend described by Miller et al. (2000) means for a multi-project transportation system, its sub-projects may require different project delivery methods simultaneously. For example, assume there are three bridges, two subways, and three highways to construct under one multi-project transportation system. The construction of the three bridges may not be started until the completion of the two subways. However, the owners' objectives are to minimize cost and duration for the whole project. This means when the owner makes selections of project delivery methods for each sub-project, they should not only consider the project cost and duration for each sub-project, but also consider the construction sequence relationship among each sub-project. This leads to a multiple-objective decision making optimization problem.

### 2.3 Uncertainty of Estimated Cost and Duration for Each Sub-Project

In this paper, the estimated cost and duration for each sub-project were assumed to be triangular fuzzy numbers, where the optimistic estimation value was regarded as the left boundary of the triangular fuzzy number, and the pessimistic estimation value as the right boundary. The highest possible value of the triangular fuzzy number was estimated based on the analysis of several experts according to the fluctuation of construction material prices, labor costs, and so on.

## 3 MODELLING APPROACH

In order to minimize the total cost and duration of the multi-project transportation system, a multiple objective decision making model was established.

### 3.1 Decision Variables

The decision variables in this model determine the selection of the project delivery method and the start time for each sub-project. Let $x_i^j$ denote the decision variable of selecting the project delivery method for sub-project i, then:

$$x_i^j = \begin{cases} 1, & \text{if project delivery method j is selected for sub-project i,} \\ 0, & \text{if project delivery method j is not selected for sub-project i} \end{cases}$$

where j is the index of project delivery (j=1: DBB; j=2: D-B; j=3: CM/GC); i is the index of sub-project (i=0, 1, 2, …, n, here sub-project 0 and n are assumed to be dummy projects and represent the start and end nodes respectively). The other decision variable is defined as $T_i$, which denotes the start time of sub-project i.

### 3.2 Objective functions

The two objectives of this model were to minimize the total cost and the total duration of the multi-project transportation system.

### *3.2.1 Total cost*

As discussed above, different project delivery methods will lead to different sub-costs for each sub-project. Let $c_i^j$ denote the cost of sub-project i when selecting project delivery method j. Then the total cost for the multi-project transportation system is:

$$f_{\cos t} = \sum_{i=0}^{n} \sum_{j=1}^{3} x_i^j c_i^j \tag{1}$$

where costs of dummy projects (i.e., i=0 and n), i.e., $c_0^j$ and $c_n^j$, are assumed to be 0.

### *3.2.2 Total duration*

Since the duration of the dummy project was assumed to be 0, the total duration of the multi-project transportation system could be expressed by the duration between the start time of sub-project 0 and the start time of sub-project n as below:

$$f_{duration} = T_n - T_0 \tag{2}$$

## 3.3 Constraints

According to the practical situation, the following constraints should be added to the decision variables.

### *3.3.1 Selection constraint*

Since any sub-project can only be completed by one project delivery method, then:

$$\sum_{j=1}^{3} x_i^j = 1, \quad \forall i \tag{3}$$

### *3.3.2 Precedence constraint*

Usually, a multi-project transportation system has a construction sequence between each sub-project, thus the start time of each sub-project $T_i$ should satisfy the precedence constraint. Let $d_i^j$ denote the duration of sub-project I when selecting project delivery method j, and let Pre(i) be the immediate predecessors set of sub-project i. Then for i=1, 2, …, n,

$$T_k + \sum_{j=1}^{3} x_k^j d_k^j \le T_i, \quad \forall k \in \Pr e(i) \tag{4}$$

# 4 NUMERICAL EXAMPLE

## 4.1 Data Description

In this example, a multi-project transportation system containing eight sub-projects was considered as described in Section 2.2, where the start node (i=0) and the end node (i=n) were assumed to be dummy projects. Here, the start time of sub-project 0 was assumed to be 0. All the necessary information is shown in Table 1.

### 4.2 Algorithm Design

To solve this model, a fuzzy simulation-based MOPSO algorithm was developed to find feasible Pareto solutions. For dealing with the triangular fuzzy number in Table 1, the fuzzy simulation algorithm initialized these parameters by generating a value between the optimistic and pessimistic values, then the MOPSO (Kennedy and Eberhart 1995, Coello et al. 2004) was employed.

Table 1. Information of cost and duration for each sub-project.

| Sub-project index | Sub-cost $c_i^j$ ($10^6$\$) | | | Sub-duration $d_i^j$ (day) | | |
|---|---|---|---|---|---|---|
| | $j=1$ | $j=2$ | $j=3$ | $j=1$ | $j=2$ | $j=3$ |
| i=0 | (0,0,0) | (0,0,0) | (0,0,0) | (0,0,0) | (0,0,0) | (0,0,0) |
| i=1 | (7.4,7.8,8.2) | (11.8,12.6,13.1) | (9.2,10.3,11.1) | (67,71,75) | (42,48,53) | (52,56,59) |
| i=2 | (14.3,14.6,14.8) | (18.8,19.2,19.5) | (16.5,16.8,17.2) | (102,110,115) | (76,79,83) | (87,90,92) |
| i=3 | (21.7,22.0,22.4) | (28.9,29.3,29.5) | (24.3,24.9,25.4) | (143,151,155) | (104,108,112) | (125,127,130) |
| i=4 | (10.6,10.9,11.2) | (16.4,16.8,17.2) | (12.8,13.1,13.5) | (78,82,86) | (43,46,49) | (58,63,68) |
| i=5 | (18.3,18.5,18.9) | (30.1,31.0,31.7) | (25.2,25.6,26.0) | (70,73,78) | (33,35,37) | (52,56,59) |
| i=6 | (7.4,7.9,8.3) | (8.6,8.9,8.4) | (4.2,4.5,4.9) | (42,47,51) | (29,32,35) | (28,31,33) |
| i=7 | (13.2,13.6,13.9) | (15.6,15.8,16.3) | (12.3,12.5,12.8) | (61,63,66) | (35,37,39) | (33,35,38) |
| i=8 | (22.0,22.3,22.7) | (30.7,31.1,31.4) | (26.4,26.8,27.2) | (88,91,92) | (48,52,55) | (67,70,72) |
| i=9 | (0,0,0) | (0,0,0) | (0,0,0) | (0,0,0) | (0,0,0) | (0,0,0) |

### 4.3 Results Analysis

Two Pareto solutions, lowest total cost and shortest total duration, are shown in Table 2. The results were obtained based on the highest values for all triangular fuzzy numbers of costs and sub-durations that can be generated through fuzzy simulation algorithms. Table 2 shows a trade-off between the total cost and total duration objectives. The choices for sub-projects 6 and 7 were CM/GC, while the choices for other sub-projects depended on whether speed, cost or another factor was the highest priority.

Table 2. Results for the lowest total cost and shortest total duration solutions.

| Sub-project index | Lowest total cost | | | | Shortest total duration | | | |
|---|---|---|---|---|---|---|---|---|
| | Start time | $x_i^j$ | | | Start time | $x_i^j$ | | |
| | $T_i$ (day) | $j=1$ DBB | $j=2$ DB | $j=3$ CM/GC | $T_i$ (day) | $j=1$ DBB | $j=2$ DB | $j=3$ CM/GC |
| i=1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| i=2 | 71 | 1 | 0 | 0 | 48 | 0 | 0 | 1 |
| i=3 | 71 | 1 | 0 | 0 | 48 | 0 | 1 | 0 |
| i=4 | 71 | 1 | 0 | 0 | 48 | 0 | 1 | 0 |
| i=5 | 153 | 1 | 0 | 0 | 94 | 0 | 0 | 1 |
| i=6 | 226 | 0 | 0 | 1 | 156 | 0 | 0 | 1 |
| i=7 | 257 | 0 | 0 | 1 | 187 | 0 | 0 | 1 |
| i=8 | 257 | 1 | 0 | 0 | 187 | 0 | 1 | 0 |
| total cost | $113.1 \times 10^6$ \$ | | | | $149.2 \times 10^6$ \$ | | | |
| total duration | 348 day | | | | 239 day | | | |

## 5 CONCLUSION

This paper provides a new viewpoint to optimize multiple-project delivery methods, including DBB, D-B, and CM/GC for multi-project transportation systems, by minimizing the total cost and total duration. To deal with the uncertainty of the estimated cost and duration for each sub-project, the fuzzy-theory method and a fuzzy simulation algorithm was employed to generate values within the optimistic and pessimistic estimated values. A multi-objective decision making model described the optimization problem, and a fuzzy simulation-based MOPSO algorithm was developed to find feasible Pareto solutions. The results show there is a trade-off between the total cost objective and the total duration objective for the decision maker, which means if the decision maker wants to shorten the total duration, the cost will increase**.**

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