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A transportation programming model considering project interdependency and regional balance ☆

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ABSTRACT

Transportation Programming (TP) plays an important role in the development of the infrastructure of a country. Given the limited budget, it is a challenging decision to select the projects to be funded and implemented from the numerous options. The problem is complicated by the fact that some of the potential projects are interdependent. The benefit (and/or the cost) of the joint project combining multiple projects can be different from the sum of the benefits (and/or the costs) if the associated projects are implemented separately. Besides, some projects cannot be selected at the same time as they are incompatible or exclusive to each other by nature. The typical examples are the projects utilizing the same resource, such as a piece of land. In addition, much more attention nowadays is paid to the fairness of budget allocation and the balance of regional development as the society becomes more democratic and diversified. Thus, in order to address the equity issue and the political feasibility, a new integer programming (IP) model based on the set covering problem (SCP) has been proposed to ensure that the regional balance issue is addressed. This SCP-based model, with the constraints taking into account the budget limitation and the projects' mutual exclusivity, is transformed into a linear programming (LP) model by Lagrangian Relaxation (LR). The key theme of this study is then to design the solution algorithm that can efficiently adjust the LP multipliers and find the feasible solutions so as to achieve a high-quality approximate solution within an acceptable computation time. Finally, a numerical experiment that can reflect the practical situations is performed to validate the applicability of the developed model and solution algorithm.

1. Introduction

Transportation Programming (TP) is a core decision problem for the development of the infrastructure of a country. Given the limited budget, it is a challenge to select the projects to be funded and implemented from the numerous potential projects. The problem is complicated by the fact that some of the potential projects are interdependent. The benefit (and/or the cost) of a joint project, which combines multiple projects, can be different from the sum of the benefits (and/or the costs) if the associated projects are implemented separately. Besides, some projects cannot be selected at the same time as they are exclusive to each other by nature. The typical examples are the various versions (or scales) of one project or the multiple projects utilizing the same resource, such as a piece of land. In the literature, it is common for the TP problem

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to be modeled by a formulation based on the knapsack problem (KP), which is not particularly suitable for dealing with project interdependency.

Another key concern for transportation programming in this study is the fairness of budget allocation. The relationship between the transport infrastructure provision and the regional equity has drawn the attention of many researchers. For example, de Almeida and Haddad (2010) recently conducted a case study for Minas Gerais, which is Brazil's third richest state and second most populous state, but with a strong regional inequality within its territory. As societies in general become more democratic and diversified, much more attention nowadays is being paid to the balance of regional development. It is believed that the traditional TP models need to be modified or enhanced to take into account the issue of regional balance so as to find an acceptable trade-off during the decision process of budget allocation.

In this study, the area being examined is thus divided into multiple regions, and the relevance (significance) of the projects to the regions is assumed to be evaluated in advance. With the aim being to raise the equality and feasibility for transportation programming, this study develops a new integer programming (IP) model based on the set covering problem (SCP), in which the significance constraint ensures that no region is ignored during the planning process. For the solution algorithm of this SCP-type IP problem, this study employs the approach of Lagrangian Relaxation (LR), which has been proved to be an effective method for the classic SCPs. The significance constraints and the budget constraint are chosen to be relaxed after attaching the associated penalties to the objective function. A heuristic procedure has been designed to handle the relaxed problem and generate the feasible solution and the lower bound.

This paper is organized as follows. The next section provides a literature review of the TP problem, and in particular elaborates upon the special features of project interdependence. In Section 3, the MIP model of the concerned TP is presented and the development of the solution algorithm is explained in detail, including the transformation of the original problem into a Lagrangian-relaxed set covering problem, the procedures in the recursive algorithm to derive the lower bound and the feasible solution. The design of the numerical experiment and the associated results are described in Section 4. Finally, the findings of this study are concluded in Section 5.

2. Literature review

In addition to its wide application in problems such as loading, packing, and material cutting, the models based on the Knapsack Problem are the major techniques used for solving the TP problems (e.g., Sinha and Muthusubramanyam, 1981). The budget is viewed as the capacity of the knapsack, and the transportation projects are thought of as the items to be selected. The KP formulation is simple, but it is nonetheless an NP-complete problem. In general, a heuristic algorithm is required to deal with large-scale problems. Regarding the KP formulations as well as the solution algorithms and applications, the survey paper by Wilbaut et al. (2008) serves as an excellence source for further information.

As for the frameworks and the mathematical models for transportation programming, the book chapter by Sinha and Labi (2007) provides the basic introduction and the related discussion. Due to the intrinsic complexity of transportation programming, many researchers have begun to extend the TP models to the version of multiple objectives from a practical point of view. For example, both Teng and Tzeng (1998) and Avineri et al. (2000) make use of the fuzzy theory to deal with the TP problems under the multi-objective context. Iniestra and Gutiérrez (2009) develop a TP model based on a variant of the multi-objective 0–1 Knapsack Problem. On the other hand, Zhong and Young (2010) transform the multi-objective problem into the single-objective problem by using the Analytic Hierarchy Process (AHP) to determine the weights. As the problem size is small, the IP solver of a software package (LINGO) is used to find the optimal solution.

The projects to be selected in most of the prior research works for transportation programming have been assumed to independent. One of the exceptions is Gomes (1990), who models the interdependencies among urban transportation system alternatives under the multi-criteria framework by developing a ranking method. Teng and Tzeng (1996) further categorize the projects into four kinds: independent, complementary, substitutive, and both complementary and substitutive. The formulation is based on a binary multi-objective multidimensional Knapsack Problem, given that the constraints for multiple types of resources are considered. They further develop a solution algorithm called the Spatial Efficiency Algorithm to find the approximate solution. Similar to the context of multiple criteria and the consideration of project interdependency in Teng and Tzeng (1996), Iniestra and Gutiérrez (2009) believe that the overall effect of a portfolio of infrastructure investment is different from the sum of all individual investments and use an evolutionary-based framework to identify the Pareto solutions. Finally, one specific feature of project interdependency, the mutually exclusive relationship, has been considered in Zhong and Young (2010).

Although some features of project interdependency have been addressed in the prior research works described in the previous paragraph, we believe that not all of the possible relationships between two (or even multiple) projects have been considered simultaneously in a model. Due to the possible synergy between two projects, the extra benefit from implementing them at the same time should be considered. On the other hand, there is a chance, though not desirable, for the simultaneous implementation of projects to result in a reduction in the overall benefit. In addition, when multiple projects are implemented as a joint project, the cost change should be modeled explicitly as well. Thus, in order to provide a higher degree of flexibility for modeling project interdependency, the combination of multiple projects is treated as a different project whenever its benefit (and/or cost) is different from the sum of the benefits (and/or the costs) of the associated projects under a separate implementation. The basic projects and the joint projects are later referred to as the *options*, for which each one is represented by a distinct binary decision variable from the modeling viewpoint.