IIT ERIF Fund: Multi-Commodity Flows and Algorithmic Graph Theory in Sustainable Transportation Decision-Making

Mid-Year Progress Report

From

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Background Information. The objective of transportation decision-making is to decide which projects to invest in and implement, such that total utility of the transportation network after project implementation viewed from economic (total cost to the transportation agency and the user), social (traffic mobility and safety), and environmental (energy consumption and vehicle emissions) dimensions is maximized. In current state-of-practices, decisions are made in accordance with project benefits that are estimated by independently capturing localized impacts of individual projects. The ignorance of network-level impacts and interdependency relationships of individual projects does not ensure globally optimal decisions. This study aims to develop a new optimization model along with efficient solution algorithms that explicitly addresses project network-level impacts and interdependency relationships for truly optimal investment decision-making to support sustainable transportation. The initial findings and research problems identified from this study will help the research team prepare large-size research proposals to continue exploring enhanced methods and models for transportation decision-making.

Progress to Date. In the past six months, the research has been mainly focused on i) formulating a new optimization model that explicitly handles project network-level impacts and interdependency relationships; ii) developing solution algorithms; and iii) conducting a computational study for testing the model and algorithm. The optimization model for selecting a sub-collection of candidate projects to achieve maximized overall benefits under budget and integrality constraints is formulated as the Graphical Knapsack Problem. It seeks a budgeted maximum-benefit subgraph in an "induced subgraph", which is a vertex-weighted graph with project benefits on the vertices and interdependence coefficients of pairwise project benefits on the edges.

In the process of estimating network-level benefits of a project, the multi-commodity minimum cost flow model is introduced. The multi-commodity flow models multiple traffic origin-destination (O-D) pairs. The objective is to channelize all O-D traffic demands through the transportation network with minimized total network-level travel time costs. The project benefits are determined as reduction in total network-level travel time costs after project implementation. In current study, only pairwise interdependency relationships of project benefits are considered. The interdependency coefficient in the benefits of a pair of projects is defined as the difference between the total benefits by simultaneously implementing two projects and the sum of two individualized project benefits by implementing one project at a time.

The Graphical Knapsack Problem gives rise to a new generalization of two classes of very important and difficult combinatorial optimization problems: the Knapsack Problem and the Heaviest Subgraph Problem. In addition to investigating some elementary algorithmic properties of this problem, such as difficulty of solving it using greedy algorithms, a Polynomial Time Approximation Scheme (PTAS) algorithm is developed for graphs with bounded tree-width that could guarantee close to optimal solution as needed in relatively fast time. The study of the characteristics of graphs that model project interactions is an interesting topic for further study.

The Chicago loop area comprised of 36 O-D zones (21 internal and 15 external, which produce 666 commodity flows) is chosen for the computational study. Detailed data on network connectivity, number of lanes per direction, per lane capacity, speed limits, and hourly O-D traffic demands have been collected and processed. A permanent license on the Frontline Solver was purchased. So far, some preliminary runs of the multi-commodity minimum cost flow model have been conducted.

Next-Step Work. The completion of the computational study for model and algorithm tests and its impact will be the topic of our continued study. We also note that as an additional outcome we are considering refining the objective function used to evaluate benefits in our model. In the current multi-commodity minimum cost flow formulation, the objective function aims to minimize the total transportation network travel time costs as the basis of project benefit estimation. This assumes that the traffic would follow a "social optimum" objective. As an alternative, we will also consider a greedy "user equilibrium" objective where each user optimizes his/her travel time at the given point of time. This creates a different set of project benefit estimations. Cross comparisons will be made on the decision-making outcomes using two different traffic assignment philosophies. In the meantime, we will also explore new algorithms that could efficiently solve the Graphical Knapsack Problem with tight bounds in the solution quality. Another item is to extend project interdependency relationships from pairwise projects to multiple projects and to be able to generate optimal or close to optimal solutions to determine projects that should be chosen for interdependency considerations.

Concurrent to the above major work items, the research team plans to submit the first joint proposal to the NSF Civil Infrastructure Systems (CIS) Sub-Program under Resilient and Sustainable Infrastructures (RSI) Program that funds interdisciplinary research in transportation asset management and in the broader context of critical infrastructure systems management.