Robotics and Computer-Integrated Manufacturing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Simulation-based multi-objective model for supply chains with disruptions in transportation

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ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form
17 December 2015
Accepted 29 December 2015

Keywords:
Minimum cost flow
Simulated annealing
Simulation optimization
Stochastic multi-objective optimization
Resilient supply chains

ABSTRACT

Unpredictable disruptions (e.g., accidents, traffic conditions, among others) in supply chains (SCs) motivate the development of decision tools that allow designing resilient routing strategies. The transportation problem, for which a model is proposed in this paper, consists of minimizing the stochastic transportation time and the deterministic freight rate. This paper extends a stochastic multi-objective minimum cost flow (SMMCF) model by proposing a novel simulation-based multi-objective optimization (SimMOpt) solution procedure. A real case study, consisting of the road transportation of perishable agricultural products from Mexico to the United States, is presented and solved using the proposed SMMCF-Continuous/SimMOpt solution framework. In this case study, time variability is caused by the inspection of products at the U.S.-Mexico border ports of entry. The results demonstrate that this framework is effective and overcomes the limitations of the multi-objective stochastic minimum cost flow problem (which becomes intractable for large-scale instances).

1. Introduction

The United States is the most important customer for the Mexican ornament flowers industry due to the geographical location of these two countries [1,2]. Road transportation is an affordable transportation method that is available to Mexican suppliers. According to the U.S. Bureau of Transportation Statistics [3], truck and rail transportation of products from Mexico to the United States increased by 3.7 percent, from $34.3 billion in May 2012 to $35.57 billion, in May 2013. Industry analysts expect this trend to continue growing in the near future.

Disruptive events are common in most transportation systems. Accidents, traffic conditions, and weather conditions (among others) are causes of disruptive events. Disruptive events are particularly important when transporting perishable products. The availability of inspection lanes and the process of drug trafficking scan and detection add variability to the crossing time on the U.S.-Mexico border ports of entry. The variability on the waiting time due to security inspections can be translated into important economic impacts [4]. Thus, disregarding factors such as the variability on transportation time results in poorly designed supply chains, which in turn lead to important economic loses [5].

Mathematical programming models have been developed to solve the problem of determining the optimal flow of units along the available transportation routes. Many of these models consider single objective functions, which compute the transportation cost and ignore the variability of time attributes on arcs. A more comprehensive model, however, might require additional considerations such as the extremization of different objectives (e.g., the transportation time, the transportation freight rates, among others). Frameworks based on the multi-objective shortest path problem (MSPP) or the multi-objective minimum cost flow (MMCF) can extremize several objective metrics; in many of such frameworks, nonetheless, deterministic attributes have been assumed. In real systems, the duration of the transportation disruptions and the availability of servers (e.g., cargo inspection agents) are stochastic factors that are time-dependent.

To incorporate the inherent uncertainties of disruptive events into the complex supply chain design optimization process, this paper presents a model that extends previous research work (*stochastic multi-objective minimum cost flow (SMMCF) Discrete model for solving the stochastic MMCF* [6] *problem with discrete*

Abbreviations: U.S., United States; SC, Supply Chain; SMMCF, Stochastic Multi-Objective Minimum Cost Flow; SimMOpt, Simulation-Based Multi-Objective Optimization; MSPP, Multi-Objective Shortest Path Problem; MMCF, Multi-Objective Minimum Cost Flow; MCF, Minimum Cost Flow; CPM, Cost Per Mile; SPP, Shortest Path Problem; SA, Simulated Annealing; TM, Trade Mark; NFL, No Free Lunch Theorem; BMCF, Bi-Objective Minimum Cost Flow; NP, Non-Deterministic Polynomial; DHS, Department of Homeland Security; Sched, Schedule; CONACYT, Mexico National Science and Technology Council

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http://dx.doi.org/10.1016/j.rcim.2015.12.008
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attributes) by considering stochastic continuous time disruptions and proposes a *novel simulation-based multi-objective optimization (SimMOpt) solution procedure for solving the continuous version* of the *SMMCF* problems (*SMMCF-Continuous*). The previous SMMCF-Discrete model considers a discrete distributed inspection time at the border ports of entry. The proposed novel SMMCF-Continuous model and SimMOpt solution procedure considers instead a more realistic, *continuously distributed inspection time* and identifies near-optimum solutions to large-scale instances of the problem of designing efficient routing plans for the international trade of perishable products.

The stochastic nature of the disruptive time is considered only for arcs that connect nodes that represent inspection operations at the ports of entry. The variability on the inspection time depends on the transportation service mode used to bring products across the border. Thus, cargo inspection time depends on the transportation mode employed. The general SMMCF model considers stochasticity related to the time attributes of some arcs connecting particular nodes, while keeping the rest of the attributes of the arcs deterministic. The main advantage of the SMMCF-Continuous model over the SMMCF-Discrete model is that the SMMCF-Continuous allows attributes, such as time, to be modeled by employing continuous probability distributions. Discretization of attributes that represent time does not accurately represent the real system. The main contribution of the proposed SimMOpt solution procedure is to overcome this limitation of the SMMCF-Discrete.

Important challenges arise when solving the SMMCF-Continuous problem. The number of possible values that coefficients representing stochastic elements can take increases exponentially. The large number of decision variables and multiple objective functions subject to constraints can become a problem in terms of convergence and computational time when using search algorithms. Some algorithms for solving this problem are subject to local-optima entrapment. Many become costly in terms of computational effort when searching solutions that depend on a large number of variables and subject to a number of hard constraints. Section 5 describes how the SimMOpt solution procedure overcomes these challenges.

There are many real applications that can be modeled as a stochastic minimum cost flow problem. For example, in real situations, the freight rate, which is assumed deterministic by the general SMMCF, follows a probability distribution. Fig. 1 shows the main components of the freight rate [7]. Fig. 2 shows the value of the U.S. based freight cost per mile (CPM) index between December 2013 and December 2014 [7]. These figures show how the

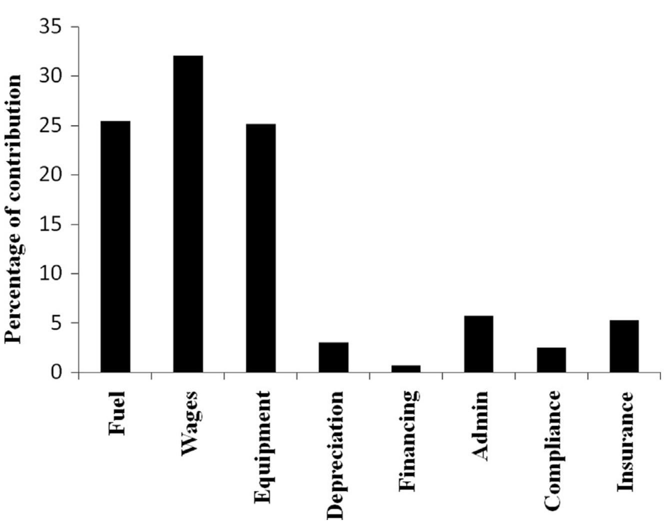

Fig. 1. Freight Rate Components (based on [7]).

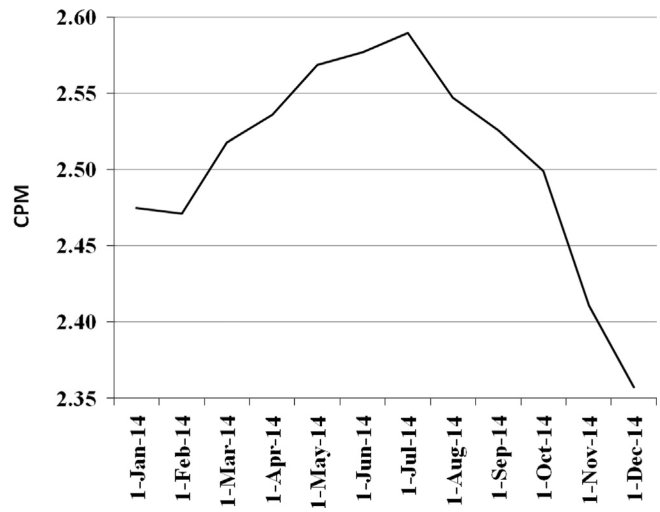

Fig. 2. U.S. CPM Index (based on [7]).

freight rates commonly change through time and how some factors contribute to the variability. The continuously distributed variation of the freight rate can be realistically modeled with the SMMCF-Continuous.

SMMCF-Discrete becomes ineffective when the statistical distribution of any of the stochastic attributes is modeled by employing a continuous probability distribution. The discretization of such distribution(s) into few classes can result in important inaccuracies while modeling the effects of time variability, for example. The SimMOpt solution procedure presented in this paper aims to overcome this limitation.

This paper is structured as follows: Section 2 presents a literature review of stochastic multi-objective minimum cost flow models and simulation models developed to treat multi-objective and/or stochastic versions of the transportation flow problem. Section 3 presents a description of the general SMMCF model and the SimMOpt solution procedure. Section 4 presents the mathematical formulation of the SMMCF-Discrete. Section 5 presents the implementation of the proposed SimMOpt solution procedure using MATLAB®™. Section 6 describes a real case study. Sections 7 and 8 present the results from using the SMMCF-Discrete model and the SimMOpt solution procedure to solve the case study. Sections 9 and 10 present the concluding remarks and future research.

2. Literature review

Different models and procedures have been developed for finding near-optimum solutions to the problem of transporting products. These models typically assume a finite vehicle capacity, a maximum flow capacity related to arcs, and a predefined number of visits to customers, among others. This section describes two of the most relevant methods used to solve this type of problem.

The first type of methods, based on linear optimization, serves as foundation for the development of the SMMCF-Discrete model. A review of this approach is presented in Section 2.1. Models that consider stochastic attributes related to each arc are of particular interest in this brief literature review.

The second type, based on simulation-optimization models, is the main foundation of the SimMOpt solution procedure. A review of this procedure is presented in Section 2.2.

Please cite this article as: H. Chávez, et al., Simulation-based multi-objective model for supply chains with disruptions in transportation, Robotics and Computer Integrated Manufacturing (2016), http://dx.doi.org/10.1016/j.rcim.2015.12.008