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Designing a reliable bio-fuel supply chain network considering link failure probabilities

Sushil R. Poudel, Mohammad Marufuzzaman *, Linkan Bian [1]

Department of Industrial and Systems Engineering, Mississippi State University, Starkville, MS 39759-9542, United States

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ABSTRACT

This study presents a pre-disaster planning model that seeks to strengthen a bio-fuel supply chain system's multi-modal facility links while accounting for limited budget availability. The model presented here determines which set of facilities and links to select that will maximize post-disaster connectivity and minimize bio-fuel supply chain related costs. The failure probability of the links between the multi-modal facilities is estimated using a spatial statistic model, which is developed from real world data. This paper develops a generalized Benders decomposition algorithm to solve this challenging $\mathcal{NP}$-hard problem. The proposed algorithm is validated via a real-world case study with data from Mississippi and Alabama. Computational results show that the proposed solution approach is capable of solving the problem efficiently. Several experiments are conducted to demonstrate the applicability of this model by testing various model parameters on bio-fuel supply chain network performance, including reliability improvement cost, availability of budget, biomass supply changes, and the risk averseness degree for decision makers. Numerical analysis indicates that, under normal conditions, the minimum cost model determines a unit bio-fuel delivery cost of $3.56/gallon. However, in case of a disaster, the unit bio-fuel delivery cost provided by the minimum cost model increases to $3.96/gallon, compared to $3.69/gallon provided by the reliable model solution.

1. Introduction

The U.S. bio-fuel industry is expanding at a phenomenal rate because of the implementation of the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 (U.S. Energy Information Administration, 2013). Both mandate the nation's annual bio-ethanol production should grow from 10.01 billion gallons in 2011 to over 36 billion gallons by 2022 (U.S. EPA, 2013). Such an increase in bio-ethanol production highlights the need for developing a reliable and efficient supply chain system that not only performs well under normal conditions but also hedges against risk under various unexpected disruption scenarios.

After a series of devastating disasters in recent years, including the U.S. Northeast blackout in 2003, Hurricane Katrina in 2005, earthquakes in China in 2008 and Haiti in 2009, and the Gulf of Mexico oil spill in 2010, it is evident that the transportation infrastructure, particularly those bearing intermodal traffic, is vulnerable to various disruption risks. Fig. 1 shows the impacts of hurricanes Katrina and Camille on the coasts of Mississippi and Alabama; each color represents the intensity of the hurricanes' devastating impact on those regions. The figure suggests that the failure probability of transportation infrastructure decreases for routes located farther away from the hurricane center. In real life cases, the multi-modal facilities located farther away from the hurricane center usually survive; however, the links that connect the multi-modal facilities may be easily disrupted due to several reasons such as bridge failure, flash flooding,[2] landslides,[3] or other unexpected events (Peeta, Salman, Gunnec, & Viswanath, 2010; Hurricanes: Science & Society, 2013). If the transportation link fails, several weeks, months, or years may be required to restore it back to the normal condition. Therefore, strengthening the weakest components of the transportation links is necessary to enhance their survivability

* Corresponding author. Tel.: +1 (662)325 9220; fax: +1 (662)325 7618.
E-mail addresses: srp224@msstate.edu (S.R. Poudel), maruf@ise.msstate.edu (M. Marufuzzaman), bian@ise.msstate.edu (L. Bian).
[1] Tel.: +1 (662)325 0507; fax: +1 (662)325 7618.

[2] A rapid rise in water levels that can occur quickly due to intense rainfall over a relatively short period of time.
[3] A landslide is a geological phenomenon in which ground movements, such as rock falls, deep slope failures, and shallow debris flows, occur and are driven downward by gravity. Landslides are caused when the stability of a slope changes from stable to unstable condition. (Hurricanes: Science & Society, 2013).

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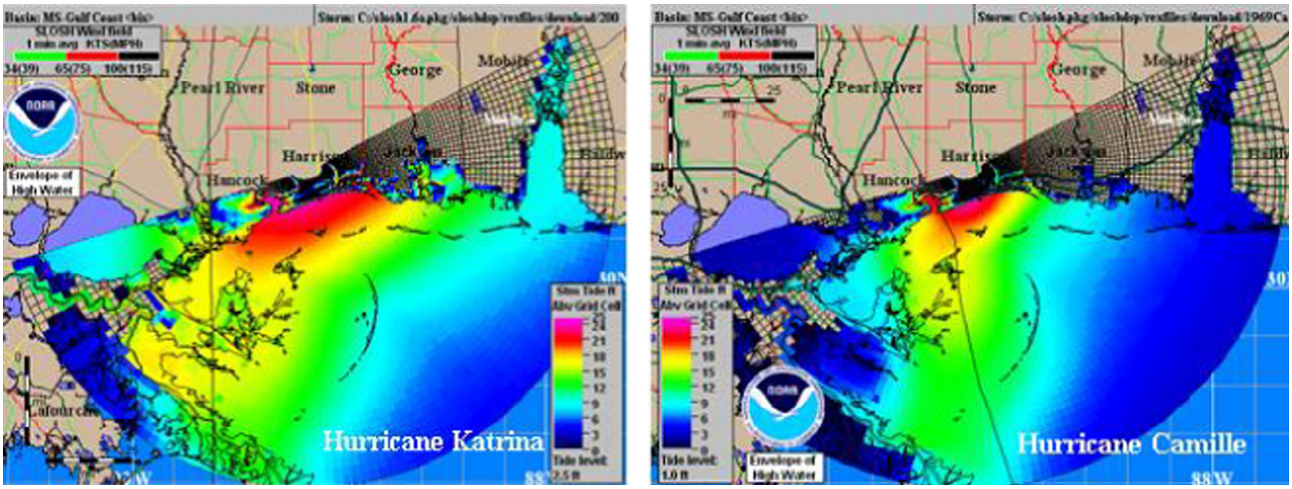

(a) Hurricane Katrina (b) Hurricane Camille

Fig. 1. Impacts of hurricanes Katrina and Camille on the coasts of Weather Underground, Inc (2014).

even after hurricanes strike. In an ideal case, the decision maker strengthen all the links to a targeted safety level, but because of the potentially high expenditure, a subset of the links should be selected to meet specified budget limitations. Thus, the optimization model presented here has the objective of maximizing the post-disaster connectivity of multi-modal facility links while minimizing the investment and transportation costs among multiple sources to their respective destination nodes in a bio-fuel supply chain network.

One major stream of research in bio-fuel supply chain literature identifies the optimal locations of bio-refineries to minimize the cost of the overall supply chain network. Such problems are generally considered as extensions of classical facility location design problem. The literature on the topic of facility location and supply chain design is very rich. The first work on facility location problem dates back to the Weber problem (Weber, 1909) and since then extensive research have been conducted on different variants of the classical facility location problem, such as Canel, Khumawala, Law, and Loh (2001), Shiode and Drezner (2003), Carrizosa and Nickel (2003), Melo, Nickel, and Saldanha-da-Gama (2005), Farahani, Drezner, and Asgari (2009), Lee and Dong (2009), Torres-Soto and Uster (2011), Jena, Cordeau, and Gendron (2015), and others. Interested readers are requested to check some most recent development of facility location problem from the review papers of Melkote and Daskin (2001), Klose and Drexl (2005), Snyder (2006), Melo, Nickel, and Saldanha-da-Gama (2009). Studies conducted by Zamboni, Shah, and Bezzo (2009), Eksioglu, Acharya, Leightley, and Arora (2009), Huang, Chen, and Fan (2010), Xie and Ouyang (2013), Xie, Huang, and Eksioglu (2014), Marufuzzaman, Eksioglu, and Hernandez (2014), Meyer, Cattrysse, and Orshoven (2015), and Walther, Schatka, and Spengler (2012) develop deterministic models optimizing both plant locations and transportation costs in bio-fuel supply chain networks. Chen and Fan (2012), Kim, Realff, and Lee (2011), and Marufuzzaman, Eksioglu, and Huang (2014) extend those formulations by incorporating stochastic variants in the optimization model. The aim is to generate reliable solutions for the design and management of a bio-fuel supply chain network. However, one of the major drawbacks of these studies is that the authors assume the supply chain network will always function perfectly, and it will never fail. In reality, supply chain networks may be potentially impacted by the unexpected failure of transportation links (Credeur, 2011; Polson, 2011).

Supply chain reliability and resilience against natural disasters have gained increasing attention. Studies conducted by Daskin (1982, 1983) first considers facility unavailability in a maximal covering location problem. Drezner (1987) extend those works by developing a reliable *p*-median location problem. Snyder and Daskin (2005) further extend those models to consider a reliable uncapacitated fixed-charge location problem (UFLP) and the p-median problem where the authors assumed that the facilities may fail randomly with identical probabilities. Over time Cui, Ouyang, and Shen (2010), Li and Ouyang (2010), Shen, Zhan, and Zhang (2011), and Li, Zeng, and Savachkin (2013) extend the existing models by relaxing the uniform disruption probability assumption introduced by (Snyder & Daskin, 2005). Studied conducted Galindo and Batta (2013) and Rawls and Turnquist (2010, 2012, 2011) are more relevant to this study where the authors attempted to develop models for pre-positioning of emergency supplies to hedge against potential natural disasters. Most recently, some studies attempt to address the impact of bio-refinery disruption in a bio-fuel supply chain network. Li, Peng, Bai, and Ouyang (2011) develop a discrete and a continuous model to design a reliable bio-fuel supply chain network. The authors consider both site-independent and dependent disruptions, and they analyze the impact of those disruption probabilities on optimal refinery deployment decisions. Wang and Ouyang (2013) propose a game-theoretical based continuous approximation model to locate bio-refineries under spatial competition and facility disruption risks. A very recent study by Marufuzzaman, Eksioglu, Li, and Wang (2014) considers the impact of intermodal hub disruption on bio-fuel supply chain network design. However, none of these previous studies account for the probability of failure along the multi-modal facility-to-facility links because of the challenges associated with collecting data about link failures. This paper considers a pre-disaster planning problem that seeks to reduce or eliminate risks between the multi-modal facility-to-facility links subject to budget constraints. A spatial statistics model is utilized to estimate the probability of link failure based on disaster disruption data that is already available at finite locations, e.g., multi-modal facilities.

Another stream of research has been conducted to develop link improvement plans for better disaster response. These studies primarily focus on factors specific to the physical characteristics of the links and the cost to upgrade them to withstand disaster under a specific severity level (Bana e Costa, Oliveira, & Vieira, 2008;