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Reliable facility location design under disruptions ☆

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ABSTRACT

Distribution networks have been facing an increased exposure to risk of unpredicted disruptions causing significant economic forfeitures. At the same time, the existing literature features very few studies which examine the impact of facility fortification for improving network reliability. In this paper, we present two related models for design of reliable distribution networks: a reliable *P*-median problem (RPMP) and a reliable uncapacitated fixed-charge location problem (RUFL). Both models consider heterogenous facility failure probabilities, one layer of supplier backup, and facility fortification within a finite budget. Both RPMP and RUFL are formulated as nonlinear integer programming models and proved to be $\mathcal{NP}$-hard. We develop Lagrangian relaxation-based (LR) solution algorithms and demonstrate their computational efficiency. We compare the effectiveness of the LR-based solutions to that of the solutions obtained by a myopic policy which aims to fortify most reliable facilities regardless of the demand topology. Finally, we discuss an alternative way to assess the effectiveness of the design solutions by using the rate of return on fortification investment.

1. Motivation

Distribution networks are referred to the entire chain of intermediaries and transportation logistics for distribution of goods and services from the suppliers to the consumers. Modern distribution networks are complex engineered systems due to their size, span, the nature of customer assignment, and the network flow. At the same time, more and more enterprises have been embracing the philosophy of lean manufacturing with an ever increasing reliance on consolidated suppliers, outsourcing, slim inventories, and just-in-time production and delivery. Inasmuch as such reductionism has boosted the operational efficiency of the companies, it has also elevated their risk exposure to unpredicted disruptions. Such disruptions, as triggered by forces of nature, process hazards, and human intervention, can have a potential to entail staggering economic ramifications. This is evidenced by the following sample of recent multi-billion enterprise forfeitures lost to disrupted distribution networks.

In March of 2000, a fire event halted a Philips's semiconductor plant in New Mexico, US for 9 months, causing a $40 million direct sales loss to Philips and an indirect loss of $2.34 billion to Ericsson's mobile phone division [28]. In March of 2001, the US banned the meat import from the European Union in fear of potential spread of the foot-and-mouth disease originated in the UK. The ban was applied to 15 countries and affected four percent of the US pork import [19,23]. In 11 September 2001, following the terrorist attack, all US borders were closed and all flights canceled for several days. This lockdown forced Ford Motors to idle several assembly lines due to the lack of components supplied from overseas [7,29]. Two years later, a deadly SARS outbreak disrupted among many other industries the furniture manufacturing sector of China, which accounted for about 15% of all furniture sold in the US [11,12]. More recently, in 2005, the aftermath of hurricane Katrina caused a severe disruption to the crude oil production in the Gulf of Mexico amounting nearly 1.4 million barrels a day [5,13,20,32]. The above and some other examples [1,2,10,27,34] reveal the acute need for distribution networks designed to effectively balance the efficiency and robustness requirements.

Design for reliability of distribution networks can be accomplished by implementation and integration of both proactive and reactive mitigation options, including incorporation of backup and redundancy measures, investment in reliability improvement of existing facilities, and assuring rapid recovery of disrupted suppliers and distributors. Ideally, network design should evolve with disruptive events by updating the risk profile of the network constituents.

2. Status of current literature

Most of the existing literature on design of distribution networks takes its roots in the classical *P*-median [33] and the

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uncapacitated fixed-charge location problems [21]. Both these problems seek to choose facility locations and assignments of customers to minimize the total transportation (and construction) cost. In both original models, all facilities are assumed to be perfectly reliable. However, as evidenced from the above examples, facilities can experience disruptions which can cause reassignment of customers to more distant available suppliers or forfeiture of their demand. This can substantially increase both the transportation costs and customer dissatisfaction. It is therefore important to consider facility failures and measures for reliability improvement in network design.

The recent literature features a number of studies on facility location in the presence of random disruptions. An excellent comprehensive review of these works can be found in [30]. Below we present an up-to-date summary of the most relevant papers in this area.

In [31], Snyder and Daskin presented two reliability models for facility location: a reliable *P*-median and a reliable uncapacitated fixed-charge location model. In both models, each customer was assigned a primary supplier and a number of backup suppliers, of which at least one was required to be totally reliable. If the current supplier failed, the customer was served by the next available backup supplier. Facility failure probabilities were assumed to be equal and mutually independent. In [6], Cui et al. relaxed the assumption of homogeneous failure probabilities in [31] to location specific probabilities. Li and Ouyang expanded this direction to correlated, site-specific failure probabilities [17].

Ref. [16] looked at an more integrated facility location design problem and considered the case in which both the supplier and retailers are disrupted randomly. The model sought to determine the optimal locations of retailers, customer assignations and inventory policy. Ref. [22] introduced the *p*-robustness criterion so that the designed network performs well in both disrupted and normal conditions. A hybrid metaheuristic algorithm was proposed.

A few recent papers have taken the analysis one step further and examined the impact of facility fortification for reliability improvement of the network. In [4], Church et al. examined two related network interdiction problems: the *r*-interdiction median and the *r*-interdiction covering problem. Both models are based on the *P*-median problem. The *r*-interdiction median problem seeks to find a subset of $r \leq P$ facilities, which if removed from the network, causes the highest loss of the network throughput. Whereas, the *r*-interdiction covering problem seeks to find such a subset which results in the maximal network coverage loss. In both models, once the critical subset is identified, some of its members can be fortified, as was done in later papers by Church and Scaparra [3,25,26].

So far, to the best of our knowledge, the only work on network design with fortification is by Lim et al. [18]. The authors analyzed the uncapacitated fixed-charge facility location model with two types of facilities: unreliable and totally reliable or "hardened". The facility failure probabilities were assumed to be independent and location specific. The model assumed one primary supplier and one totally reliable backup supplier for each customer. The objective of the model was to determine the optimal number and location of both types of facilities and the customer assignment. The model was formulated as an integer programming model and a Lagrangian relaxation-based solution algorithm was developed. Although the authors incorporated the fixed cost of locating a reliable facility in the objective function, the total available fortification budget was not considered. In other words, the formulation essentially assumed an unlimited fortification budget. Since this assumption does not restrict the number of reliable facilities, the optimal solution may not fit available fortification resources.

In our paper, we develop two related models for facility location design under the risk of disruptions: a reliable *P*-median problem (RPMP, Section 3) and a reliable uncapacitated fixed-charge location problem (RUFL, Section 4). Similar to [6,18], in both our models, we assume that the facility failure probabilities are independent and location specific. As in [18], we also assume one layer of supplier backup. To further enhance the network reliability, we incorporate fortification of selected facilities. As a result of fortification, the facility reliability is improved at some cost. The cost of facility fortification is considered to be location specific and made up of two components: a fixed setup cost and a variable cost for reliability improvement. In both models, we assume that if fortified, the facility becomes totally reliable. Both models incorporate a finite fortification budget constraint. Both models seek to choose the optimal facility location and fortification strategy as well as the assignment of customers.

Both the RPMP and RUFL problems are formulated as nonlinear integer programming models which are shown to be $\mathcal{NP}$-hard. For both models, we develop Lagrangian relaxation-based solution algorithms (Sections 3 and 4). We present computational results demonstrating the efficiency of the developed algorithms (Sections 5.2 and 5.3). We compare the effectiveness of the LR-based solutions to that of the solutions generated by a myopic policy which aims to fortify most reliable facilities regardless of the demand topology (Section 5.4). The comparison is done at different levels of the fortification budget. Finally, we discuss an alternative way to assess the effectiveness of the design solutions by determining the rate of return on fortification investments (Section 5.5).

Comparing to Lim et al. [18] and Cui et al. [6], our paper presents the following *main advances*:

(i) Our model incorporates a fortification budget constraint. As a result, it provides a more realistic decision support for network design and *assures that the optimal solution is matched to available reliability improvement resources*, no matter how scarce or abundant these resources are.
(ii) Our formulation enables the strategic decision maker to assess the rate of return on fortification investment and compare it to that of alternative investment opportunities. For example, a company may choose to invest in network fortification only if the rate of return exceeds the minimum acceptable rate of return (MARR [24]).
(iii) Our model allows periodic fortification upgrades whereby reliability of an existing network can be improved as additional fortification budget becomes available. Examples include gradual release of fortification resources or availability of excess cash flow which can be channeled into fortification. To allocate additional fortification budget for an existing network, the model has to be re-solved with fixed facility location decision variables. The ability of our model to support gradual fortification results from incorporation of the budget constraint and separation of the location selection and fortification decision variables, which are combined in Lim et al. [18].

3. The reliable *P*-median problem (RPMP)

The model extends the reliable *P*-median facility location problem introduced by Snyder [31] by considering heterogeneous facility failure probabilities and facility fortification. The model seeks to minimize the total expected transportation cost by optimally locating *P* facilities, allocating a finite fortification budget, and assigning the customers. We first formulate this problem as a nonlinear integer programming model and then develop a Lagrangian relaxation-based solution algorithm.