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Challenges in service network expansion: An application in donated breastmilk banking in South Africa

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ABSTRACT

Neonatal infections are the leading cause for neonatal deaths in developing countries, resulting in more than 1.5 million infant fatalities annually. The most effective prevention against neonatal infections is exclusive breastfeeding. However, reasons such as maternal death during birth, maternal illnesses such as HIV and TB-meningitis, and lack of rooming-in facilities prevent the infant to be breastfed by his/her mother. One way to mitigate these infections is by supplying pasteurized donor-expressed breastmilk. In this paper, we consider the network expansion of the donated breastmilk distribution supply chain in South Africa. As with the distribution of most public sector and humanitarian relief goods and services, the transportation of donated breastmilk is hampered by the inherent uncertainty in the environment, and by the fact that in addition to efficient usage of resources, distribution should be made in an equitable manner. We incorporate uncertainty into our models by means of multiple scenarios, which are determined based on different assumptions about population size, HIV prevalence, and status of public health in the country, income, and education. We consider various equity-based objectives and propose rounding-based heuristics to solve these. We focus on two delivery schemes; one which uses out-and-back transportation, and one that makes multiple stops on the delivery route. Using computational experiments, we analyze the trade-offs between the objectives as well as the effects of various public health policies, network expansion budget, and assumptions on supply and demand. We also describe the teaching materials resulting from this paper, which include a case study, a supply/demand estimation tool, and an interactive decision support tool.

1. Introduction

Each year, more than 2.8 million newborn babies die within four weeks of their birth (neonatal period). Although neonatal mortality rates are decreasing in all regions of the world, the decline is much slower in Sub-Saharan Africa, where 31 out of each 1000 live births result in a neonatal death. Preventable infectious diseases are among the leading causes of neonatal deaths, accounting for more than 28% in Sub-Saharan Africa [47]. Exclusive breastfeeding is the primary prevention against neonatal diseases; it is estimated that breastfeeding can potentially prevent more than 800,000 deaths in the developing world annually [7]. Despite this fact, only 39% of children below six months of age are exclusively breastfed globally [46].

In many developing parts of the world, access to exclusive breastfeeding using mother's own milk (MoM) is prevented by factors such as maternal death during birth, maternal illnesses such as HIV and TB-meningitis, and lack of rooming-in facilities in public hospitals. These factors particularly affect premature-born infants, who are much more vulnerable to fatal infections such as Necrotizing Enterocolitis (NEC) in the first days of life. Providing pasteurized donor breastmilk (PDB) to premature infants with no access to MoM for the first fourteen days of life is highly effective in preventing and treating NEC and other infections [49]. For this

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purpose, there has been a concerted effort throughout the world to provide PDB to these infants using donated breastmilk banks (e.g., [2,40]).

This paper considers a network expansion problem for the donated breastmilk distribution chain in South Africa, in response to an increasing demand of donated breastmilk over the recent years. As with many societal problems involving the allocation and distribution of scarce resources to multiple beneficiaries (e.g., goods/service distribution from public facilities such as public libraries, hospitals, nursing homes; distribution of relief supplies such as food, medical services, tents following a disaster; allocation of health commodities such as donated kidney, blood), uniqueness of the problem settings and lack of historical data results in uncertainties in the commodity supply and demand. To overcome this challenge, we develop various scenarios with different supply and demand quantities based on different assumptions on the population size, HIV prevalence, income and education levels, and status of public health in the country.

As a consequence of the focus on the well-being of all the beneficiaries, including those hardest to serve, in public health and humanitarian goods and services, an important characteristic in such environments is to provide an equitable allocation and distribution, along with an efficient or effective allocation based on metrics such as profit, cost, or makespan. In the public sector, equity is especially important, since many government agencies may be specifically setup to affect change for the neediest of the population, or may need to justify that their actions are equitable to their donors and taxpayers. In addition to the trade-off between equity and efficiency, modeling for equity involves two important challenges. First, there is no single universal equity measure that works well in all possible settings, therefore definition of an appropriate equity objective is context-dependent. Second, even when such a measure can be defined, finding a solution to the corresponding model is generally computationally more challenging than its efficiency-based counterpart. In this paper, various measures are put forward to define equity in our context and models are developed based on these. We propose heuristics for the solution of these problems, and through computational experiments, we analyze the trade-off between the objectives as well as the effects of various public health policies, network expansion budgets, and assumptions on supply and demand quantities.

Decision making under uncertainty has been extensively studied within the scope of societal and health or humanitarian applications. Recent reviews of uncertainty in modeling in the humanitarian context can be found in Apte [1] and Çelik et al. [9]. Our paper contributes to this stream of literature by analyzing different equity objectives and the trade-off between efficiency and equity within the context of facility location and routing under uncertainty.

Due to the variety of its applications in the societal context, equity is a widely-studied phenomenon in various disciplines, which include political science (e.g., determining the number of representatives of each state in the US Senate), sociology and social psychology (e.g., people's perceptions of the equity of rewards in exchange transactions), jurisprudence (e.g., disparities in local government services), economics (e.g., distribution of wealth), public administration (e.g., employment opportunities), and geography (e.g., distribution of water rights) [25]. The equity measures used in these applications can be categorized into three classes, each of which are based on a different theory of justice [51]: (i) Aristotle's *proportional equity principle*, where the resources are allocated in proportion to the beneficiaries' needs, (ii) *classical utilitarianism*, where the main aim is to maximize the total welfare of the whole system, and (iii) the Rawlsian *maximin* or *difference principle*, which refers to maximizing the welfare of the worst-off beneficiaries in the system [37]. The equity measures we present in this paper are combinations of the first and third principles, where the objective is to maximize the minimum proportion of the demand covered.

Equity has been widely studied in numerous application areas of operations research including air traffic flow management [5,22,48], telecommunication networks [33–35], and queueing systems [50]. In humanitarian supply chains, equity is considered as one of the primary objectives in the distribution of relief commodities or services [6]. From the routing perspective, where efficiency is traditionally measured in terms of the total travel time or cost, there has been an increased interest in the equitable relief distribution over the recent years. Tzeng et al. [44] develop a multiobjective model for a joint facility location and commodity transportation problem, where the objectives are minimizing cost and travel time as well as maximizing proportion of total demand satisfied. Campbell et al. [8] consider minimizing the maximum arrival time of supplies and the total arrival times of supplies, and show the trade-off between efficiency and equity within the context of the classical traveling salesman and vehicle routing problems. Balcik et al. [4] aim to minimize the maximum percentage of unsatisfied demand over all locations, whereas Huang et al. [17] focus on the trade-off among three objectives for efficiency (measured by total travel time), efficacy (measured by demand-weighted sum of arrival times), and equity (measured by disutility-weighted sum of arrival times). The challenges of defining an equity-based objective, computationally solving models that involve equity measures, and resolving the efficiency-equity trade-off are underlined in almost all of the studies in this stream.

There exists a considerable amount of research on equitable facility location within the context of both for-profit and health/humanitarian supply chains. Marsh and Schilling [25] present an overview of various equity measures used in the facility location literature. These include minimizing the maximum travel distance or unsatisfied demand, variance or coefficient of variation of distribution, Gini coefficient, the difference between maximum and minimum service (range), and sum of absolute deviations. The conclusion from Ref. [25] is that there is no perfect measure and the definition of an appropriate measure is context-dependent. More recent studies on equitable facility location are presented in Refs. [14,15,18,19,23,24,32]. Despite the number of studies on equitable facility location, very few of these consider multiple levels in the supply chain and to the best of our knowledge, there exists no study that considers multiple equity objectives.

In distributing the donated breastmilk to the needy infants, two alternatives exist. In the existing system, only a single demand location is visited in each delivery route (out-and-back deliveries). In this paper, we also consider the alternative in which demand locations can be visited in sequence. Since this involves facility location and vehicle routing decisions to be made jointly, this alternative version of the problem resembles the *location-routing problem* (LRP). A recent literature review for the LRP is presented in Ref. [30]. While various solution approaches exist, very few exact methods have been proposed due to the extensive computational burden [20,21]. Heuristic methods can be classified under four groups: (i) sequential methods, in which the location problem is first solved with out-and-back or approximate distances, followed by routing, (ii) clustering-based methods (e.g., [29,41]) first cluster the demand points into groups and solve the location and routing problems for each cluster, (iii) iterative methods (e.g., [36]) iteratively solve the location and routing subproblems by passing information from one solution to the other, and (iv) hierarchical methods, where the main algorithm solves the location problem and subroutines in each step solve the routing problem. More