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ORIGINAL ARTICLE

Beneficiary appointment and delivery planning in a conflict setting

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Abstract

In this study, we explore the challenges faced by humanitarian organizations engaged in relief efforts for internally displaced individuals during armed conflicts. Based on our semistructured interviews with three local nongovernmental organizations (LNGOs) in Syria, we introduce a new appointment scheduling problem to improve decision-making for aid delivery planning in conflict settings. Operating in a highly resource-constrained environment, these LNGOs face complexities that necessitate effective decision support tools to streamline supply delivery at relief facilities, where a large number of registered beneficiaries are served. Our proposed appointment scheduling problem aims to optimize the allocation of delivery times for various supplies, taking into account the urgency of needs and operational limitations. We present a heuristic that addresses the complexities of the proposed scheduling problem in a flexible way. The heuristic can accommodate simple rules derived from LNGOs' operational policies on the ground, such as imposing a single visit per beneficiary, delivering a single supply type per day, and preallocating time slots to conflict groups. We present a case study based on the Latakia district of Syria to assess the performance of our heuristic and the effectiveness of simplified delivery strategies. Our results not only showcase the efficiency of the heuristic, but also provide valuable managerial insights. We find that cross-training of staff is more beneficial when supplies are relatively abundant. Furthermore, the simplified delivery policies are effective in certain conditions contingent upon various factors, including supply scarcity, difficulty of travel, and the level of conflict in the population.

KEYWORDS

aid delivery, beneficiary appointment scheduling, heuristics, humanitarian operations, Syrian conflict

1 | INTRODUCTION

Armed conflicts are among the slow-onset man-made disasters, which usually emerge gradually based on a congruence of different events and leave millions of people in need of humanitarian assistance for long periods of time. For instance, the Syrian conflict, which has been going on since 2011, is one of the worst humanitarian crises the world has faced since World War II (The European External Action Service, 2021). Millions of people have lost their lives or have been displaced to seek security and assistance for survival. Among the displaced, some have remained in Syria as internally displaced people (IDP), and some have crossed into other countries (such as Turkey, Lebanon, Jordan, Egypt, and countries in Europe). In 2021, there were 6.7 million IDP in Syria and more than 6.6 million Syrian refugees in the world (UNHCR, 2022a).

Since the beginning of the Syrian conflict, international humanitarian organizations and donors have been collaborating with local nongovernmental organizations (LNGOs) to

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provide essential relief items and services (Al Adem et al., 2018; UNHCR, 2022a, 2022b). While all processes in the upstream humanitarian supply chain, such as procurement and transportation, are managed by international organizations, the final delivery of aid is conducted by the LNGOs due to their access to the affected communities. However, the operational landscape for LNGOs is challenging, characterized by a scarcity of resources and diverse operational constraints arising from the complexities of the conflict setting. Despite the substantial research attention devoted to understanding the challenges faced by humanitarian organizations in relief delivery, there remains a gap in understanding the specific characteristics of LNGOs' operations in conflict settings (Oloruntoba & Banomyong, 2018). The relatively limited focus on conflict settings can be attributed to their inherent challenges, including the lack of public attention and various obstacles in engaging with local organizations, such as communication limitations, security concerns, and language barriers.

In this study, we first conducted semi-structured interviews with three LNGOs, which have been serving the IDP in Syria since the start of the conflict. Our interviews targeted understanding the important factors that affect relief delivery in this context and identifying the main decision-making needs of the agencies. Based on the information from the interviews regarding the objectives and complexities of the conflict setting, we introduce a new appointment scheduling problem to support effective planning of aid delivery and propose a mathematical model and heuristic to guide practical decision-making.

During our interviews, each LNGO, whose names are kept confidential for security reasons, was operating one relief service facility in Latakia City to serve a large number of registered beneficiaries dispersed throughout the Latakia district. The service facility is basic and not equipped with advanced logistics (e.g., warehousing) systems or information technology tools. Depending on the current needs, relief projects, and targeted beneficiary groups (e.g., children or pregnant women), LNGOs plan the delivery of different relief supplies (such as food and nonfood items, and vouchers) in each day of the week at the facility. Once delivery dates are determined and announced for a supply, beneficiaries travel to the service facility to collect aid materials. Since LNGOs announce the delivery days to all targeted beneficiaries at once via mass messaging (e.g., through social media groups), the current system has a number of undesirable consequences for the agencies and beneficiaries, including congested facilities, long waiting times, overwhelmed staff, unsatisfied beneficiaries even after multiple trips to the facility, and failure to satisfy the most urgent needs.

Motivated by the challenges revealed by our exploratory study, we introduce the Beneficiary Appointment Scheduling Problem (BASP), which determines the type of supplies to distribute at the relief facility during different time slots each day over a week, the beneficiaries to be served in each slot, and the staff to assign to each slot. We consider a variety of limitations that affect the feasibility and effectiveness of delivery plans and beneficiary appointments such as the amount and type of supplies, availability of staff with required skills, facility space, and the compatibility of different beneficiary groups that can be at the facility during the same time period such as gender and political identity. To capture agencies' most important concerns in relief delivery planning, the primary objective of the BASP is set to maximize the quantity of urgent supplies distributed across the planning horizon. We also consider a secondary objective, which aims to minimize the number of visits made by the beneficiaries over the planning horizon to collect different types of supplies. While the BASP shares similar features and constraints with some existing scheduling problems and applications in different settings (such as multiappointment scheduling in healthcare and course timetabling), which are explained in Section 2.2, there exists no study that integrates all relevant features of our conflict setting and a new objective, which requires developing a new model and solution approach.

Solving the resultant complex scheduling problem for realistic problem instances (i.e., hundreds or thousands of beneficiaries served with multiple types of supplies by using a large team of staff during a typical planning horizon such as 1 or 2 weeks) is difficult. We develop an efficient two-phase heuristic, based on a clustering- and insertion-based constructive scheduling approach, enhanced with local search. The heuristic requires low computational resources and can be easily installed on the computers or portable devices (such as tablets and cell phones) of the LNGOs. We illustrate our approach in a case study based on the Latakia district in Syria. We evaluate the quality of appointment schedules based on a number of key performance indicators (KPIs). Our results show that the proposed heuristic can lead to the provision of high-quality solutions. Moreover, we present practical insights regarding the effects of cross-training agency staff (i.e., enhancing their skill set to work in different types of relief projects), compatibility of beneficiaries in terms of gender and political groups, as well as different delivery strategies under varying supply availability settings. Our proposed approach is flexible and can be adapted in line with such alternative variants the agencies might implement (e.g., distributing one supply per day [1SPD] or imposing one visit per beneficiary). We present a numerical analysis to compare alternative policies with different complexity levels.

The main contribution of this study is to introduce a new beneficiary appointment problem for supporting aid delivery operations in conflict settings, informed by insights gathered through interviews with local agencies actively operating in Syria. We introduce a new BASP along with a practical heuristic designed to improve the planning and organization of relief deliveries. Our work provides new managerial insights into resource management in this setting and evaluates the implications of using alternative simplified policies for LNGOs.

The article is structured as follows. In Section 2, we review the relevant literature. In Section 3, we summarize the findings of our interviews with the LNGOs. In Section 4, we

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introduce the problem and present our mathematical model and heuristic, as well as describe how the proposed methods can be adapted to implement simple policies. In Section 5, we present a numerical study to illustrate the performance of the heuristic and develop practical insights. In Section 6, we discuss the challenges associated with translating the proposed decision support tool into practice. In Section 7, we conclude the article and present future research directions.

2 | LITERATURE REVIEW

In this section, we position our study within the relevant literature on humanitarian operations in conflict settings and scheduling problems.

2.1 | Humanitarian operations in conflict settings

While there has been a substantial body of research dedicated to various humanitarian logistics problems, the majority of existing problems address rapid-onset natural disasters. Humanitarian problems faced in conflicts have received increasing attention in recent years. However, the existing studies often reflect the perspectives of influential humanitarian organizations and donor countries, and the voices and experiences of local organizations operating within conflict zones, particularly in the developing world, are neglected (Oloruntoba & Banomyong, 2018). Therefore, there is a critical need for research that explores the operational challenges in these less visible conflict settings from the perspective of local organizations.

Recent global conflicts, such as those in Syria and Yemen, have prompted a growing number of studies to address the emerging challenges in conflict settings. Various methodologies tackle a range of challenges and issues. For instance, Bayram (2016) reviews studies on large-scale network evacuation and suggest using game-theoretic approaches for humanitarian organization evacuation planning during conflicts. Jola-Sanchez et al. (2016) conduct an empirical study based on hospital data during the Colombian conflict to explore the effects on hospital efficiency. Beamon and Kotleba (2006) develop inventory policies to support relief operations during the South Sudan conflict using simulation. Our article can be positioned among the humanitarian logistics studies that develop operations research (OR) models to support decision-making for effective aid delivery in conflict settings.

Decision-making problems in conflict settings are characterized by unique contextual needs, requirements, and constraints, such as the setting being urban, rural, or camp-based, the status, locations, and needs of beneficiaries, security concerns, and more. A variety of problems exists to serve people affected by conflicts (see e.g., Oloruntoba and Banomyong (2018) and Seifert et al. (2018) for reviews of studies that focus on serving refugees). For example, Smadi et al. (2018) present a covering model to design a water distribution system within a refugee camp in Jordan. Jeong et al. (2020) focus on using flying warehouses for humanitarian logistical response in conflict zones. Arslan et al. (2021) formulate a location-routing problem to locate and serve refugee camps along the Turkish–Syrian border. Kian et al. (2022) address a network design of facilities to support the roll-out of cash-based interventions in Syria. Santa González et al. (2023) tackle the logistical planning of mobile healthcare clinics in Iraq.

In the humanitarian logistics literature, last mile aid delivery problems typically focus on reaching dispersed communities in affected regions by managing scarce resources (e.g., supplies, vehicles). Only a few studies address challenges in serving beneficiaries from a central service facility, involving different decisions and features compared to visits made to beneficiary locations. Our study addresses this gap, exploring an aid delivery context not previously explored in existing literature on conflict settings. Specifically, our proposed model and practical heuristic address a setting where (i) registered beneficiaries are served by local agencies at a relief facility, (ii) beneficiaries travel to the facility to receive goods at designated appointment times, (iii) communication about appointment times is possible, (iv) supplies must be delivered by trained staff with specific skills, (v) there exist incompatible population groups that cannot be served in the same time slots, and (vi) prioritization of deliveries is necessary due to limited supplies.

The characteristics of conflict settings differ significantly from those of other humanitarian last-mile aid delivery contexts, such as relief efforts after natural disasters. One key distinction is the presence of incompatible groups that must not be mixed during delivery scheduling. Additionally, the training of staff members is important, particularly in meeting specific needs such as reporting requirements of donors. Finally, while multiperiod planning may be relevant across different settings, it gains particular significance in conflict environments as serving registered beneficiaries by considering their number of visits for picking up different types of supplies is an important objective for the agencies. Our proposed problem and model incorporate these concerns, whereas our case analysis offers insights into effectively addressing them.

While our study is directly motivated by the operations of local agencies operating in the Syrian conflict, the proposed approaches have broader applicability, supporting decision-making in other conflict settings. Moreover, our approach can be applied to other humanitarian settings, such as the recovery phase of disasters or the delivery of long-term aid (e.g., food, hygiene supplies, cash, and vouchers), where scheduling aid deliveries to target groups (e.g., pregnant women, malnourished children, and people with chronic healthcare needs) may require considering incompatibility issues, as well as staff skills and the number of beneficiary visits.

Given that limited exploratory studies address the intricate challenges of serving conflict-affected populations, we bridge the gap in the literature for evidence-based models

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and solutions that address the practical needs of humanitarian agencies, as pointed to by De Vries and Van Wassenhove (2020). This mirrors the methodology employed by Charles et al. (2016), Gralla et al. (2016), and Jahre et al. (2016) and places a strong emphasis on empirical evidence obtained through practitioner engagements to conceptualize a problem tailored to the unique operational conditions of conflict settings.

2.2 | Scheduling problems sharing similarities with the BASP

The BASP exhibits similarities with several scheduling problems extensively studied in the OR literature, sharing key features such as:

- The time horizon for delivering supplies is multiple working days.
- A beneficiary may request multiple types of supplies.
- Many beneficiaries require the same scarce supplies (i.e., many beneficiaries require the same supply and there is not enough supply to satisfy the demand of all the beneficiaries).
- Team members require specific skills to deliver a supply, and more than one staff is typically needed for each delivery.
- The staff is allowed to change teams throughout the working day.
- Setup time is required for a team to switch from delivering one supply type to another.
- Beneficiaries may not be allowed at the agency simultaneously due to incompatible characteristics like political factions or gender issues.
- The facility has limited space available for delivery.

Detailed discussions of these features are provided in Sections 3 and 4. Many scheduling problems and applications share some of these features with the BASP. Notable examples are: course timetabling, in which classes or exams have to be assigned time slots, personnel, and classrooms over a multiday time horizon; employee scheduling, in which employees have to be assigned to jobs to define suitable workloads; airport ground technician scheduling, in which teams of skilled workers have to be assigned to routes for loading and unloading baggage from aircraft at the airport; multiappointment scheduling problems in hospitals, in which patients require multiple visits each needing a set of skilled and simultaneously available resources; and finally scheduling incompatible tasks, in which jobs of unitary duration require a mix of resources and incompatibilities prevent certain pairs of jobs from being processed simultaneously.

Table 1 summarizes which features of the BASP are considered in the mentioned scheduling applications. Although existing scheduling problems may share some of the constraints and objective function of the BASP, the latter simultaneously integrates these features and the objective function for the first time in the literature.

We do not provide a comprehensive literature review for the related problems for the sake of brevity, and we do not explicitly refer to the algorithms commonly employed for solving them due to the extensive and diverse nature of the literature. However, problems with similar or higher degree of complexity for the multiappointment scheduling problems in hospitals (these problems share the most similarities with the BASP) are typically solved by means of heuristic or metaheuristic algorithms (e.g., Cordier & Riane, 2013; Griffiths et al., 2012; Kazemian et al., 2017; Rezaeiahari & Khasawneh, 2017).

Given the requirements of the decision-making environment, the lack of advanced computing facilities, the complexity and variety of the constraints, and the size of the instances to solve, a heuristic algorithm is the most suitable methodology in order to obtain high-quality solutions for the proposed problem within a limited amount of computing time. We develop a heuristic algorithm that can efficiently handle the extensive set of constraints in our problem.

3 | SYSTEM DESCRIPTION

In this section, we describe the characteristics of the aid delivery system in our complex emergency setting based on our exploratory study with LNGOs operating in Syria. We provide information on the agencies and interviews (Section 3.1) and describe the important characteristics of the aid delivery environment in our setting (Section 3.2).

3.1 | Agencies and interviews

To understand the objectives and complexities of aid delivery relief operations in a conflict-affected region, we conducted semistructured interviews with local agencies that have delivered relief aid for several years in the Latakia Governorate, which is one of the 14 governorates of Syria. With an estimated population of about 1.4 million in 2016, Latakia is situated in the northwest of the country, sharing an international border with Turkey to the north and bordering the Mediterranean Sea to the west (see Figure 2 in Section 5.1).

The brief profiles of the three interviewed LNGOs, which are referred to as LNGO #1, LNGO #2, and LNGO #3, are provided below.

- LNGO #1 has been operating in Latakia since 1960 and involves 150 staff members. Since the beginning of the Syrian crisis, the agency has been involved in both relief and recovery activities such as distributing food and nonfood items, vouchers, reconstructing schools, and providing psychological support.
- LNGO #2 was established in 1940 and has 180 members. The agency has been delivering in-kind aid (school kits, food, and clothes) and vouchers, and also operates a medical dispensary to provide health services (small surgeries, blood tests).

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TABLE 1 BASP features and related literature.

	Multi-day	Multi-supply	Competing supplies	Skills and crew	Crew changes	Setup time	Incompatibility	Limited space
Course timetabling (e.g., Bettinelli et al., 2015)	✓	✓				✓		✓
Employee scheduling (e.g., Van den Bergh et al., 2013)	✓			✓				✓
Airport ground technician scheduling (e.g., Dall'Olio & Kolisch, 2023)				✓	✓	✓		
Multiappointment scheduling in hospitals (e.g., Marynissen & Demeulemeester, 2019)	✓	✓	✓	✓	✓	✓		✓
Scheduling incompatible tasks (e.g., Caramia & Dell'Olmo, 2003)							✓	

- LNGO #3 has been active in Syria since 1996 and has 60–70 members in Latakia. The agency has been managing a comprehensive set of relief and recovery programs related to education, vocational training, water and sanitation, shelter, psycho-social support, and health.

At the time of interviews, each LNGO had regular staff members and also employed volunteers, depending on the requirements of active projects. Although volunteers were hired temporarily, since the crisis had been going on for several years, they were trained and experienced in performing the tasks. That is, volunteers were not employed in an ad-hoc way. Since both regular members and volunteers were assigned to delivery tasks based on their training and skills, we simply refer to all employees as "staff" in this article.

While the LNGOs differed in terms of the size and scope of the relief projects, during the interview period (February–December 2019), each LNGO was operating a single relief service facility at the city center to deliver in-kind (both food and nonfood) and monetary aid (vouchers) to serve the needs of a large number of beneficiaries across the Latakia Governorate. Additionally, Latakia was not an active war zone during that time period, but received significant migration from the neighboring districts severely affected by the conflict (such as Idlib, Aleppo, and Hama). Beneficiaries were able to access the facilities run by the LNGOs without facing major security threats.

The interviews with the LNGOs were conducted in two distinct phases. The questions involved in both phases are provided in Online Appendix A.1. In the initial phase, our objective was to gain insights into the overall characteristics and challenges inherent in the relief delivery environment within the conflict setting. The primary aim was to identify opportunities for enhancing relief operations through improved decision-making. The first round revealed a critical need for developing a practical decision support tool capable of facilitating weekly distribution plans and communicating scheduled appointments to beneficiaries for supply pickup—a need that our study addresses comprehensively. In the second phase of interviews, we focused on the crucial elements of the existing delivery system and their intricate interactions. This exploration was necessary for conceptualizing and formally defining our problem and, subsequently, for developing a model and solution method that aligns with practical needs.

Due to confidentiality concerns and communication challenges, interviews were conducted as follows. The research team prepared a set of questions and shared it with the LNGOs. One member of the research team, who was located in Syria and had field experience, communicated with the regular staff (face-to-face and via phone) iteratively until all responses were sufficient and clear with the remainder of the team. The LNGO staff who responded to interview questions were experienced regular staff, who managed food, nonfood, and voucher projects.

3.2 | System description: Delivering aid in a conflict setting

In this section, based on the findings of our interviews with the LNGOs, we describe the important aspects of the current relief delivery system.

3.2.1 | Relief projects and donations

During the interview period, each LNGO was managing multiple aid programs concurrently, delivering both in-kind and monetary aid (i.e., vouchers) at their facilities associated with different relief projects managed by international donors. While only in-kind aid was delivered in the early years of the conflict, around 80% of resources were dedicated to voucher projects in recent years. For example, during the interview period, LNGO #1 was distributing around 500 kits and 300 vouchers per week. While LNGOs favored the voucher projects as they "gave more choices to beneficiaries" (LNGO #1) and "allowed circulating funds and stimulate small traders and businesses" (LNGO #3), voucher projects were more difficult to manage as "they required a lot of paperwork, which could not be handled by untrained staff, and also continuous monitoring of the local vendors and markets" (LNGO #1, LNGO #3). That is, the skill requirements

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for staff to manage voucher projects of different donors can be different.

Our interviewed LNGOs specified that all relief projects in Syria were sponsored by international agencies. For example, "in-kind food rations were being supplied by WFP Syria, emergency items, hygiene kits, shelters were provided by UNHCR Syria, and education tools for children had always been supplied by UNICEF Syria" (LNGO #1).

3.2.2 | Needs assessment and demand

During the conflict in Syria, LNGOs were mainly responsible for executing aid deliveries, serving as intermediaries between international agencies and beneficiaries. Statistics on sectoral needs (such as nutrition, health, water, sanitation, etc.) were regularly posted by the UN-OCHA. Based on these assessments, international agencies determined the relief projects to be conducted to satisfy beneficiary needs, also by accounting for the opinions and capacities of the LNGOs. The findings of the joint assessment committee were utilized by the LNGOs to determine the amount and urgency of needs for the targeted beneficiary groups in each district.

All LNGOs specified that the incoming donations were usually insufficient for the needs of the targeted groups, which made effective prioritization critical. LNGOs prioritized deliveries by assigning urgency levels for groups of beneficiaries. Beneficiary needs were regularly assessed by a joint committee including members from the LNGOs and international agencies. While no standard scheme existed to set these urgency scores (also referred to as "severity score" or "priority score"), several scoring systems are being used in the humanitarian sector to distinguish the level of humanitarian needs for certain population groups. These systems usually specify the indicators (e.g., income, gender) that affect the urgency of needs at different levels (e.g., individual, community, subdistrict), which depends on the specific characteristics of the context. All the indicators are then scored on a given scale (e.g., one to three, one to five, or out of 100), and a weighted final score is computed based on the weights given to different indicators. We refer the interested reader to example needs assessment reports that utilize such scoring schemes in practice (e.g., Assessment Working Group, 2013; Benini et al., 2017).

Additionally, all beneficiaries were registered by the LNGOs, and their demographics (e.g., address, gender, contact information) were known. Political group information was associated with the location of the beneficiary, because distinct groups usually reside in different neighborhoods. The LNGOs usually contacted the beneficiaries using short text messages and social media groups.

3.2.3 | Relief facilities

Our interviews revealed that the number, type, and size of the facilities managed by the LNGOs generally depended on the number and scope of the relief projects conducted at any time. At the time of the interviews, each LNGO managed one relief service facility in the city center, where items were stored and delivered to beneficiaries. LNGOs chose facility locations based on "available facility capacity (including space for waiting areas, offices, storage) and accessibility to a large number of beneficiaries" (LNGO #3).

3.2.4 | Delivery planning

In our interviews, the LNGOs specified that they were always in close communication with donors regarding the types and amounts of donations that would be available for the upcoming relief projects and the arrival dates of the supplies to the facilities. Accordingly, LNGOs made long- and short-term delivery plans as follows.

First, in the long term, they "made plans usually at the beginning of each month according to the expected amount and type of supplies coming from donors" (LNGO #3). Once donations were received, LNGOs were usually under pressure from donors to complete distributions within a short period of time. However, it was difficult to make detailed delivery plans before supplies were received, as the exact timing of supply arrivals was difficult to predict. Therefore, for each upcoming relief project, LNGOs determined the list of targeted beneficiaries in advance. They also made staff planning decisions based on the requirements of the project and staff availability.

For shorter term planning, which we address in this study, LNGOs explained that the delivery days (over a week or two) were determined based on the available supplies at the facility. LNGOs often distributed multiple types of supplies in a day. Daily delivery targets were set such as to "serve 100 beneficiaries each day from 08:00 until 15:00." Announcements to the targeted beneficiaries were usually made a few days before the delivery by using mass messages (e.g., social media groups) (LNGO #3).

According to our interview findings, the delivery process was similar across the LNGOs. For instance, LNGO #1 explained that "three volunteers served each beneficiary. The distribution took around 30 minutes per beneficiary, which involved registering and picking up the supplies." LNGO #3 stated that "the delivery included two sessions; the first session was registering on desk by a volunteer and took around 15-20 minutes, and the second session was delivery by hand by one or two volunteers and could take 15-20 minutes." Agencies mentioned that service times could depend on the type of supply, for example, bulky items took longer time to deliver.

4 | PROBLEM DESCRIPTION AND MODEL

In this section, we specify the decision-making needs of the agencies (Section 4.1), define the BASP (Section 4.2),

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and present our mathematical formulation for the problem (Section 4.3).

4.1 | Decision-making needs

As revealed by our interviews with the LNGOs (Section 3), the current aid delivery system, in which agencies announce delivery days of relief supplies to all beneficiaries at once, creates a number of undesirable consequences, as listed below:

- Ineffective prioritization and unsatisfied needs. Beneficiaries who arrive to pick up supplies may not be served during the operating hours and urgent needs are not prioritized.
- Multiple trips to the facilities. Beneficiaries have to make several visits to the facilities to pick up supplies. Since most beneficiaries live in the suburbs, the repeated visits can create additional expenses and frustration.
- Long waiting times for the beneficiaries at the facilities since exact delivery times during the day are not known.
- Congested facilities and overwhelmed staff.

LNGOs are interested in improving their current delivery planning system by giving appointments to beneficiaries for picking up supplies. That is, registered beneficiaries are only served during their appointment times, and no walk-in beneficiaries are accepted. However, it is difficult for LNGOs to make these plans systematically given the large number of beneficiaries with different needs, several projects to be managed simultaneously, unavailability of skilled staff for managing different projects, and shortage of aid supplies in relation to needs.

Our aim is to provide LNGOs with an algorithm for planning deliveries and scheduling beneficiary appointments so that they can determine which beneficiaries to visit the facility each day at what time slots, and which supplies will be delivered to the beneficiaries by which team of staff members at each time slot. Besides producing feasible daily delivery schedules, the algorithm must also allow agencies to prioritize beneficiaries based on the urgency of their needs. In this way, aid can be delivered to the beneficiary groups on their assigned days and periods effectively and without any hassle.

Besides serving the needs of the agencies in this particular conflict setting, this algorithm can be adapted to other operational settings where different types of services must be provided by setting appointment times for different population groups or individuals. The algorithm is designed to be used by managers without the technical expertise in optimization, it should run on old computers within short execution times, and it should allow the agencies to adjust parameters (e.g., planning horizon length, staff and beneficiary data, resources, schedule granularity) and perform what-if analyses to evaluate the effects of alternative rules and arrangements such as distributing only 1SPD or hiring and training new staff.

4.2 | Problem definition

Based on the decision-making needs of agencies, we define the BASP. In the BASP, we consider a local humanitarian agency, which manages multiple relief projects to distribute different types of relief supplies to a number of beneficiaries in a conflict-affected area from a single facility. The agency has to plan the delivery of aid to a set of targeted beneficiaries, whose needs, urgencies, and relevant characteristics (i.e. gender, political group) are known. In BASP, a beneficiary can represent an individual, a family, or a household, depending on the requirements of the setting (e.g., type of supply).

The BASP focuses on three sets of decisions in an integrated manner: (i) delivery planning, which determines the types and amounts of supplies to be delivered each day, (ii) beneficiary appointment scheduling, which addresses the decisions of which beneficiaries will be served at what time slots, and (iii) staff scheduling, in which staff are assigned to time slots and appointments based on their availability and skills.

The BASP is a multiperiod problem because these decisions must be made for a specific planning horizon (such as 1 or 2 weeks). The primary objective of BASP is to *maximize the urgency-weighted supplies delivered* over the planning horizon, which is identified as the primary concern of the agencies from the interviews. The secondary objective is that of inviting each beneficiary to the facility as few times as possible to collect their supplies.

In conceptualizing our problem, we made several assumptions, which are based on the information and feedback obtained from agencies. Accordingly, the main assumptions of BASP are as follows:

- **Supply**. The type and volume of supplies (i.e., in-kind materials including food and nonfood items and vouchers) available to distribute to the targeted population over the planning horizon (e.g., a week) are known.
- **Demand**. Each beneficiary may need multiple supplies with varying levels of urgency. We assume that each beneficiary may demand a single unit of each supply type (e.g., school kit, family food package). The case where demand amounts may differ for each beneficiary is a straightforward extension. Given the scarcity of supplies, deliveries should be based on the urgency of need. The urgency score for each supply type for each beneficiary depends on the operating context, supplies, and agency characteristics.
- **Beneficiary characteristics and compatibility**. Some beneficiary groups should not be served simultaneously at the facility due to incompatible characteristics. In our setting, groups from different political views need to be scheduled at different times to avoid disputes. Moreover, single unaccompanied women are at harassment risk, and hence, they must be served in different slots than men. We assume that the characteristics of beneficiaries that affect their compatibility (e.g., gender, political faction) are known as only preregistered beneficiaries are served.

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- **Staff**. The delivery of each type of supply requires a team of staff members who need to have received the required training. The staff members have different skills in terms of which supplies they can deliver. Each unit of supply requires a fixed number of skilled staff to be served.
- **Facility space**. For the delivery of each supply, space at the facility is needed (for keeping aid materials in the delivery area, and for allowing staff and beneficiary movement). The space available at the facility (such as desks and booths) and the space required for delivering each supply type (in terms of number of desks) are known beforehand.
- **Delivery and preparation times**. Each day in the planning horizon is divided into a number of time slots (e.g., 15 min). The delivery of a supply requires a fixed and known number of time slots. Before a set of staff can start serving a supply, there is a preprocessing time required to set up the desk space, as well as a reorganization time to finish the service process. If the same supply is served sequentially to multiple beneficiaries by the same set of staff, the preprocessing and reorganization times are incurred only once. Moreover, a time buffer between consecutive supply deliveries for the same beneficiary is imposed to take into account unexpected delays.

A feasible solution for the BASP consists of assignments of time slots and available staff with compatible skills to the supply needed by the beneficiaries. The problem can be considered as a variant of a multiappointment scheduling problem, in which each beneficiary might require multiple appointments over the time horizon.

Several unexpected events can occur while implementing the constructed schedules (such as longer supply setup or delivery times, late show up of beneficiaries, or staff taking longer breaks). However, in this study, we follow a deterministic approach to formulate the BASP to keep the proposed methods simple and implementable. It is possible to formulate sophisticated stochastic or robust optimization models that endogenously incorporate a variety of uncertainties. However, collecting data and characterizing probability distributions may not be practical in this setting for the agencies. Moreover, it may not be sustainable for agencies to find solutions by running sophisticated algorithms that involve probabilistic scenarios.

4.3 | Mathematical model

To formulate the BASP, we define a set B of beneficiaries, S of supplies, V of staff, D of days, and T of time slots for each day. The parameter q_{bs} takes a value of 1 if beneficiary $b \in B$ requires supply $s \in S$, and 0 otherwise. If $q_{bs} = 1$, the parameter u_{bs} denotes the urgency level of delivering supply $s \in S$ to beneficiary $b \in B$. The binary parameter f_{ij} denotes whether beneficiaries $i, j \in B$ can be served at the same time due to compatibility concerns.

Each supply $s \in S$ requires n_s staff members to be delivered. The skills of a staff member $v \in V$ for serving supply $s \in S$ is represented by the binary variable e_{vs}. At the beginning of the planning horizon, q_s units of supply $s \in S$ are available.

The delivery of supply $s \in S$ to each beneficiary takes t_s slots, and requires c_s and r_s slots of preparation and reorganization time, respectively. Delivering each supply $s \in S$ requires a_s units of desk space, whereas the overall desk capacity of the facility is denoted by A. The parameter g denotes the minimum gap between two consecutive services to a beneficiary. Furthermore, ϵ is a small constant. Finally, the decision variables of the BASP are the following:

$$y_{btsd} = \begin{cases} 1 & \text{if delivery of supply } s \in S \text{ to beneficiary} \\ & b \in B \text{ starts at slot } t \in T \text{ on day } d \in D \\ 0 & \text{otherwise,} \end{cases}$$

$$\bar{y}_{btd} = \begin{cases} 1 & \text{if beneficiary } b \in B \text{ receives a delivery at} \\ & \text{slot } t \in T \text{ on day } d \in D \\ 0 & \text{otherwise,} \end{cases}$$

$$z_{vtsd} = \begin{cases} 1 & \text{if staff member } v \in V \text{ starts delivering} \\ & \text{supply } s \in S \text{ at slot } t \in T \text{ on day } d \in D \\ 0 & \text{otherwise,} \end{cases}$$

$$w_{bd} = \begin{cases} 1 & \text{if beneficiary } b \in B \text{ visits the facility} \\ & \text{on day } d \in D \\ 0 & \text{otherwise.} \end{cases}$$

Using these sets, parameters, and decision variables, we present a binary integer programming model for the BASP below:

$$\text{maximize} \sum_{b\in B}\sum_{s\in S}\sum_{d\in D}\sum_{t\in T} u_{bs} y_{btsd} - \epsilon \sum_{b\in B}\sum_{d\in D} w_{bd} \tag{1a}$$

subject to

$$\sum_{b\in B}\sum_{t\in T}\sum_{d\in D} y_{btsd} \le q_s, \quad s \in S \tag{1b}$$

$$y_{btsd} \le w_{bd}, \quad b \in B, s \in S, t \in T, d \in D \tag{1c}$$

$$\sum_{b\in B}\sum_{s\in S}\sum_{t'=\max\{0,t-t_s\}}^{t} a_s y_{bt'sd} \le A, \quad t \in T, d \in D \tag{1d}$$

$$y_{btsd} + \sum_{s'\in S, s'\neq s}\sum_{t'=t}^{\min\{t+t_s+g,|T|\}} y_{bt's'd} \le 1, \quad b \in B, s \in S, t \in T, d \in D \tag{1e}$$

$$z_{vtsd} + \sum_{s'\neq s}\sum_{t'=\max\{c'_s, t-c_s-t'_s-c'_s+1\}}^{t} z_{vt's'd} + \sum_{t'=\max\{c_s,t-t_s+1\}}^{t} z_{vt'sd} \le 1, \quad v \in V, s \in S, t = c_s, \ldots, |T| - t_s - c_s + 1, d \in D \tag{1f}$$

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$$\sum_{b\in B} n_s y_{btsd} = \sum_{v\in V} z_{vtsd} e_{vs}, \quad t \in T, d \in D, s \in S \tag{1g}$$

$$y_{btsd} \le \bar{y}_{btd}, \quad b \in B,\ s \in S,\ t = 1, \dots, |T| - t_s,\ d \in D \tag{1h}$$

$$\bar{y}_{btd} + \bar{y}_{b'td} \le 1 + f_{bb'}, \quad b \in B,\ b' \in B : b' \ne b, \quad s \in S,\ t = 1, \dots, T - t_s,\ d \in D \tag{1i}$$

$$\sum_{t\in T, d\in D} y_{btsd} \le q_{bs}, \quad b \in B,\ s \in S \tag{1j}$$

$$\sum_{t=0}^{c_s} z_{vtsd} + \sum_{t=|T|-t_s-c_s+1}^{|T|} z_{vtsd} = 0, \quad s \in S,\ d \in D \tag{1k}$$

$$y_{btsd} \in \{0, 1\}, \quad b \in B, t \in T, s \in S, d \in D \tag{1l}$$

$$z_{vtsd} \in \{0, 1\}, \quad v \in V, t \in \{c_s + 1, \dots, |T| - c_s - t_s + 1\}, \quad s \in S \tag{1m}$$

$$w_{bd} \in \{0, 1\}. \quad b \in b, d \in D \tag{1n}$$

$$\bar{y}_{btd} \in \{0, 1\}, \quad b \in B, t \in T, d \in D. \tag{1o}$$

The objective function (1a) maximizes the weighted difference of the two objectives, namely, urgency-weighted satisfied demand and total number of visits to the facility, the latter of which is multiplied by a small constant as it is a secondary objective. Constraints (1b) ensure that the total amount of items distributed throughout the planning horizon is less than the available supply, whereas constraints (1c) stipulate that deliveries are made to beneficiaries visiting the agency on the same day. Constraints (1d) ensure that the required space for making deliveries is less than the available space. Constraints (1e) are for coordinating the timing of deliveries for each beneficiary over a day. They ensure that different supplies cannot be delivered to a beneficiary at overlapping times (i.e., a beneficiary can pick one type of supply at a certain time). Moreover, if there must be a gap between consecutive deliveries, the gap must be respected as well. Constraints (1f) enforce a staff member to be assigned to a task only if there is no other setup or delivery activity over the same period, whereas constraints (1g) ensure that the total number of required staff is less than the available set of staff with the required skills. Constraints (1h) and (1i) prevent the assignment of two beneficiaries at the same time period on the same day if they cannot be assigned together according to their gender and political identity. Through constraints (1j), we ensure that deliveries cannot be delivered to a beneficiary if that supply is not requested. Constraints (1k) prevent a staff member from starting a delivery at the beginning of a day or ending a delivery at the end of a day without preparation. Constraints (1l)–(1o) define the domains of the variables.

Variables z_{vtsd} can be employed to both represent an individual staff member and a crew of staff members. In the latter scenario, $n_s = 1$ in constraints (1g). This flexible interpretation of the variables allows the agency to either assign the workload to each individual staff member over the planning horizon or create a priori teams of staff who jointly perform deliveries.

We provide an illustrative example of the proposed model's solution on a small instance in Online Appendix B. The examples illustrate the solution characteristics, and the difficulties in guaranteeing all the constraints are simultaneously satisfied while delivering as many urgent supplies as possible. The mathematical model for the BASP can be solved to optimality by available off-the-shelf solvers only for instances with a small number of beneficiaries and staff. In the next section, we therefore present a heuristic algorithm.

4.4 | Heuristic algorithm

We propose a two-stage heuristic that makes the decisions of the BASP sequentially, using a clustering approach coupled with a scheduling algorithm, which is depicted in Figure 1.

In the first stage of the proposed heuristic, a clustering algorithm extracts a set of beneficiaries to be possibly served in a working day. A scheduling algorithm is then responsible for scheduling as many as possible of their deliveries in the given working day. This process is iterated for any working day, until all working days have been successfully scheduled. In what follows, we briefly describe these two parts of the heuristic approach in further detail. The technical details of the clustering and scheduling algorithms with diagrammatic representations and pseudocodes are provided in Online Appendix C.

Clustering. Our preliminary interviews clarified that the number of beneficiaries registered at an agency can be sizeable (i.e., several thousand). The clustering algorithm identifies a subset of beneficiaries to be served in a working day at the agency so that the daily scheduling problems are also maintained to be more tractable. The subset of promising beneficiaries is determined based on the following characteristics:

- The maximum number of beneficiaries in the cluster is not exceeded. For each working day, we set a maximum number of beneficiaries to be considered for delivery. This keeps the scheduling algorithm more tractable.
- The supplies requested by the beneficiaries in the cluster are "similar." For each cluster c, we compute a measure of relative demand of each supply $s \in S$, by dividing the number of units of supply $s \in S$ currently requested by the beneficiaries in cluster c by the number of units of all supplies requested by the beneficiaries in cluster c, denoted by $FD(c, s)$. The demand similarity of beneficiary $b \in B$ and cluster c is computed as $(1/|S|) \times \sum_{s\in S} FD(c, s) q_{bs}$. This avoids excessive setup times, as the staff would waste time

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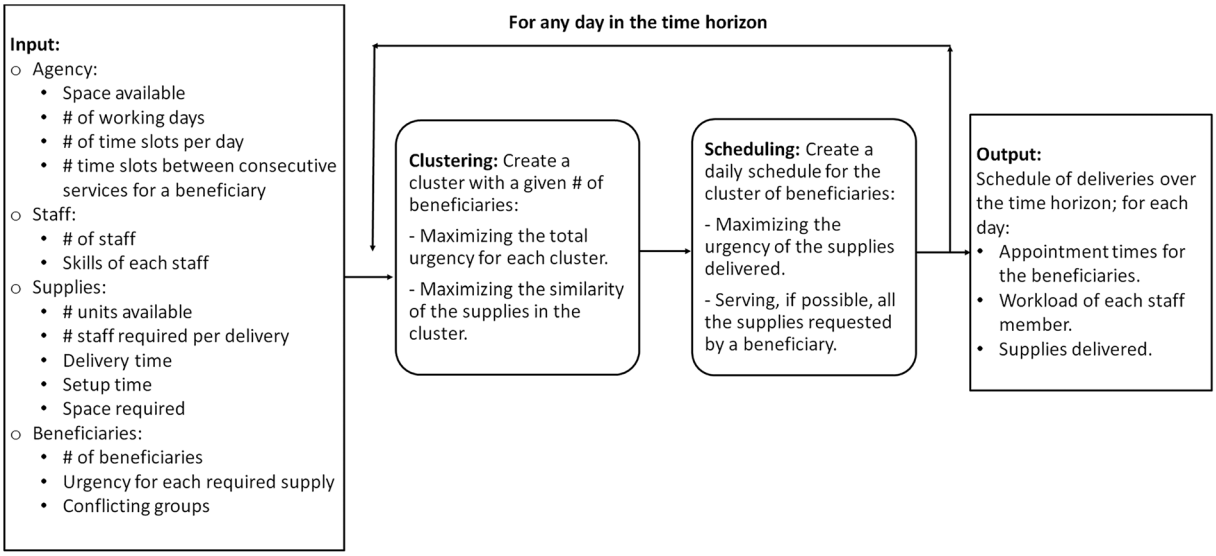

FIGURE 1 Heuristic algorithm framework.

when switching between the deliveries of different types of supplies.

- The urgency of the supplies requested by the beneficiaries in the clusters is maximized.

Scheduling. Once the clustering algorithm returns the most promising subset of beneficiaries, a scheduling heuristic creates workload schedules for a given day, planning deliveries of supplies for this subset of beneficiaries. The main idea is to include as many supply requests with high urgency as possible in the daily schedule and to perform a limited local search to attempt to include all supplies of the same beneficiary (to minimize their weekly trips to the agency), which further improves the total urgency-weighted demand satisfied.

An initial supply delivery schedule is built using an insertion heuristic. The order of insertion is important to obtain good schedules, so we schedule beneficiaries based on urgency, while guaranteeing that a target number of requests of the same (most urgent) supply are attempted to be included in the solution sequentially, so that fewer setups might be necessary.

Scheduling the delivery of a supply in a working day at a given time involves verifying the availability of the supply, a team of staff with the necessary training, space at the facility, the beneficiary (i.e., they could be collecting another supply at that time), as well as the compatibility of the beneficiaries in terms of political identity and gender. These restrictions have to be satisfied for the whole duration of preparation and delivery.

Once a feasible solution is obtained, we implement a local search step, in which a supply $s \in S$ scheduled to be delivered to beneficiary b is instead delivered to beneficiary b', if this allows beneficiary b' to collect any outstanding supply request (and avoid additional trips at the relief facility for beneficiary b'). Given the recommendations of the NGOs, we only allow beneficiary exchanges improving the secondary objective function (minimize the number of trips at the facility), without hindering the primary objective (maximize the urgency of the supplies delivered). The local search step could be adapted to alternative requirements.

The strength of the proposed heuristic is that it can handle a large number of restrictions effectively and solve large instances quickly. Furthermore, it allows performing what-if analyses on different policy-based parameters (such as the training level of staff), exploring the sensitivity of results to different beneficiary compositions (e.g., the composition of different political factions and proportion of single, unaccompanied women), and comparing the impact of alternative delivery policies with varying complexity levels (e.g., serving 1SPD or ignoring urgency levels). In the next section, we validate our heuristic by comparing its solutions to that of the optimization model and illustrate its implementation on realistic case instances to derive practical insights from the solutions.

4.5 | Simplified policies

An LNGO might prefer a simplified delivery strategy for their supplies, or an agency operating in another context might have different requirements. Therefore, we study several benchmark variants, which may produce suboptimal solutions for the original BASP but can be easier to implement by the LNGOs and/or preferable for beneficiaries. The proposed mathematical model and heuristic are flexible to incorporate these modifications, and hence offer a generalizable approach that can be easily adapted to different settings.

- **One supply type per day (1SPD)**: LNGOs may prefer assigning specific days to serve each supply for practical purposes. To mimic this, the first variant we consider (abbreviated 1SPD) focuses on distributing a single supply type per day. The mathematical model can be adapted

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to handle this simplified policy by iteratively solving the model $|D|$ times, in turn, setting $q_s = 0$ for all supplies but one and $|D| = 1$. Similarly, the heuristic algorithm can be executed once for each day (the first supply on the first day, the second supply on the second day, and so on), considering only the demand for the supply corresponding to that day.

- **One trip per beneficiary (1TPB)**: Although our interviews with the LNGOs point to maximizing total urgency as the primary objective, different settings may require that a given beneficiary visit the facility as few times as possible, particularly when beneficiaries are located further away from the LNGO facilities or do not have sufficient means to travel multiple times. For this end, we implement a variant of the BASP (1TPB) that limits any beneficiary's maximum number of visits to one. The mathematical model should include the additional constraint

$$\sum_{d \in D} w_{bd} = 1, b \in B \tag{2}$$

and the heuristic algorithm can be adapted as follows. Once a feasible schedule for day $d \in D$ is obtained, any beneficiary served any supply is removed from the set B. This will guarantee that no beneficiary will visit the facility more than once in D.

- **Fixed slots for gender and incompatible political factions (PreA)**: The BASP produces schedules that prevent clashes based on gender and political factions. While this results in effective allocations in terms of satisfying urgent demand, it may also lead to schedules in which minority incompatible groups or factions may be underserved. As a benchmark, we preallocate a fixed set of time slots on predetermined days to incompatible factions in proportion to their size in the population. Neutral factions can still be allocated appointments in these preallocated slots. If we assume that T_r slots are reserved, for example, to a protected political faction to attend the facility at the beginning of day d, variables $\bar{y}_{btd}, t = 1, \ldots, T_r$ are set to be equal to zero, if b belongs to an incompatible political faction and should not be at the facility in the fixed slots. Similarly, the variables can be set to zero, for the gender that should not attend the facility. In the heuristic algorithm, the code has been set up to preset the value of the political faction (and the gender) allowed at the facility for each time slot. Any insertion or local search move will then have to respect this constraint during the execution.

We test these policies on a set of instances and present our results as well as managerial insights in Section 5.2.4.

5 | COMPUTATIONAL STUDY

We present our computational experiments that serve multiple purposes. First, we evaluate the quality of the schedules generated by the proposed heuristic, coded in VBA, by comparing them to optimal solutions. We use a smaller set of instances that can be optimally solved by the CPLEX solver for this end. Second, we draw managerial insights from the heuristic solutions obtained for larger sized realistic instances. To this end, we explore three different avenues. First, we analyze the impact of the level of staff cross-training on the efficiency and effectiveness of deliveries. Second, we investigate the impact of conflicts and that of taking them into account on the resulting deliveries. Lastly, we assess the extent to which obtaining accurate information on beneficiary needs plays a role in delivery effectiveness and use the heuristic to evaluate alternative planning and delivery policies that exhibit different levels of complexity. All experiments are conducted on a 64-bit Windows Server with two 2.0 GHz Intel Xeon CPUs and 32 GB RAM.

5.1 | Instance generation

Since the BASP is a new problem, there are currently no established benchmark instances available in existing literature. Moreover, due to challenges around communicating with LNGOs and accessing data, the proposed approach could not be tested on real instances. Therefore, we evaluate our approach on a set of representative instances derived from publicly available data relevant to the region where the interviewed LNGOs operate, supplemented by information gathered through the interviews.

In our case study, we derive beneficiary-related input parameters by leveraging data from multisector needs assessment surveys by Humanitarian Needs Overview (HNO) (HNO, 2022) in the Latakia district. We consider the 63 suburban neighborhoods and towns in the district, excluding the city of Latakia due to limited neighborhood-level data. A map of the Latakia district and its neighborhoods is provided in Figure 2. The HNO's needs assessment survey provides estimates for healthcare, nutrition, education, nonfood items, and water at the district level. Using population data, we disaggregate these estimates to the neighborhood level.

The number of beneficiaries $|B|$ is set as 80 and 15,000 for the smaller and larger instances, respectively. Each beneficiary is assumed to reside in one of the 63 neighborhoods, with specific locations randomly assigned based on neighborhood population proportions. The number of supplies requested by a beneficiary is sampled from a discrete random distribution ranging from 1 to $|S| = 5$. The supplies are assigned randomly, proportional to the expected requests of that supply by the population in the same neighborhood. The urgency associated with a supply is a random number between 1 (lowest) and 5 (highest).

Following discussions with LNGOs, we assume that each neighborhood is associated with one of three main political factions (groups), labeled A, B, and C. This results in a distribution of 35%, 45%, and 20% of the overall population for factions A, B, and C, respectively. To avoid disputes at the facility, beneficiaries who are members of factions A and B are prohibited from being served at the same time, while faction C is considered neutral, allowing its members

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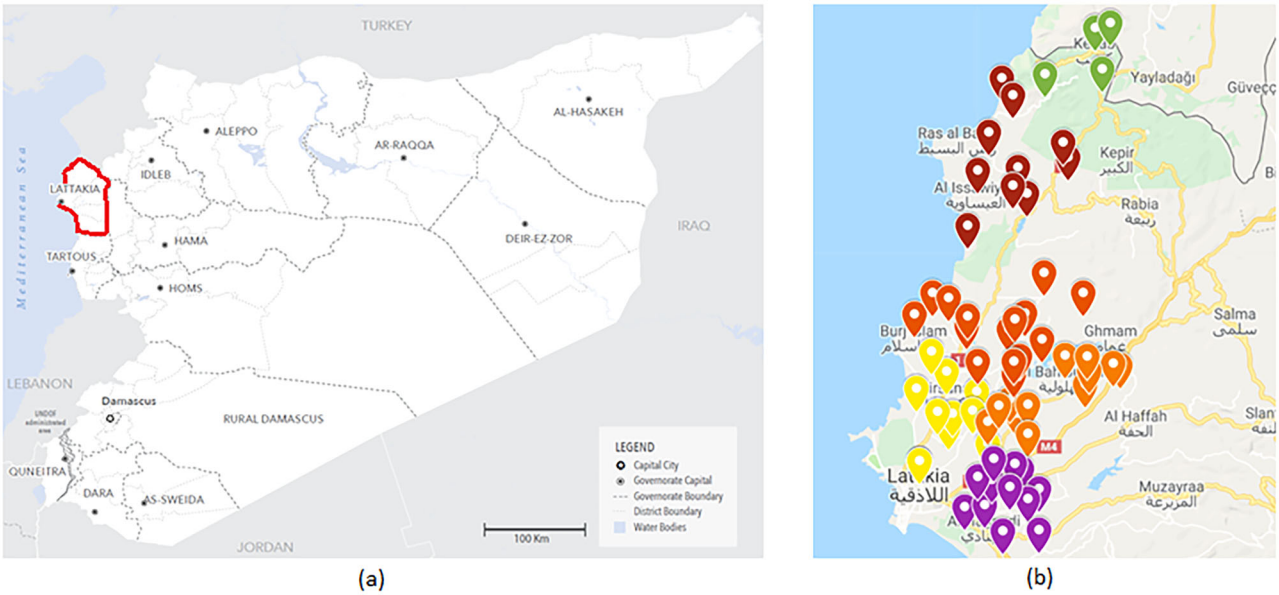

FIGURE 2 Locations of (a) Latakia district in Syria and (b) the 63 neighborhoods within the district, with colors representing different subdistricts (Source: Google Maps).

to be served simultaneously with any other political faction. Additionally, a beneficiary is randomly assigned to be a single woman with probability $p_{single} = 0.3$, which can only be served simultaneously with other single women. We test the effects of having a smaller or larger group of single women in our analyses.

Each instance covers a planning horizon of one working week (5 days), with each day consisting of 16 time slots in the smaller instances and 40 slots in the larger ones. The latter is set so that each slot represents approximately 10 min. Smaller instances involve 15 staff members and 20 desks, while larger instances involve 25 staff members using a total of 40 desks.

In our experiments with smaller instances, CPLEX obtains results with large optimality gaps (on average 12.26%) when staff, space, preparation, delivery, and reorganization time requirements differ among the supply types. In other words, increasing heterogeneity of instance parameters results in increased computational difficulty. Hence, for these instances, we assume that each supply type requires two members of staff, one unit of space (i.e., desk), and one-time slot for preparation, delivery, and reorganization, which allowed us to obtain optimal solutions within an hour for all small instances. Under these settings, CPLEX can solve all smaller instances to optimality. In larger instances, all of these parameters are first randomly generated between 1 and 3 except for the preparation and reorganization times, which are randomly generated between 1 and 2 time slots. For these instances, CPLEX fails to obtain a feasible solution within 2 h. Consequently, we use heuristic results for our analysis of larger instances.

The total amount of each supply type available to distribute during the week is randomly generated between 10 and 90 for smaller instances. For larger instances, we consider settings with high and low supply availability, where for "higher supply," the available amount is generated randomly between 150 and 350 units, and for "lower supply" instances, each item has a capacity randomly generated between 50 and 100 units. In both cases, total supply can cover less than 10% of the total demand. However, it is not a binding factor for the higher supply case, where staff and space availability limit the delivery of all available supplies. In our baseline instances, the number of supply types each staff member is trained to deliver is uniformly distributed between 1 and 5. The minimum gap between consecutive deliveries to a beneficiary is taken as one-time slot. A summary of parameters used in our instances is provided in Table 2. We perform tests on 10 instances and report averages for each setting.

5.2 | Results and analysis

In this section, our initial experiments aim to assess the heuristic's schedule quality by comparing it to CPLEX's optimal solutions for smaller instances (Section 5.2.1). Subsequently, we present our results based on larger instances to develop insights that can support LNGOs in making delivery plans and managing scarce resources. We perform tests to explore the impact of staff cross-training on critical performance metrics (Section 5.2.2), investigate beneficiary incompatibilities' effects on aid delivery performance (Section 5.2.3), compare alternative practical delivery policies (Section 5.2.4), and highlight generalizable managerial insights from our experiments.

We compare solutions based on several KPIs such as the total urgency level satisfied across delivered supply (**TU**), the total number of beneficiary visits to the facility (**TV**), utilization of staff (**SU**), utilization of space (desks) (**DU**), number of beneficiaries served (**BS**), and number of supplies delivered (**SD**). For larger instances, we also analyze the total urgency per supplies delivered (**TU/SD**). Among these, TU

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TABLE 2 Main parameters used in instance generation.

Parameter	Small	Large
$\|B\|$	80	15,000
$\|V\|$	15	25
$\|T\|$	16	4040
$\|D\|$	5	
$\|S\|$	5	
A	20	40
g	1	
n_s	2	$U\{1,3\}$
q_{bs}	$U\{1,5\}$	
u_{bs}	$U\{1,5\}$	
e_{vs}	$U\{1,5\}$	
t_s	1	$U\{1,3\}$
c_s/v_s	1	$U\{1,2\}$
a_s	1	$U\{1,3\}$
q_s	$U\{10,90\}$	$U\{50,150\}$
		$U\{150,350\}$

and TV represent the primary and secondary objectives of the BASP, respectively. Solution effectiveness is evaluated through TU, TV, BS, SD, and TU/SD metrics, reflecting service level and quality. Schedule efficiency is assessed using metrics that focus resource utilization such as SU and DU.

5.2.1 | Mathematical model and heuristic comparison

Table 3 presents the values of KPIs obtained by solving the BASP with CPLEX and the heuristic, and the optimality gaps for the heuristic solutions. As reported in the table, the average optimality gap of the heuristic solutions is 2.20%, which shows that the proposed heuristic can find high-quality solutions. Furthermore, while CPLEX requires an average of 1212.3 s for these instances, all heuristic solutions are obtained within 10 s.

Over the 10 instances, the average total urgency level satisfied (TU) in the heuristic solutions is within 2% of the optimal results. The main difference arises from the secondary objective of the total number of visits to the facility (TV), where on average the heuristic results in more than 20 additional visits to the facility. This is due to the clustering step of the heuristic aiming to minimize setup times to schedule as many beneficiaries as possible in a day. However, this also allows the heuristic to serve slightly more beneficiaries and more supplies (BS and SD), because it favors similarity of beneficiaries in terms of demanded supplies during the clustering phase. In a setting where the number of visits is relatively more important, the heuristic can be run under the 1TPB policy, so that no beneficiary needs to visit the facility more than once. The utilizations of staff members and desks are almost identical in both solutions. These results validate that the proposed heuristic algorithm can find favorable solutions for the BASP in terms of important effectiveness and efficiency metrics, and does so within a much shorter computational time and smaller resource requirement than the commercial solver, without the need for any special software or powerful computing resources.

5.2.2 | Effects of cross-training

One of the unique features of the problem settings for the BASP is the need to serve beneficiaries specific supplies by staff members who have been trained to serve that supply. We assess the potential value of staff training for the LNGOs by performing tests considering lower and higher supply levels. For each supply level, we compare the solutions obtained for five training settings. In the baseline, each staff member has the skills to deliver an expected number of three supply types. We also consider settings where all employees are trained for a single supply, two supplies, four supplies, and all supplies. Figure 3 shows the two main KPIs of TU and TV under these settings. We present detailed results in Online Appendix D.

Managerial Insight 1. *Cross-training of staff to deliver different types of supplies has a positive impact on total urgency satisfied when staff training is low, especially under higher supply. There are diminishing returns to increasing staff training, which is more pronounced under higher supply*.

In scenarios with higher supply, the improvement from training for one supply to two or three is more pronounced compared to a more scarce supply. This is because, in situations where supply is not the limiting factor, the availability of staff becomes crucial, and cross-training enhances overall availability. Conversely, in lower supply scenarios, where supply availability is a constraining factor, the impact of additional staff training is marginal on the TU objective. Increased cross-training also allows for satisfying higher urgency per supply served, as evidenced in Table D.2 in the Online Appendix.

These findings offer actionable insights for LNGOs in staff training decisions, guiding them on which staff members to train for distributing specific supplies. For example, when all staff members can serve a single supply, training five of the 25 staff members to serve Supply 1 (a voucher) results in an 8% increase in TU and 14% increase in SU. Such analyses can be crucial in leveraging the possibility of additional training to achieve more effective schedules.

As also indicated by the results in Figure 3, both in high and low supply cases, there are diminishing returns; with four or five supplies per staff, there is negligible improvement from the baseline. This is also reflected in the staff utilization (SU): with higher supply and little training, SU is very low, as lack of training prevents more efficient service. A similar pattern is observed with lower supply, but to a lesser extent, as supply availability is not as binding in this case. Albeit intuitive, this kind of analysis would be helpful for the LNGOs to systematically assess the bottlenecks created by different levels of resources.

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TABLE 3 Comparison of heuristic results with optimal solutions on small instances.

Inst.	Total urgency (TU)		Total # of visits (TV)		Staff utilization (SU)		Desk utilization (DU)		Beneficiaries served (BS)		Supplies delivered (SD)		CPU time		Heuristic's Opt. Gap
	Opt.	Heur.	Opt.	Heur.	Opt.	Heur.	Opt.	Heur.	Opt.	Heur.	Opt.	Heur.	Opt.	Heur.	
1	372	370	71	88	36.3%	36.9%	19.9%	19.6%	71	73	130	129	1258.2	5.2	1.01%
2	362	352	68	92	35.5%	35.5%	19.3%	20.1%	68	70	119	121	997.1	7.8	3.49%
3	298	294	66	85	46.9%	46.1%	21.4%	21.1%	66	67	92	93	1294.6	6.3	2.02%
4	406	390	66	93	36.5%	37.3%	20.5%	20.4%	66	70	128	129	1427.3	4.0	4.68%
5	394	393	70	89	37.4%	37.3%	29.3%	28.7%	70	70	122	122	1213.1	8.2	0.75%
6	407	404	73	100	39.0%	38.4%	23.6%	22.6%	73	77	132	134	1165.4	7.3	1.43%
7	367	367	80	98	37.4%	37.8%	23.5%	23.7%	80	80	133	133	1308.2	8.0	0.50%
8	336	322	60	75	29.5%	29.7%	18.3%	18.7%	60	60	100	98	1342.8	4.7	4.70%
9	403	399	72	98	43.4%	42.8%	21.4%	22.1%	72	72	135	137	1101.4	5.3	1.67%
10	372	367	72	85	36.1%	35.9%	20.4%	20.4%	72	72	124	126	1014.7	6.7	2.20%
Avg.	371.7	365.8	69.8	90.3	37.8%	37.8%	21.8%	21.7%	69.8	71.1	121.5	122.2	1212.3	6.4	2.20%

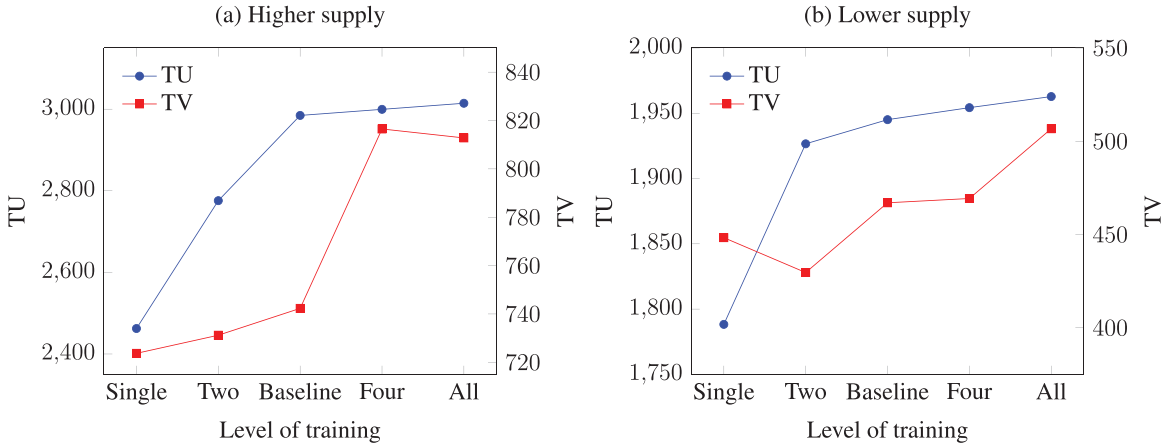

FIGURE 3 Total urgency satisfied (TU) and total number of visits (TV) for each training level under (a) higher and (b) lower supply.

5.2.3 | Effects of political faction and gender based conflicts

Another distinct characteristic of a conflict-based environment is the existence of incompatible groups that cannot be mixed together. In our case, two sources of beneficiary-related conflicts prevent the formation of more efficient schedules, namely, (i) two beneficiaries associated with the two political factions in conflict with each other (factions A and B) cannot be served at the same time slots and (ii) a single unaccompanied woman can only be served simultaneously with the same gender group. We perform experiments to analyze the effects of these two types of conflicts, both in terms of how the interaction between these two types of conflicts affects the solutions and how the composition of the population plays a role in the effectiveness of the deliveries.

As indicated in Section 5.1, in our baseline experiments, single women constitute $p_{single} = 30\%$ of the overall population, and political factions A, B, and C have an association of 35%, 45%, and 20% of the population, respectively. In our analysis, we compare four additional scenarios for the composition of political factions by randomly reassigning some proportion of the population in the baseline scenario to different groups. The four additional scenarios and the corresponding composition of political factions are given in Table 4. These involve an equal composition of all factions, two equally sized conflict factions (and no neutral faction), a dominant neutral faction, and a dominant conflict faction. We also vary the p_{single} parameter as 0%, 10%, 30%, and 50%.

In addition to the TU and BS measures, Table 4 also shows the share of each faction in the set of beneficiaries served (% of BS). Similarly, when $p_{single} > 0$, we also show what percentage of the population served belongs to the vulnerable group of single women (WS/BS).

Managerial Insight 2: *When multiple incompatible and neutral groups exist, the share of supplies to be received by each group depends on the overall composition. When the groups are of similar size or incompatible factions are smaller, neutral groups receive a higher proportion of the supplies than their relative size in the population. A conflicted*

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TABLE 4 Total urgency levels and number of beneficiaries served for varying political faction and gender compositions.

	Political faction composition						% of BS			
p_{single}	Scenario	A	B	C	TU	BS	A	B	C	WS/BS
0%	Baseline	35%	45%	20%	2984.7	466.3	31.5%	47.2%	21.3%	N/A
	Equal decomposition	33%	33%	33%	3105.8	470.0	30.5%	29.1%	40.4%	N/A
	Conflict factions only	50%	50%	0%	2769.3	358.7	50.8%	49.2%	0.0%	N/A
	Dominant neutral faction	20%	20%	60%	3349.0	470.0	14.7%	14.5%	70.7%	N/A
	Dominant conflict faction	60%	20%	20%	2463.3	367.1	73.3%	9.1%	17.6%	N/A
10%	Baseline	35%	45%	20%	2939.1	456.0	30.5%	47.5%	22.0%	2.1%
	Equal decomposition	33%	33%	33%	3084.1	466.2	29.6%	30.1%	40.3%	2.2%
	Conflict factions only	50%	50%	0%	2763.9	350.1	49.8%	50.2%	0.0%	2.6%
	Dominant neutral faction	20%	20%	60%	3267.5	456.7	12.6%	13.8%	73.6%	2.4%
	Dominant conflict faction	60%	20%	20%	2399.3	357.3	75.3%	9.5%	15.2%	2.5%
30%	Baseline	35%	45%	20%	2566.9	455.3	29.8%	50.5%	19.8%	23.5%
	Equal decomposition	33%	33%	33%	2595.9	396.0	29.0%	32.2%	38.9%	22.0%
	Conflict factions only	50%	50%	0%	2683.6	317.8	48.7%	51.3%	0.0%	24.6%
	Dominant neutral faction	20%	20%	60%	2738.1	422.3	13.8%	13.7%	72.4%	21.2%
	Dominant conflict faction	60%	20%	20%	2156.2	332.1	73.3%	9.4%	17.3%	24.8%
50%	Baseline	35%	45%	20%	2127.5	393.0	30.6%	50.7%	18.7%	39.2%
	Equal decomposition	33%	33%	33%	2470.3	372.9	28.5%	31.2%	40.3%	41.3%
	Conflict factions only	50%	50%	0%	2316.3	290.0	52.3%	47.7%	0.0%	42.9%
	Dominant neutral faction	20%	20%	60%	2479.7	373.1	14.1%	11.4%	74.5%	40.1%
	Dominant conflict faction	60%	20%	20%	2120.4	277.3	69.3%	9.3%	21.3%	43.6%

group is only favored when its relative size in the overall population is significantly larger than others.

Under an equal decomposition of the targeted beneficiaries, we observe that the neutral faction (C) is overrepresented within the served population. This is because in such a scenario, the schedule avoids political faction conflicts by serving as many higher urgency members of the neutral faction as possible. This is further evident under the dominant neutral faction scenario. When one of the conflicted factions is dominant, then this group is overrepresented in the served population. We observe that the % of BS for the neutral faction is fairly representative of its relative size in the population in this case.

These discrepancies in distribution point out that the highly constrained operational environment may lead to serving different population groups in an unbalanced way. While the proposed heuristic ensures effectiveness by satisfying the most urgent needs of individual beneficiaries, such an imbalance may be of concern to the LNGOs. In such a case, LNGOs should consider increasing the urgency scores or allocate specific slots for (i) conflict factions when the composition of all factions is equal or the neutral faction is dominant, or (ii) nondominant conflict factions when at least one conflict faction is dominant.

Managerial Insight 3: *The share of supplies delivered to the group in conflict with all other groups in the population (i.e., the vulnerable group) depends on its relative size. Such a group is significantly overlooked when its relative size is small, whereas its share in receiving the delivered supplies significantly improves as its size is larger*.

In our experiments, when single women (the vulnerable group) constitute 10% of the population, we observe similar TU values to those when there are no single women. This is because when the vulnerable population forms a small minority, its members are substantially overlooked when determining who is served so that the constraints due to the conflict can be avoided. When the proportion of single women increases, we observe a considerable change in their inclusion in the served population. In this case, the vulnerable population is too large to be ignored when determining the group of beneficiaries to be served.

Consequently, if a balanced distribution across different groups is of concern, the LNGOs can consider strategies including increasing urgency scores or allocating specific slots to serve vulnerable groups more effectively, and choose the most desirable alternative for the specific context by evaluating the KPIs.

5.2.4 | Comparison of benchmark appointment and delivery planning approaches

The proposed heuristic approach for the BASP employs a clustering and scheduling algorithm and results in beneficiary appointment schedules that are both effective and efficient. On the other hand, different LNGOs in other contexts may

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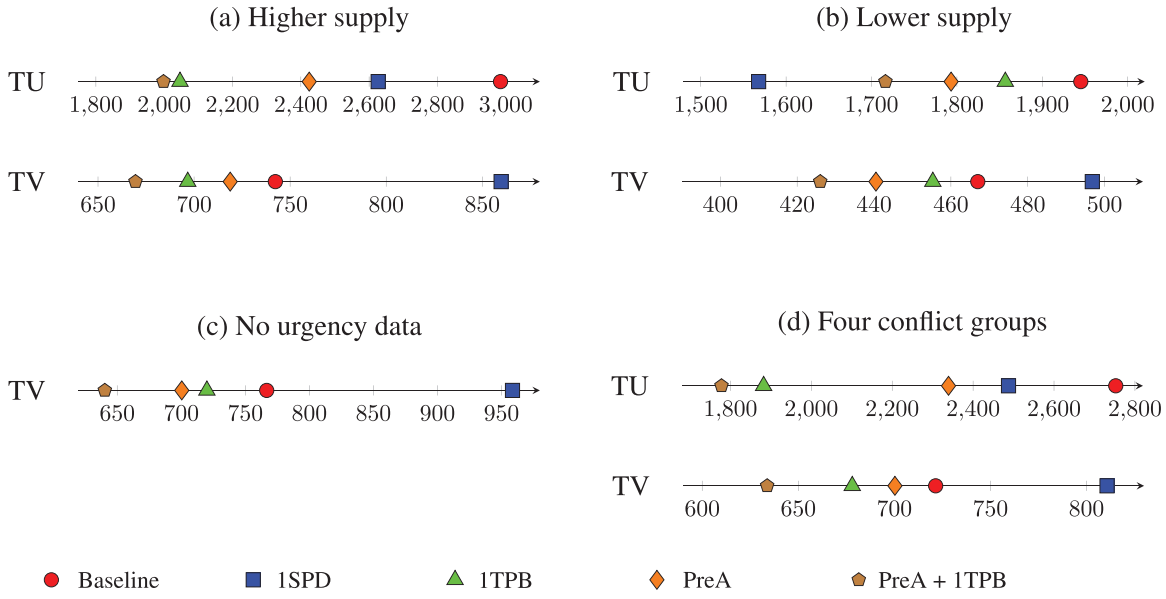

FIGURE 4 Total urgency satisfied (TU) and total number of visits (TV) under the baseline, one supply per day (1SPD), one trip per beneficiary (1TPB), preallocation of slots to incompatible groups (PreA), and hybrid PreA & 1TPB policies with (a) higher supply (base case), (b) lower supply, (c) no urgency data, and (d) four conflict groups.

have other objectives they prioritize and/or may apply simpler policies that are easier to implement in practice. The proposed heuristic is flexible enough to be adapted to implement and evaluate a number of such policies that were implied by some of the responses from our interviews with the LNGOs. In what follows, we evaluate three such policies, namely, 1PSD, 1TPB, and preallocation of slots for incompatible groups (PreA), which were previously defined in Section 4.5. We note that these policies are by no means mutually exclusive. However, our preliminary experiments show that their combinations lead to very restrictive environments, with substantial losses in all KPIs. Only combining PreA with 1TPB leads to comparable results with other policies, which we include in our results.

To ensure the robustness of our findings, we test these policies under four different settings. In addition to the aforementioned higher and lower supply settings, we also consider two alternative settings, where (i) there is no urgency level data and (ii) there are four incompatible factions instead of two. For the former, we set the urgency levels of each demand in the data to be 1. For the latter, we split each of the two incompatible factions in half and assume that all resulting factions are incompatible with each other. The resulting KPI levels of the benchmarks are compared to that of the baseline under the four scenarios in Figure 4. A detailed summary of our runs is reported in Tables D.1 through D.4 in the Appendix.

Managerial Insight 4: *Our proposed approach performs particularly well relative to simpler policies when accurate needs assessment data are available. In the absence of such data, simplified policies such as serving one type of supply per day or restricting each beneficiary to a single visit result in allocations with similar performance*.

In all scenarios where urgency data are available and accurate (Figures 4a, b, and d), the heuristic solution to the BASP produces higher TU values than its benchmarks. With less scarce supply (Figures 4a and d), it performs 10% better than 1SPD, 30% better than 1TPB, and 20% better than PreA. With lower supply, the same differences are 20% for 1SPD and 5% for 1TPB, and 8% for PreA. The differences are more pronounced when supply capacity is not binding, as in that case, effective clustering and scheduling play a more important role in determining the effectiveness of allocations due to the binding impact of time slots, staff members, desks, and conflicts. When urgency data are not available (Figure 4c), the BASP solution can no longer exploit urgency levels to determine clusters and schedules effectively, and it obtains similar results with 1SPD and 1TPB (both within 2% of the BASP solution).

Consequently, LNGOs can benefit better from the BASP solution (i) when there is at least some level of differentiation between the urgency levels of beneficiaries by means of a needs assessment and (ii) when supply capacity is not a binding constraint. Those without data on urgency levels (e.g., simply with a list of beneficiaries and the supplies they need) or with so little supply capacity that almost all supplies can be delivered with available resources, LNGOs making use of 1SPD or 1TPB can obtain similar results.

Among the benchmark policies, 1TPB works better when supply capacity is binding. Otherwise, 1SPD results in a more effective allocation. When the capacity of a supply is not sufficient to fill a full day's schedule, 1SPD results in an ineffective and inefficient allocation, as reflected in Figure 4(b). In other cases when supply availability is not binding, we observe the performance of 1SPD to be fairly robust, performing consistently better than other benchmarks. Hence,

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using the 1SPD policy would be recommended in cases where the supply is sufficiently large and visits to the facility do not require substantial effort or costs (e.g., when beneficiaries do not have to travel long distances). The 1TPB policy works in the opposite direction to 1SPD, where in the lack of sufficient supply, the policy can take advantage of serving multiple supplies to the same beneficiary in a single visit. In such a case, 1TPB yields KPIs not too far from those of the BASP, with the added benefit that more beneficiaries can be served. Although 1SPD and 1TPB are not alternatives to one another, implementing them together has the effect of canceling their advantages in all scenarios, leading to substantially inferior results to implementing only one of them.

Managerial Insight 5: *Preallocating slots for specific groups only work well when supply is scarce or there is a high level of incompatibility in the population*.

By design, PreA creates a more constrained scheduling environment by allocating specific time slots on specific days to incompatible faction members. On the other hand, it may be used to ensure that the share of each group in the served population is aligned with its proportion in the overall population. Comparing Figures 4(a) and (b), a more scarce supply leads to a less tight schedule, and thus preallocating part of the slots to incompatible factions results in a less drastic effect and closer results to those of the BASP solution. A scarce supply is also the only case where implementing a combination of the benchmark policies (PreA + 1TPB) results in a less than 15% TU loss from the BASP solution result. Increasing the number of incompatible factions (as in Figure 4d) also imposes a more constrained problem in terms of incompatibilities and leads to a closer overall performance for PreA compared to the BASP solution.

Our results in this section underscore the importance of needs assessment to accurately determine the urgency of supplies for the beneficiary groups. Our analysis provides valuable insights into the effects of supply scarcity and level of conflict on the effectiveness of alternative policies. Our results can also be extended to other settings than conflicts, including disaster recovery in the existence of vulnerable/incompatible groups or long-term aid. Importantly, the versatility and flexibility inherent in the proposed heuristic approach make it a valuable tool for evaluating alternative allocation policies under different settings.

6 | DISCUSSION: IMPLEMENTATION CHALLENGES AND THE WAY FORWARD

While our study significantly contributes to the understanding of decision-making in conflict settings through the introduction of a novel problem, a practical solution approach, and valuable insights, it is important to acknowledge two major limitations. These limitations are primarily associated with challenges related to implementation and data availability.

First, the proposed decision support tool in our study is currently in the form of a software prototype, lacking field testing and implementation. The transition to production-ready software, suitable for active deployment by organizations in the field, necessitates further steps (Nygard, 2018). Such an endeavor would require close collaboration with end users to rigorously test and adapt the tool to align with their specific systems. Unfortunately, practical obstacles, including communication challenges with local organizations due to security concerns, a high employee turnover rate, and resource constraints, compounded by the disruptive impact of the COVID-19 pandemic, have hindered our ability to execute the implementation phase. These challenges are representative of those faced in many conflict settings, highlighting the need for increased awareness within the academic and practitioner communities regarding the necessity of developing decision support tools and technology before crises emerge.

Secondly, due to challenges in data availability, the implementation of our proposed methods relies on a case study featuring synthetically generated data. Although our case data set incorporates knowledge gained through interviews and publicly available information (e.g., interagency needs assessment reports, HNO, 2022) specific to the context, we acknowledge that real organizational data could not be employed for two primary reasons. First, concerns related to data confidentiality discouraged organizations from sharing beneficiary-related data, potentially jeopardizing their operational licenses. Second, even the less sensitive data are not stored in clean, automated, and shareable formats. Moreover, due to resource limitations (i.e., staffing and budget), it may not always be possible to collect and maintain crucial data (such as beneficiary characteristics, and urgency levels) in an up-to-date manner. To address these challenges, we conduct extensive analyses to understand the potential effects of data inaccuracies and by employing simplified operational policies. In the long term, there is a pressing need to develop benchmark data sets that can be used to validate and test models and solution approaches addressing complex and low-resource settings. This should be a collaborative effort involving humanitarian organizations with diverse operational experiences.

Lastly, while our study focuses on a specific context motivated by the Syrian conflict, it is vital to acknowledge the diversity of conflict settings. These environments can vary in actors and challenges, underscoring the necessity to carefully consider the local context, including the cultural and political aspects unique to each affected region. Addressing these differences and ensuring the adaptability of decision-making tools across diverse conflict zones demands a collaborative effort that involves stakeholders with extensive contextual knowledge and operational experience. We hope that this study stimulates increased attention and collaborative efforts to address the unique challenges of delivering aid in conflict environments.

7 | CONCLUSION

This study focuses on decision-making needs of local humanitarian agencies, which provide long-term aid to IDP in a conflict-affected region. Based on the interviews conducted

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with several local agencies operating in Syria, we address the need for developing effective decision support systems for organizing aid deliveries. We present a mathematical programming model and a simple heuristic algorithm to support delivery planning and beneficiary appointment scheduling decisions. Our results and insights underscore the importance of cross-training staff and considering the incompatible characteristics of beneficiary groups. We also test the performance of alternative simpler practical variants and show that serving a single supply per day may be reasonable, while it is always crucial to prioritize deliveries based on urgency levels and similarity of needs across beneficiaries. Since our proposed heuristic runs efficiently without requiring special software, agencies can play with the input parameters and evaluate solutions on a set of KPIs before reaching the most suitable delivery plan for a setting. Our numerical analysis highlights the various challenges related to data availability and accuracy in conflict settings. We also show that the proposed tool is flexible to accommodate simpler policies, which may be preferable to implement in difficult humanitarian settings.

While our study focuses on the delivery of aid in a conflict-affected area, the proposed model and heuristics can be adapted to other long-term aid delivery settings to schedule the appointments of registered beneficiaries effectively. For example, different planning approaches can be developed for settings in which communicating with beneficiaries for appointment times is not possible. Moreover, settings in which different organizations collaborate to share resources (e.g., facilities, volunteers) can be studied. Additionally, avoiding mass distribution of aid materials and organizing deliveries by taking social distancing constraints have also become particularly important during the COVID-19 pandemic (Konyndyk & Saez, 2020), and the proposed method can be extended to help humanitarian agencies organize deliveries at their facilities while keeping the physical distance among beneficiaries and reducing infection spread risk in the community. Finally, the number of displaced people is predicted to increase due to climate change effects (Chowdhury et al., 2020). Future research can consider adapting the proposed approaches to develop models and policies for effectively providing long-term relief aid to people on the move.

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