Medical staff planning for field hospital deployments: the START hospital

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Abstract

Purpose – The deployment of a field hospital can play an important role in the response to an emergency. This paper is concerned with the management of emergency staff to a field hospital from a roster of volunteers with different characteristics. This paper aims to propose a mathematical optimisation model that selects the necessary profiles of the roster according to several criteria and provides travel planning taking into account the total cost of the operation.

Design/methodology/approach – This study uses a multi-criteria optimisation model to take into account the preferences of the three main stakeholders involved in the deployment of the field hospital: the cooperation organisation, the staff and the end users. The model considers the possibility of using commercial or chartered flights, allows staff to indicate their preferred availability, considers the grading of volunteers according to their skills and training and provides a final flight schedule for all the medical personnel needed to operate the field hospital. Compromise programming is used to provide a Pareto optimal solution, which is compared with solutions provided by Goal programming.

Findings – The model has been validated using data from the operation in a case study of the deployment of the Spanish START hospital in Turkey 2023, demonstrating the practical utility of the model in similar operations.

Originality/value – The study innovates by considering a multi-criteria model that takes into account the main actors involved in the response – cooperation organisation, staff and end users – in an integrated way and proposes new measures of efficiency.

Keywords Humanitarian logistics, Disaster response, Scheduling, Emergency medical services

Paper type Research paper

1. Introduction

Emergency logistics refers to the planning and execution of logistics activities to meet urgent and unforeseen logistics needs during emergencies. The effectiveness and efficiency of emergency logistics are critical to saving lives and mitigating the impact of emergencies. Emergency logistics involves, among other things, the management of commodities (e.g. medical supplies and personnel, specialised rescue equipment and teams, food, etc.) to be deployed to the affected areas as soon as possible to accelerate relief effort, see Özdamar *et al.* (2004). Among these operations, the dispatch of emergency medical personnel in the aftermath of major disasters such as earthquakes occupies an important place.

The earthquake that struck southern Turkey and northwestern Syria on February 2023 caused an estimated 59,500 deaths – 51,000 in Turkey and 8,500 in Syria – and injured some 122,000 people. On 6 February, the Turkish government issued an international appeal for assistance, and the response was coordinated by the World Health Organization's Emergency Medical Team (EMT) and the European Civil Protection Mechanism, known as Team Europe. The Spanish government, through the Spanish Agency for International Development Cooperation (AECID), offered to send the START team (Spanish Technical Aid Response Team).

AECID is the main Spanish cooperation agency dedicated to the fight against poverty and the search for sustainable human development. AECID, through the Humanitarian Action Office (HAO), is responsible for the coordination and management of Spanish humanitarian aid aimed at protecting and saving lives and alleviating human suffering.

To respond to emergencies, since 2016 AECID has been developing the START project, created with the aim of improving the humanitarian response to health emergencies. To this end, the

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team has the capacity to respond to an emergency anywhere in the world in less than 72 h and to set up a field hospital, a mobile medical unit that can be set up near any disaster site to provide temporary treatment to the wounded on the spot.

The Spanish offer to send the START team was accepted by the Turkish authorities on the morning of 7 February. The team arrived in Adana (Turkey) in the early hours of 10 February (see AECID, 2023). START brought its field hospital, which is open 24 h a day and has a surgical and inpatient capacity of up to 24 people; it can treat an average of 200 people a day and perform up to seven major operations or 15 minor operations a day. The hospital has a triage area, general emergency services, surgery, obstetrics, paediatrics, trauma, physiotherapy and psychology. It also has resuscitation equipment, basic general anaesthesia, radiology and its own laboratory, pharmacy and equipment sterilisation systems.

The Spanish field hospital set up by the START team was fully operational within 48 h and treated a total of 7,387 people during its 33 days of operation. To achieve this, the Spanish emergency medical team was organised in three shifts of medical personnel, logisticians and humanitarian experts from Spain, for a total of 195 professionals throughout the mission, which had to be planned to meet the expected needs and to manage the mission in a cost-and-human efficient way. The health workers are part of a roster and AECID has to respond to the emergency with the necessary profiles and coordinate the deployment of the personnel, which is organised in shifts. This operation, and the logistical complexity of staff planning and scheduling, was the motivation for developing the research included in this paper.

There is an extensive literature on staff scheduling problems (see Ernst *et al.*, 2004; Van den Bergh *et al.*, 2013 for good reviews on the subject) and more specifically on healthcare scheduling and nurse rostering problems (see Burke *et al.*, 2004; Causmaecker and Vanden Berghe, 2010, and Youn *et al.*, 2022, among others), most of them solved by integer programming (Mischek and Musliu, 2017), sometimes combined with the use of metaheuristics, as in Wickert *et al.* (2019). The humanitarian medical supply chain problem has also been addressed, see Dolinskaya *et al.* (2018), and there are several works on medical staff planning in humanitarian logistics, although this problem has received less attention in the literature than other humanitarian logistics problems. Niessner *et al.* (2018) present three simulation-optimisation models, including the allocation of staff (physicians, doctors) for the treatment and transport of emergency patients to deal with mass casualty incidents. Shavarani *et al.* (2020) consider the assignment of medical staff to operating rooms in disaster preparedness. Ahadian *et al.* (2023) present a model that aims to reallocate medical staff to prevent a shortage of hospital beds. Oksuz and Satoglu(2023) propose an integrated optimisation model for facility location, casualty allocation and medical staff planning for post-disaster emergency response.

However, in the case of international aid in response to a natural disaster, such as the deployment of a field hospital, the planning problem mainly concerns the relocation of local staff to the affected region and the management of flights, and the fact that the organisation relies on volunteers to staff the hospital. The management of volunteers has been addressed in several works, see Falasca and Zobel(2012), Paret *et al.* (2021), Matinrad and Granberg (2023), among others. Regarding field hospitals, the experience of deploying a field hospital in early disaster response can be found in Kreiss *et al.* (2010), regarding the humanitarian response to the 2010 Haiti earthquake, while Rezvykh *et al.* (2022) investigates the optimal number and complement of teams required in earthquake conditions, using simulation to size the required workflow. To the best of our knowledge, the problem of dispatching volunteers to a field hospital in an emergency has not been addressed in the literature.

The aim of this work is to help a cooperation agency manage and plan the deployment of a field hospital. In particular, it deals with the management of the staff (in the case of AECID, made up of volunteers from the Spanish Public Health Service), both doctors and nurses. Due to the complexity of the management, this paper presents a mathematical optimisation model to support the decision-making process described above. The model generalises the current AECID procedures by introducing more flexibility in the management of the roster and can be used in any emergency. It is tested with data from the case study of the last deployment of the START hospital in Turkey.

The main contributions of this paper are:

- A novel mathematical optimisation model is introduced.
- Several criteria concerning the main actors involved in the response, the cooperation agency, the medical staff and the end users, are introduced and new measures are developed.
- The model is validated with data from the real operation.

The rest of the paper is structured as follows: First, the main characteristics of the field hospital deployed by AECID are described in Section 2. Then, the generalised problem to be modelled is described in Section 3; Section 4 presents the mathematical optimisation model in detail; Section 5 introduces the case study and Section 6 is dedicated to the computational experiment; finally, Section 7 concludes and outlines the main lines of future research.

2. The START hospital

The HAO launched the START field hospital in 2016 and, after four years of preparation, was accredited by the WHO as an Emergency Medical Team (EMT). EMTs are health teams that support local medical teams in the country in the event of a disaster. EMTs can be classified according to the type of services they can provide, such as:

- Type 1: These are emergency teams capable of providing a primary care service for 12 hours every day of the week.
- Type 2: These are teams that, in addition to providing the services of Type 1, have the capacity to perform general and emergency obstetric surgery. They are available 24 hours a day, 7 days a week.
- Type 3: It has all the characteristics of Type 2 plus the capacity to provide surgery, complex orthopaedic and reconstructive care and intensive care.
- Specialised teams: These are specialised teams and are complementary to EMT 2 and 3, some of the specialised services they provide can be: epidemics, complex rehabilitation or psychosocial care.

The START hospital is classified as an EMT 2. Since its launching, it has been deployed in Dondo, Mozambique (2018), Bata, Guinea Ecuatorial and Haiti (2021) (this year in a reduced version, mainly composed of some experts) and Iskenderum, Turkey (2023) . It should be noted that during the

COVID pandemic, no calls could be responded to because all healthcare personnel were needed in their home hospitals.

In terms of hospital staff, AECID has recruited five people: a team coordinator, a health expert, a logistician, a water and sanitation expert and an administrator. In addition, there is a roster of 500 health professionals from the Spanish National Health System (SNHS). When a call is made with the profiles needed to respond to a request for assistance, the people on the roster have 24 h to respond and the teams are formed according to the personnel available. Depending on the type of emergency and how long the hospital will be on site, there are a number of teams that rotate every fixed period of time.

AECID has a roster of about 500 medical and nursing staff from the SNHS who have applied for registration by filling in a form. AECID regularly announces the registration process, which takes one month, together with a list of the required profiles. Once a profile is filled, no further applications will be considered. New calls for applications will continue to be published for profiles that require staff. A minimum of 3 years' experience is required, as well as language skills (French and English) for some positions. Each application is assessed on its own merits and scored out of 10. Candidates are ranked and selected on the basis of their scores. The maximum time a person can spend on a mission is estimated to be 15 days, unless there are special circumstances.

When a request for a hospital mission is received, depending on the type of emergency and the local response capacity, certain health profiles are required and the number of people needed to cover each health profile is determined. AECID calls up the roster with the required profiles and within 24 h each member of the roster indicates their availability (YES/NO). Only major difficulties, such as illness, allow a no reply.

AECID then has to plan the medical staff for the estimated duration of the mission and contract the necessary flights to transport both personnel and material to the emergency hospital in 15-day shifts, trying to meet the request in the best possible way while minimising the cost of the operation.

This structure could be made more flexible by considering other criteria for managing the roster, taking into account the needs of the cooperation agency, the staff and the end users, as suggested in the next section. The current management of AECID can be considered as a particular case.

3. Problem description

In the event of an international emergency call for the deployment of the field hospital, and given a roster of medical and nursing staff in which each person has been assigned a grade according to their experience, training and other characteristics included in the call, the agency will call up the roster with the required profiles. Note that each person is allowed to register for several skills if he/she has the appropriate training. Within 24 h, each member of the roster indicates his or her availability for each half-week period of the planned horizon. The answer per period can be 2 (fully available in the period), 1 (available only if needed) or 0 (not available). In addition, each person can be deployed in the emergency mission for 7–15 days (2–4 consecutive periods).

These assumptions give more flexibility to the medical staff, who may register but be unavailable during some periods of the time of the rota.

Flights must be reserved for staff and equipment. Equipment will be picked up in the first period and returned in the last. For medical staff, either charter flights can be hired or regular seats on scheduled airlines can be purchased. It should be assumed that airlines often offer discounts for group travel if the group consists of a minimum number of people.

The planning aims to manage three important aspects: the selection of appropriate health personnel to meet the needs of the emergency (both in terms of availability and grades obtained), and the appropriate financial management to cover the travel of health personnel.

In summary, the main assumptions of this problem are as follows:

- The required duration of emergency assistance is predetermined.
- Individuals are expected to commit at the initial planning stage in half-weekly increments.
- It is possible to book charter flights. There must be a charter flight in the first and last periods.
- Group discounts for regular flight arrangements are allowed.
- Different capabilities to fulfil multiple roles as part of an emergency response are permitted.
- Costs of individual tickets and charter flights are known.
- Each person can be assigned to only one round trip.
- The availability (0, 1 or 2) and grades (0–10) of each person are known.
- A person can participate in the mission between 2 and 4 periods.

Note that these assumptions consider the current management as a particular case. Nevertheless, this model gives more flexibility to the conditions to meet the preferences of the cooperation agency, the medical staff and the end users.

4. Mathematical optimisation model

In the following, the mathematical optimisation model for shift scheduling is presented in detail, taking into account the assumptions described above. To make the mathematical notation easier to read, calligraphic capital letters have been used for sets of indices, Latin capital letters for parameters, lowercase Greek letters for binary variables, Greek capital letters for auxiliary variables (products of binary and continuous variables to be linearised) and lowercase Latin letters for integer variables. In addition, the super-indices o, r, s and d denote outward, return, standard and discounted flights, respectively.

4.1 Sets of indices

$\mathcal{J} = \{1, \ldots, J\}$, set of health profiles required to manage the emergency, where J is the number of profiles.

$\mathcal{I} = \{1, \ldots, I\}$, set of people on the roster, where I is the number of volunteers. Note: Only people on the roster who are available during a given period of the mission should be considered.

$\mathcal{T} = \{1, \ldots, T\}$, set of periods to attend the emergency, where T is the number of periods considered.

$\mathcal{L} = \{1, \ldots, L\}$ set of types of charter flights, where L is the number of types considered.

4.2 Parameters

H_{jt}, number of health professionals of profile j needed during the emergency in period t, for $j \in \mathcal{J}, t \in \mathcal{T}$.

C_{tl}, cost of a charter flight of type l in period t, for $t \in \mathcal{T}, l \in \mathcal{L}$.

F_t^o, F_t^r, cost of outward and return flights in period t, respectively, for $t \in \mathcal{T}$.

K, number of passengers required to qualify for a discount.

D_t^o, D_t^r, cost of the outward and return flights, respectively, when a discount is applied because there is a group of K or more people travelling in period t, for $t \in \mathcal{T}$.

A_{it}, availability of person i in period t. It is equal to 2 if he/she is fully available, 1 if he/she has some difficulties but can attend the emergency, and 0 otherwise, for $i \in \mathcal{I}, t \in \mathcal{T}$.

G_i, grade of person i. It is between 0 and 10, for $i \in \mathcal{I}$.

$P_{ij} = 1$,if person i on the roster can cover profile j, 0 otherwise, for $i \in \mathcal{I}, j \in \mathcal{J}$

$\underline{B}, \overline{B}$, minimum and maximum periods a person can be involved in the emergency if he/she is present, respectively.

$\underline{E}_l, \overline{E}_l$, minimum and maximum number of people flying on a charter flight of type l, for $l \in \mathcal{L}$, respectively.

4.3 Decision variables

$\alpha_{it}^o, \alpha_{it}^r = 1$if person i of the roster takes an outward (resp. return) flight in period t, 0 otherwise, for $i \in \mathcal{I}, t \in \mathcal{T}$

$\beta_{ijt} = 1$if person i of the roster attends the emergency with profile j in time period t, 0 otherwise, for $i \in \mathcal{I}, j \in \mathcal{J}, t \in \mathcal{T}$

$\gamma_{tl} = 1$if a flight of type l is chartered in period t, 0 otherwise, for $t \in \mathcal{T}, l \in \mathcal{L}$.

$\delta_t^o, \delta_t^r = 1$if the number of people travelling in period t on an outward (resp. return) flight is less than the number of people for which the discount D applies, 0 otherwise, for $t \in \mathcal{T}$.

$\mu_{ij} = 1$if person i in the roster is working with healthcare profile j, 0 otherwise, for $i \in \mathcal{I}, j \in \mathcal{J}$.

x_t^s, x_t^d, number of people on the roster taking an outward flight with the standard (resp. discounted) fare in period t, for $t \in \mathcal{T}$.

y_t^s, y_t^d, number of people on the roster taking a return flight with the standard (resp. discounted) fare in period t, for $t \in \mathcal{T}$

z_t^o, z_t^r, number of people on the roster taking a chartered flight, outward or return, respectively, in period t, for $t \in \mathcal{T}$

u_{jt}^-, u_{jt}^+, number of people who are above or below the required number of people of profile j in time t, for $j \in \mathcal{J}, t \in \mathcal{T}$

Φ_{it}^o, Φ_{it}^r, auxiliary variable to model the average availability of each person attending the emergency for person i and period t, for $i \in \mathcal{I}, t \in \mathcal{T}$

Γ_{it}, auxiliary variable to model the average availability of people attending the emergency for person i and period t, for $i \in \mathcal{I}, t \in \mathcal{T}$

Λ_{it}, auxiliary variable to model the average grade of people attending the emergency for person i and period t, for $i \in \mathcal{I}, t \in \mathcal{I}$

4.4 Objective functions

The model takes into account three attributes corresponding to each of the three actors involved in the emergency: the cooperation agency, the volunteers and the end users, measured in terms of cost, average availability and grades of the volunteers, respectively, as defined below:

Cost, travel costs to be borne by the cooperation agency. The cooperation agency *wants* to minimise these costs.

$\overline{Avail}$, average availability of volunteers participating in the emergency. Volunteers want to maximise their availability (calculated individually for each person with $\overline{av}_i$).

$\overline{Grade}$, average qualification of the volunteers attending the emergency. The end users aim to maximise this measure.

The first attribute considers the total cost of the trips and should be minimised. The first sum takes into account the cost of charter flights and the rest of the cost of air travel, which includes all trips with and without discounts:

$$\min Cost = \sum_{t \in \mathcal{T}} \sum_{l \in \mathcal{L}} (C_{tl}\gamma_{tl}) + \sum_{t \in \mathcal{T}} \left(F_t^o x_t^s + D_t^o x_t^d + F_t^r y_t^s + D_t^r y_t^d \right) \tag{1}$$

The second attribute takes into account the average availability of the people who will eventually participate in the emergency. This attribute should be maximised:

$$\max \overline{Avail} = \frac{\sum_{i \in \mathcal{I}} \overline{av}_i}{\sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} \alpha_{it}^o} \tag{2}$$

where:

$$\overline{av}_i = \frac{\sum_{j \in \mathcal{J}} \sum_{t \in \mathcal{T}} A_{it}\beta_{ijt}}{\sum_{t \in \mathcal{T}} t\alpha_{it}^r - \sum_{t \in \mathcal{T}} t\alpha_{it}^o - 1} \qquad \forall i \in \mathcal{I}$$

Finally, the third attribute considers the average grade of the people attending the emergency. This attribute should be maximised by taking into account the preferences of the end users:

$$\max \overline{Grade} = \frac{\sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} G_i \alpha_{it}^o}{\sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} \alpha_{it}^o} \tag{3}$$

Note that we can measure the number of people attending the emergency with the expression $\sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} \alpha_{it}^o$ thanks to the constraints defined below.

Finally, to know whether the problem is infeasible or not, the following objective function must be considered:

$$\min \sum_{j \in \mathcal{J}} \sum_{t \in \mathcal{T}} u_{jt}^+ \tag{4}$$

where the variable u_{jt}^+ counts the number of people needed if there is no availability.

4.5 Constraints

All vacancies in each health profile must be filled:

$$\sum_{i \in \mathcal{I}} P_{ij}\beta_{ijt} \geq H_{jt} \qquad \forall j \in \mathcal{J}, t \in \mathcal{T} \backslash \{T\} \tag{5}$$

All vacancies in each health profile must be filled. If this is not the case, u_{jt}^+ is positive and indicates the additional number of people needed to cover that profile. Conversely, if u_{jt}^- is strictly positive, the number of people in that profile in period t is higher than required.

$$\sum_{i\in\mathcal{I}} P_{ij}\beta_{ijt} - u^-_{jt} + u^+_{jt} = H_{jt} \quad \forall j\in\mathcal{J}, t\in\mathcal{T}\backslash\{T\} \tag{6}$$

A person can be selected to attend the emergency in period t with the health role j if he/she is available at that time and can also play that role. This constraint is included as an upper bound on the variable β:

$$\beta_{ijt} \le \min\{A_{it}, P_{ij}\} \quad \forall i\in\mathcal{I}, j\in\mathcal{J}, t\in\mathcal{T} \tag{7}$$

Each person can only fly once (outbound and return). Note that a person is selected if $\sum_{t\in\mathcal{T}}\alpha^o_{it} = 1$, otherwise the sum is 0:

$$\sum_{t\in\mathcal{T}} \alpha^o_{it} \le 1 \quad \forall i\in\mathcal{I} \tag{8}$$

$$\sum_{t\in\mathcal{T}} \alpha^r_{it} \le 1 \quad \forall i\in\mathcal{I} \tag{9}$$

A person can only attend the emergency between the limits for the minimum and maximum number of periods if he/she is selected to travel:

$$\underline{B}\sum_{t\in\mathcal{T}}\alpha^o_{it} \le \sum_{t\in\mathcal{T}} t\alpha^r_{it} - \sum_{t\in\mathcal{T}} t\alpha^o_{it} \le \overline{B}\sum_{t\in\mathcal{T}}\alpha^o_{it} \quad \forall i\in\mathcal{I} \tag{10}$$

Each person can attend the emergency for a maximum of $\overline{B}$ periods, that is, the sum of the variables β in all times and profiles is bounded by $\overline{B}$. This constraint should not be necessary if the previous one is in the model, but it helps to strengthen the mathematical optimisation model:

$$\sum_{j\in\mathcal{J}}\sum_{t\in\mathcal{T}} \beta_{ijt} \le \overline{B} \quad \forall i\in\mathcal{I} \tag{11}$$

The periods in which a person flies, whether it is an outward or return flight, are obtained using the following constraints, which are crucial for the model:

$$\sum_{j\in\mathcal{J}}\beta_{ijt} - \sum_{j\in\mathcal{J}}\beta_{ijt-1} = \alpha^o_{it} - \alpha^r_{it} \quad \forall i\in\mathcal{I}, t\in\mathcal{T}\backslash\{1\} \tag{12}$$

Each person can only work on one health profile per period:

$$\sum_{j\in\mathcal{J}}\beta_{ijt} \le 1 \quad \forall i\in\mathcal{I}, t\in\mathcal{T} \tag{13}$$

The number of flights (outward and return) is counted. On the right-hand side of the equation, the total number of flights is broken down into standard and discounted fares, and also takes into account the number of people travelling on a charter flight:

$$\sum_{i\in\mathcal{I}}\alpha^o_{it} = x^s_t + x^d_t + z^o_t \quad \forall t\in\mathcal{T} \tag{14}$$

$$\sum_{i\in\mathcal{I}}\alpha^r_{it} = y^s_t + y^d_t + z^r_t \quad \forall t\in\mathcal{T} \tag{15}$$

Depending on the number of people travelling, only the standard fare or the discounted fare may apply (the discount only applies if the number of flights is at least K). The same applies to outward [(16)–(17)] and return [(18)–(19)] flights:

$$0 \le x^s_t \le (K-1)\delta^o_t \quad \forall t\in\mathcal{T} \tag{16}$$

$$K(1-\delta^o_t) \le x^d_t \le I(1-\delta^o_t) \quad \forall t\in\mathcal{T} \tag{17}$$

$$0 \le y^s_t \le (K-1)\delta^r_t \quad \forall t\in\mathcal{T} \tag{18}$$

$$K(1-\delta^r_t) \le y^d_t \le I(1-\delta^r_t) \quad \forall t\in\mathcal{T} \tag{19}$$

A maximum of one charter flight will be hired per period:

$$\sum_{l\in\mathcal{L}}\gamma_{tl} \le 1 \quad \forall t\in\mathcal{T} \tag{20}$$

The number of people travelling on a chartered flight is limited for outward and return flights. Note that if there is no chartered flight, the number of people travelling on a chartered flight in that period is zero, as the γ_{tl} variables are zero. Note also that if charter flights can make the outward and return flights on the same day, the same time t can be considered for both flights:

$$\sum_{l\in\mathcal{L}}\underline{E}_l\gamma_{tl} \le z^o_t \le \sum_{l\in\mathcal{L}}\overline{E}_l\gamma_{tl} \quad \forall t\in\mathcal{T} \tag{21}$$

$$\sum_{l\in\mathcal{L}}\underline{E}_l\gamma_{tl} \le z^r_t \le \sum_{l\in\mathcal{L}}\overline{E}_l\gamma_{tl} \quad \forall t\in\mathcal{T} \tag{22}$$

In the first and last periods, a charter flight must be hired to transport the START hospital and, if necessary, some medical staff. This constraint is optional:

$$\gamma_{1l} = \gamma_{Tl} = 1 \tag{23}$$

To know the number of health roles a person assumes during the emergency, it is necessary to define the binary variable μ in such a way that it equals one if person i assumes role j at least once in the time horizon in which he/she participates in the emergency. Note that these constraints and the variable μ make it possible, if desired, to minimise the number of roles played by a person:

$$\sum_{t\in\mathcal{T}}\beta_{ijt} \le \overline{B}\mu_{ij} \quad \forall i\in\mathcal{I}, j\in\mathcal{J}$$
$$\sum_{t\in\mathcal{T}}\beta_{ijt} \ge \mu_{ij} \quad \forall i\in\mathcal{I}, j\in\mathcal{J}$$

A person i plays the health role j only if he/she has the qualifications to do so. This constraint is included as an upper bound for the variable μ:

$$\mu_{ij} \le P_{ij} \quad \forall i\in\mathcal{I}, j\in\mathcal{J} \tag{24}$$

Note that the attribute $\overline{av}_i$ needed for expression (2) is non-linear. To linearise its expression, it is necessary to note that:

$$\overline{av}_i = \frac{\sum_{j\in\mathcal{J}}\sum_{t\in\mathcal{T}} A_{it}\beta_{ijt}}{\sum_{t\in\mathcal{T}} t\alpha^r_{it} - \sum_{t\in\mathcal{T}} t\alpha^o_{it} - 1} \quad \forall i \in \mathcal{I}$$

is equivalent to:

$$\sum_{t\in\mathcal{T}} t\alpha^r_{it}\overline{av}_i - \sum_{t\in\mathcal{T}} t\alpha^o_{it}\overline{av}_i - \overline{av}_i = \sum_{j\in\mathcal{J}}\sum_{t\in\mathcal{T}} A_{it}\beta_{ijt} \quad \forall i \in \mathcal{I}$$

The quadratic terms $\alpha^o_{it}\overline{av}_i$ and $\alpha^r_{it}\overline{av}_i$ are linerised using the Fortet inequalities introduced in Fortet(1960). To do this, it is necessary to use the continuous variables $\Phi^o_{it} := \overline{av}_i\alpha^o_{it}$ and $\Phi^r_{it} := \overline{av}_i\alpha^r_{it}$ and the following linear constraints that meet these definitions:

$$\Phi^o_{it} \leq 2\alpha^o_{it} \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (25)$$

$$\Phi^o_{it} \leq \overline{av}_i \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (26)$$

$$\overline{av}_i - \Phi^o_{it} \leq 2\left(1 - \alpha^o_{it}\right) \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (27)$$

and, equivalently,

$$\Phi^r_{it} \leq 2\alpha^r_{it} \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (28)$$

$$\Phi^r_{it} \leq \overline{av}_i \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (29)$$

$$\overline{av}_i - \Phi^r_{it} \leq 2\left(1 - \alpha^o_{it}\right) \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (30)$$

The non-linear expression is then linearised as:

$$\sum_{t\in\mathcal{T}} t\Phi^r_{it} - \sum_{t\in\mathcal{T}} t\Phi^o_{it} - \overline{av}_i = \sum_{j\in\mathcal{J}}\sum_{t\in\mathcal{T}} A_{it}\beta_{ijt} \quad \forall i \in \mathcal{I} \quad (31)$$

obtaining the average availability of each person $i \in \mathcal{I}$.

The attributes $\overline{Avail}$ and $\overline{Grade}$ are expressed with a non-linear expression and must be linearised in an analogous process as before, where $\Gamma_{it} := \overline{Avail}\alpha^o_{it}$ and $\Lambda_{it} := \overline{Grade}\alpha^o_{it}$. Then, the following constraints have to be included:

$$\Gamma_{it} \leq 2\alpha^o_{it} \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (32)$$

$$\Gamma_{it} \leq \overline{Avail} \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (33)$$

$$\overline{Avail} - \Gamma_{it} \leq 2\left(1 - \alpha^o_{it}\right) \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (34)$$

$$\sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}} \Gamma_{it} = \sum_{i\in\mathcal{I}} \overline{av}_i \quad (35)$$

and:

$$\Lambda_{it} \leq 10\alpha^o_{it} \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (36)$$

$$\Lambda_{it} \leq \overline{Grade} \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (37)$$

$$\overline{Grade} - \Lambda_{it} \leq 10\left(1 - \alpha^o_{it}\right) \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (38)$$

$$\sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}} \Lambda_{it} = \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}} G_i\alpha^o_{it} \quad (39)$$

Finally, the domain of the variables:

$$\beta_{ijt} \in \{0,1\} \quad \forall i \in \mathcal{I}, j \in \mathcal{J}, t \in \mathcal{T} \quad (40)$$

$$\mu_{ij} \in \{0,1\} \quad \forall i \in \mathcal{I}, j \in \mathcal{J} \quad (41)$$

$$\alpha^o_{it}, \alpha^r_{it} \in \{0,1\} \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (42)$$

$$\gamma_{tl} \in \{0,1\} \quad \forall t \in \mathcal{T}, l \in \mathcal{L} \quad (43)$$

$$\delta^o_t, \delta^r_t \in \{0,1\} \quad \forall t \in \mathcal{T} \quad (44)$$

$$x^s_t, x^d_t, y^s_t, y^d_t, z^o_t, z^r_t \geq 0 \quad \forall t \in \mathcal{T} \quad (45)$$

$$\Phi^o_{it}, \Phi^r_{it}, \Lambda_{it}, \Gamma_{it} \geq 0 \quad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (46)$$

$$u^+_{jt}, u^-_{jt} \geq 0 \quad \forall j \in \mathcal{J}, t \in \mathcal{T} \quad (47)$$

$$Cost, \overline{Avail}, \overline{Grade} \geq 0 \quad (48)$$

Note that variables x^s_t, x^d_t, y^s_t, y^d_t, z^o_t and z^r_t can be relaxed as positive variables although their nature is integer, due to the relationship of these variables with sums of binary variables in equations (14)–(19) and (21)–(22).

4.6 Multi-criteria approaches

For any multi-criteria approach, it is necessary to study the payoff matrix. The diagonal of the matrix will contain the ideal values, which are the best values that an attribute can achieve without considering the other attributes, while the rest of the elements will be the values of the other attributes in the solution achieved. The ideal and non-ideal values are defined as follows:

$Cost^*, \overline{Avail}^*, \overline{Grade}^*$, ideal values for the defined attributes.

$Cost^{**}, \overline{Avail}^{**}, \overline{Grade}^{**}$, non-ideal values for the defined attributes.

A simple way of dealing with multiple objective functions is to combine them into a single-objective (SO) function as a weighted sum, where each objective function is normalised by the range between the ideal and non-ideal values (see Zadeh, 1963). The single-objective becomes:

$$\min w_c \frac{cost}{Cost^{**} - Cost^*} - w_a \frac{\overline{Avail}}{\overline{Avail}^* - \overline{Avail}^{**}} - w_g \frac{\overline{Grade}}{\overline{Grade}^* - \overline{Grade}^{**}} \quad (49)$$

where the values w_c, w_a and w_g are the weights for each sum if it is desired to give some sums more weight than others. Note that the last two sums have negative signs and opposite denominators as these attributes are to be maximised. A possible approach to tackle the problem is through weighted sum scalarisation, to obtain the Pareto frontier. This process is very time-consuming and in our case reference point methods will be preferred as they offer a specific solution for each particular parameter setting.

The two multi-criteria reference-point methods used in this study are Goal Programming, first introduced in Charnes *et al.* (1955) (see Ignizio, 1985 and Romero, 1991 for good surveys) and Compromise Programming, introduced in Cochrane and Zeleny(1973).

For the Goal Programming approach, the following objective function is considered:

$$\min w_c \frac{Dev_c^-}{Cost^{**} - Cost^*} - w_a \frac{Dev_a^+}{\overline{Avail}^* - \overline{Avail}^{**}} - w_g \frac{Dev_g^+}{\overline{Grade}^* - \overline{Grade}^{**}} \quad (50)$$

together with the following constraints that define the goals for each attribute:

$$Cost \leq Cost^g \equiv Cost + Dev_c^+ - Dev_c^- = Cost^g \quad (51)$$

$$\overline{Avail} \geq \overline{Avail}^g \equiv \overline{Avail} + Dev_a^+ - Dev_a^- = \overline{Avail}^g \quad (52)$$

$$\overline{Grade} \geq \overline{Grade}^g \equiv \overline{Grade} + Dev_g^+ - Dev_g^- = \overline{Grade}^g \quad (53)$$

$$Dev_c^+, Dev_c^-, Dev_a^+, Dev_a^-, Dev_g^+, Dev_g^- \geq 0 \quad (54)$$

where $Cost^g$, $\overline{Avail}^g$ and $\overline{Grade}^g$ are the goals for each attribute and Dev_c^+, Dev_c^-, Dev_a^+, Dev_a^-, Dev_g^+ and Dev_g^- are the positive and negative deviations from each goal. Note that the negative deviation in cost and the positive deviations in availability and grade are minimised as they are not desirable.

For the Compromise Programming approach, the objective function to be considered also depends on the ideal and non-ideal values, as follows:

$$\min w_c \frac{cost - Cost^*}{Cost^{**} - Cost^*} - w_a \frac{\overline{Avail}^* - \overline{Avail}}{\overline{Avail}^* - \overline{Avail}^{**}} - w_g \frac{\overline{Grade}^* - \overline{Grade}}{\overline{Grade}^* - \overline{Grade}^{**}} \quad (55)$$

Note that while Goal Programming penalises deviations from the goals, Compromise Programming minimises the deviation from the ideal point. In each objective function, the attributes are normalised over the range of variation between the ideal and non-ideal values.

It is worth pointing out that Compromise Programming obtains optimal Pareto solutions, whereas Goal Programming could achieve solutions that are not on the Pareto front.

5. Case study

On 6 February 2023, two earthquakes occurred mainly in southern Turkey and northern Syria. The first occurred at 4:17 local time, 34 km west of the Turkish city of Gaziantep (see Figure 1), 37.226 °N 37.014°E, with a magnitude of 7.8 Mw, a duration of 65 s and a depth of 10.0 km (more details in Map services and data available from USGS, U.S. Geological Survey, 2023b). The second earthquake occurred 9 h later, at 13:24 local time, with a magnitude of 7.5 Mw, southeast of the town of Ekinözü, with a duration of 45 s and a depth of 7.4 km (more details in Map services and data available from USGS, U.S. Geological Survey, 2023a). The earthquakes were felt in neighbouring countries, including Syria, Lebanon, Iraq and Cyprus.

These earthquakes had about 1,000 aftershocks and caused more than 59,000 deaths (about 51,000 in Turkey and 8,000 in Syria) and more than 121,000 injuries (107,000 in Turkey and 14,000 in Syria). The winter season and low temperatures contributed to these high figures.

The President of Turkey, Recep Tayyip Erdoğan, declared a three-month state of emergency and the Turkish government raised the alert level to 4, requesting international assistance and receiving support from around 70 countries, including Spain. In particular, AECID activated its humanitarian protocol to deal with this emergency, including the deployment of the Spanish START. More than 80 people were present at the hospital, including health professionals, logisticians and staff from AECID's Humanitarian Action Office.

The START team arrived in the city of Adana (Turkey) on Friday 10 February. The day before, a chartered cargo plane had arrived from Madrid with the START field hospital and all the equipment needed to set it up. After coordination with the Turkish health authorities and the World Health Organisation's Emergency Medical Team Coordination Team, the hospital was located in the city of Iskendurun, mainly to treat victims from the Arsuz district. The medical mission started on Monday 13 February. Turkish volunteers took part in the mission, providing language interpretation and logistical support.

After 14 days in Turkey, 77 of the 82 members of the Spanish emergency medical team had to return to Spain. The team cared for more than 2,500 people, working long shifts. The team consisted of 64 professionals, including medical staff, logisticians, cooks and psychosocial workers.

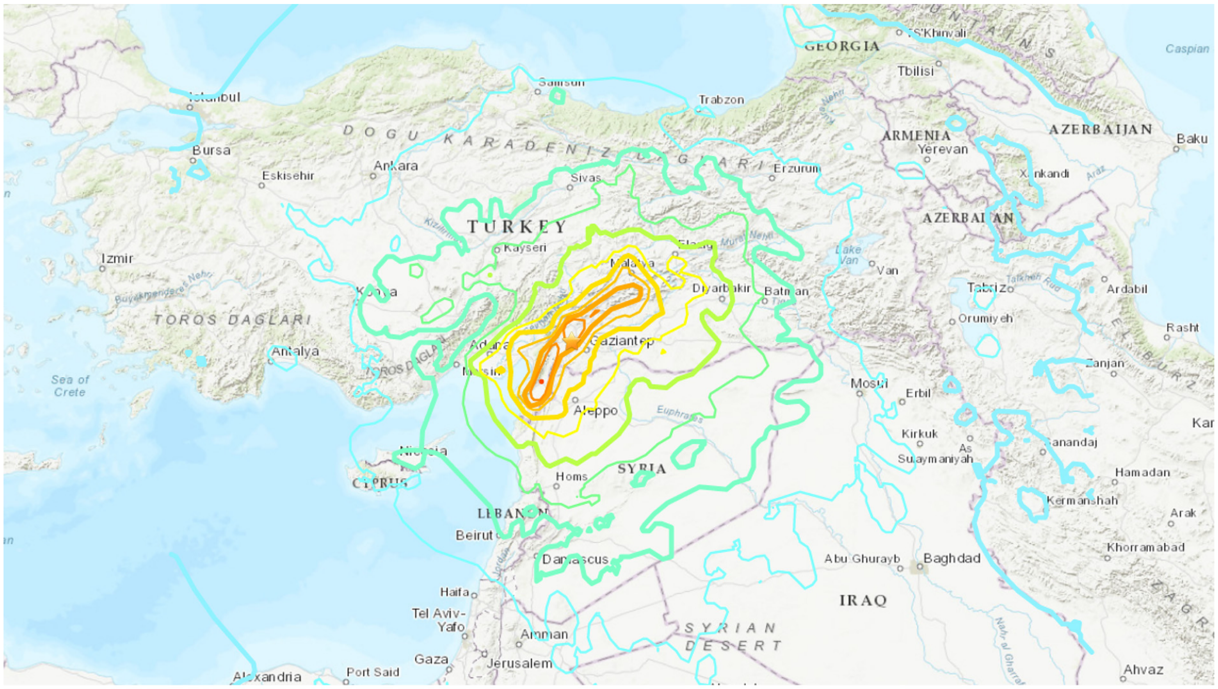
The third and final shift took place on 8 March, with a total of 58 people involved in the emergency response. The third shift provided a service without an operating theatre and with reduced hospital capacity, thanks to the progress made by the Turkish government in restoring health services to the population. Table 1 lists the personnel who made up the three START shifts in Turkey.

The START was active for 33 days (from 13 February to 17 March) and treated a total of 7,387 patients, 224 patients per day, with up to 195 people working in three shifts. Emergency care, adult and paediatric consultations, gynaecology, traumatology, physiotherapy, surgery, admissions, radiology, laboratory and psychosocial support services were provided.

6. Computational experiment

In this section we present the data used and the results of the computational experiments carried out to validate the model presented above. The data are available in Martín-Campo *et al.* (2024b) and the Python code implemented in Martín-Campo *et al.* (2024a).

Figure 1 Earthquakes in Turkey



(a)

(b)

Notes: (a) First earthquake. Gaziantep; (b) Second earthquake. Ekinözü. Map services and data available from USGS, U.S. Geological Survey, 2023a
Source: Map services and data available from USGS, U.S. Geological Survey, 2023b

Table 1 Staff in the different shifts

	1st Shift	2nd Shift	3rd Shift
Departure date	10 Feb	23 Feb	9 Mar
Total staff	82	64	58
Health staff	56	51	36
Logisticians	16	10	13
Psychosocial care	12	2	2
Pharmacists	1	–	1
Cooks	3	3	3

Source: Authors' own creation

The model was implemented in Python using Gurobipy and solved using Gurobi v.11.0.1 (Gurobi Optimization, LLC, 2024) with default settings except for the maximum runtime, which is set to 7,200 s. The experiments were run on a 12th generation Intel(R) Core(TM) i7-1280P CPU 2.00 GHz with 14 physical cores, 20 logical processors, 16GB RAM and Windows 11 OS.

6.1 Data description

The case study takes into account the general information reported in Table 2. The unknown information has been randomly generated as indicated below.

The round-trip prices were generated according to a uniform probability distribution between 100 and 1000 (taking the extremes of the interval from real prices for flights to Turkey). For charter flights, our simulation includes two types of aircraft. The prices of these aircraft are fixed for all periods and are based on the real costs associated with this type of air service. The prices were assumed to be 75000€and 180000€for types 1 and 2 respectively, and different numbers of passengers capacity. The criterion used by AECID to generate the number of people in the roster for each health profile was followed, i.e. a ratio of 10 people per position. The total number of health professionals is therefore 510. The health profiles and associated requirements are based on the number of people required to be accredited as an EMT2 hospital. Table 3 reports a detailed breakdown of these requirements, indicating the number of professionals needed for each profile during each period of the emergency response and the abbreviation of the profile used later.

In the process of determining staff availability for all periods, each person is first assigned to a general profile and then the value of each period is defined. The first step is to classify individuals into one of three different levels of availability: 0 means very limited availability, 1 means standard availability and 2 means high availability. This information is used to simulate availabilities for each person in the roster, giving greater probability to the values 0 or 2 depending on the label previously assigned.

Another randomly generated data set is the set of compatible profiles for each person in the roster. The probability distribution used is the Bernoulli distribution, where only similar roles have been determined to be compatible.

Finally, the grades of the people on the roster were randomly generated between 5 (the minimum grade to be on the list) and 10 (the maximum grade). Note that different intervals with different probabilities were considered (intervals 5–7, 7–9, 9–10 with probabilities of 0.4, 0.5 and 0.1, respectively). The average grade of the simulation is 7.39.

Note that in a real-life situation all these values will be available in advance, as volunteers will introduce them either when entering for the roster, either when requested for the mission. The data regarding cost of flights in a specific moment of time has to be collected by the Agency, even if no optimisation model is used.

Table 2 General parameters in the case study

Number of periods (T)	10
Number of profiles (J)	23
People in the roster (I)	510
Types of charter flights (L)	2
% discount for group travel	20
Number of people to obtain a discount (K)	10
Maximum number of periods in emergency ($\overline{B}$)	4
Minimum number of periods in emergency ($\underline{B}$)	2

Source: Authors' own creation

6.2 Computational results

The computational results include the multi-criteria study to take into account the three attributes defined above: cost, staff availability and staff grades. Prior to this study, it is necessary to study the feasibility of the problem by optimising the model with the objective function (4). If the value of the objective function is 0 then there is no infeasibility and the rest of the optimisation can be carried out. Otherwise, it is necessary to fix in the model the number of people to be sent according to the optimal solution of the previous problem and continue with the optimisation.

6.2.1 Payoff matrix

The study of the confrontation between the attributes is essential to deal with a multi-criteria analysis. In this phase, the payoff matrix involves three different optimisation processes where the set of constraints remains fixed and the objective function is modified to take into account the corresponding attribute [cost (1), availability (2) and grade (3)]. The resulting payoff matrix is:

$$\begin{pmatrix} 262417 & 1.82 & 7.48 \\ 537317 & 2.00 & 7.34 \\ 324783 & 1.78 & 8.39 \end{pmatrix} \left| \begin{array}{c} 153 \\ 208 \\ 157 \end{array} \right.$$

Note that the first, second and third columns of the payoff matrix contain information on the cost (in €), the average availability (between 0 and 2) and the average grade obtained (between 5 and 10), respectively. The column at the right of the matrix is extra and contains the number of people attending the emergency, as this is an important indicator of the solution obtained. The diagonal of the payoff matrix reports the ideal values ($Cost^*$, $\overline{Avail}^*$ and $\overline{Grade}^*$) for each attribute, and the remaining elements are the values of the attributes in each of the optimisations performed. The non-ideal value $Cost^{**}$ is defined as the maximum of the remaining cost values, and $\overline{Avail}^{**}$ and $\overline{Grade}^{**}$ are defined as the minimum of the remaining values for each attribute (in these cases the optimisation criterion is maximisation). Note that the confrontation between the cost and the other two attributes is high, as the cost increases significantly as the average availability or grade increases. Remember that the average grade of the staff (data) is 7.39 and the optimisation achieves a schedule with people with an average grade of 8.39. It can be

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Table 3 Healthcare professional profiles and numbers

Profile	Abbreviation	N. people
Medical director of care area	MDCA	1
Director of operations nurse	DONS	1
General surgeon	GS	2
Gynaecologist and obstetrician	GO	2
Orthopaedic and trauma surgeon	OTS	2
Specialist in anaesthesia and resuscitation	SAR	2
Emergency doctor emergency physician	ED	4
Paediatrician	PE	2
Specialist in X-ray diagnosis or radiology	SR	1
Specialist in epidemiology/preventive medicine	SEP	1
Clinical psychology	CPS	1
Psychiatry	PS	1
Hospital pharmacist	HPH	1
Operating room nurses	ORNS	5
Emergency nurses	ENS	8
Hospitalisation nurses	HNS	7
Obstetric and gynaecological nurses	OGNS	2
Physiotherapist	PH	1
Laboratory technician	LT	1
X-ray diagnosis technician	RT	1
Operating room nursing assistants	ORNA	2
Hospitalisation nursing assistants	HNSA	2
Pharmacy technician	PT	1

Source: Authors' own creation

observed that the number of people travelling is similar for the cost optimisation and the average grade optimisation, but the costs are significantly different. This is due to the fact that maximising the average grade means that people with higher grades will travel in different periods, which is more expensive as discounted fares cannot be applied.

Note that each of the ideal values fully satisfies each of the actors in the operation individually (cooperation agency, volunteers and end users). However, it is necessary to agree on a decision that balances the preferences of the three actors, given the conflict between their preferences.

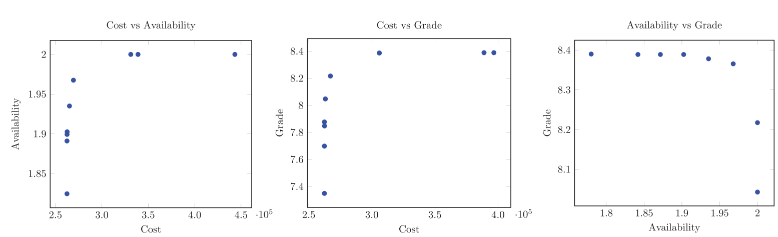
To better illustrate the confrontation between the three objective functions, some points of the bi-dimensional projections of the Pareto front are shown in Figure 2. The Pareto front is the set of non-dominated solutions, i.e. the set of solutions that cannot be improved (in one objective) without worsening any other solution in the set. The points were obtained using the well-known ε-constraint method. For two objectives, this method consists of solving a sequence of optimisation problems (considering one objective) by successively bounding the value of the other objective by a value called ε. The different optimisation problems were solved by setting a time limit and a relative gap of 1%. The latter setting can produce points that are not exactly on the Pareto front, but close to it. Observe in Figure 2 that improving one of the objectives worsens the other, demonstrating the confrontation between them.

The Pareto front can be approximated by connecting the points in Figure 2. However, obtaining the full description of the Pareto front is very time-consuming and may not be necessary to obtain a well balanced solution, as Section 6.2.3 illustrates.

6.2.2 *Differences to actual operation hypotheses*

One of the purposes of the model presented in this work is to provide more flexibility in a field hospital deployment operation by taking into account the availability and turns of the personnel. It is worth pointing out that the model considers the current conditions as a particular case. To illustrate how the model solves the current situation, the model is solved by setting the number of

Figure 2 Approximation to Pareto front projections**Source:** Authors' own creation



periods that a person can attend the operation exactly to 4 periods (2 weeks), i.e. $\underline{B} = \overline{B} = 4$. The resulting payoff matrix is:

$$\begin{pmatrix} 350141 & 1.67 & 7.40 \\ 506771 & 1.83 & 7.40 \\ 507909 & 1.65 & 8.04 \end{pmatrix} \Bigg| \begin{matrix} 150 \\ 152 \\ 151 \end{matrix}$$

The first important observation is that, with the data studied, the problem would be infeasible if staff were restricted to being present for exactly 4 periods, as three extra persons would be needed to cover all health posts [objective function (4) takes a value of 3]. Without considering the cost of these three people, it can be observed that all measures, cost, availability and grade, are worse compared to the payoff matrix obtained above. In particular, the minimum cost operation, availability and grade are 33.43%, 9.29% and 4.35% worse, respectively, than those that take flexibility into account. Furthermore, the ideal values obtained in this case are even worse than those obtained using any of the multi-criteria approaches presented below. Therefore, the inclusion of flexibility in the staffing periods allows for more efficient solutions in each of the measures considered.

6.2.3 Multi-criteria approaches settings

When *SO* is used, a vector of weights (one for each objective) must be specified. To show how the model provides different solutions depending on the vector of weights, several optimisations were performed considering the vectors: (1, 3) which emphasises cost over the other objectives, (1, 3) which emphasises availability, (1, 3) where the average grade is most important and (1), with the same importance for all objectives. Weights $w_c = w_a = w_g = 1$ have been used in the rest of the multi-criteria approaches to ensure a fair comparison. However, these weights should be set by the mission managers depending on their preferences for the different attributes.

Table 4 reports the different solutions obtained. The first observation is that the dispersion of the objective values, when *SO* is used, is quite low compared with the dispersion observed in the payoff matrix. With equal weights the cost has a deviation of 13.065% from its ideal value, while the deviations of the average availability and the grade from their ideal values are 0% and 1.084%, respectively, suggesting that increasing the weight of the cost, w_c, would better balance the final solution in the three objectives. This is confirmed when cost is preferred to availability and grade [weights (1, 3)], as the cost is reduced up to 292760€ (1.35% less than the previous one), the availability remains the same and the average grade is 8.29, just one hundredth below the previous one. In the other two cases, the cost worsens. When grade is preferred, the worst availability is obtained.

In the Goal Programming approach, goals were defined as:

Table 4 Different weight vectors comparison for *SO*

Weights (*C*, *A*, *G*)	Cost	Availability	Grade	N. people
(1)	296701	2	8.30	165
(1, 3)	292760	2	8.29	163
(1, 3)	298186	2	8.31	165
(1, 3)	296843	1.98	8.35	162

Source: Authors' own creation

$$\begin{aligned} Cost^g &= (1 + p_c)Cost^* \\ \overline{Avail}^g &= \overline{Avail}^* - p_a\left(\overline{Avail}^* - \overline{Avail}^{**}\right) \\ \overline{Grade}^g &= \overline{Grade}^* - p_g\left(\overline{Grade}^* - \overline{Grade}^{**}\right) \end{aligned}$$

where p_c is the percentage of cost allowed over the ideal value and p_a and p_g are the percentages of the range of variation of the ideal and non-ideal values of availability and grades, respectively. Note that these percentages should be defined by the decision-maker.

Table 5 reports the relevant data from the solution obtained by using: Weighted Sum Single-Objective Optimisation (SO), Goal Programming (GP1 with $p_c = p_a = p_g = 0.10$, i.e. 10% deviation from the ideal values for availability and grades and GP2 with $p_c = p_a = p_g = 0.05$) and Compromise Programming (CP) approaches. As indicated above, the weights have been set to $w_c = w_a = w_g = 1$ in all cases.

It can be observed that the results are similar for all the approaches, with the number of people involved in the operation varying between 160 and 165 people, costs between 288535 and 296701, average availability between 1.98 and 2.00 and average grades between 8.28 and 8.33. These results show a good balance between the attributes and are in any case preferable to those based on a single criterion.

Regarding the Goal Programming approaches, *GP*1 satisfies all the proposed goals, since all the deviations from the goals are negative. This means that the solution found satisfies all the goals proposed by the three mission actors. However, for *GP*2, the cost goal is not met, while the availability and grades goals are met. In this case, the imposed goals prevent finding a solution that satisfies the three actors. Furthermore, this case suggests to modify the weights of the three attribute deviations if one of them should be given more importance. It is also observed that the cost for *GP*1 is the lowest among the alternatives, but results in the lowest availability and grades. Finally, it should be noted that the number of flights with discounted fares is lower for *GP*2. This is probably due to the fact that obtaining higher values for average availability and grades discourages groups of people from applying for discounted fares.

CP achieves a Pareto optimal solution when optimality is proved. This approach achieves a well-balanced solution through the three objectives. Although the cost deviation is over 10%, the number of people travelling at standard fares instead of discounted fares is very low (only *SO* achieves a solution with the same number of passengers travelling at standard fares).

In conclusion, the solutions presented, although different, offer a good balance between the different objectives and each of them provides the final planning of the personnel. It is up to the decision-maker to choose the most appropriate multi-criteria method according to the characteristics of the mission to be carried out. For example, Figure 3 shows an extract of the planning of the personnel along the periods for the solutions obtained with CP. This planning is obtained as an output of the implemented code and shows, for each person, his/her number, the periods in which he/she attends the emergency and the roles he/she plays.

The detailed aspects of the solution can be found in the files reported in Martín-Campo *et al.* (2024b).

6.3 Optimisation performance

The performance of the mathematical optimisation is reported below. In terms of model dimensions, the number of variables is 20921 continuous, 521 integer and 139270 binary, giving a

Table 5 Results obtained for SO, GP1, GP2 and CP approaches

Attributes	SO	GP1	GP2	CP
N. people in the operation	165	160	162	163
Operation cost	296701	288535	295455	293099
Deviation to goal	–	−123.7	19917.10	–
Deviation to ideal cost (%)	13.065%	9.953%	12.590%	11.692%
Average availability	2.00	1.98	1.99	2.00
Deviation to goal (%)	–	−0.002	−0.050	–
Deviation to ideal $\overline{avail}$ (%)	0.000%	1.010%	0.503%	0.000%
Average grade	8.30	8.28	8.33	8.30
Deviation to goal (%)	–	−0.000	0.090	–
Deviation to ideal $\overline{grade}$ (%)	1.084%	1.311%	0.715%	1.084%
Flights				
Cost of chartered flights 1	150000	150000	150000	150000
Cost of chartered flights 2	0	0	0	0
Total cost of regular flights	146707	138535	145455	143099
N. People outward (std/disc/chart)	(3,142,20)	(3,137,20)	(13,129,20)	(3,140,20)
N. People return (std/disc/chart)	(0,145,20)	(7,133,20)	(9,133,20)	(0,143,20)

Source: Authors' own creation

total number of 160712 variables, while the number of constraints is 98257.

Table 6 reports the optimisation performance for each of the optimisations. The headings are: Infeasibility (I), Cost (C), average Availability (A), average Grade (G), Single-Objective (SO), Goal Programming ($GP1$ and $GP2$), and Compromise Programming (CP). The values $\underline{z}$, $\overline{z}$ and t report the value of the objective function in the best solution found, the best upper bound and the runtime (in seconds) provided by Gurobi. Note that the times that the maximum runtime (7,200 s) is reached are shown in bold. For CP, the maximum runtime has been allowed to exceed to obtain a non-dominated solution.

Note that, for the optimisations G, SO, $GP2$ and CP the stopping criterion based on time, 7200 s, is reached. This means that the optimality of the solution obtained cannot be proved. Note also that when optimality is proved, both $\underline{z}$ and $\overline{z}$ are the same.

7. Conclusions

In the immediate aftermath of a disaster, a field hospital may need to be set up to care for patients who have been left without medical care due to the destruction of the local hospital infrastructure. This needs to be done quickly and efficiently. Some countries, such as Spain through AECID, have field hospitals that can be deployed where needed as part of their international cooperation.

Figure 3 Extract of the planning for a solution obtained with compromise programming (CP)

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	
Person 002			PS	PS	PS	MDCA				
Person 004						ED	MDCA	MDCA	ED	
Person 014						DONS	DONS	DONS	DONS	
Person 016	HNS	DONS								MDCA
Person 023	ED	ED								DONS
Person 027			ED	GS	GS	GS				GS
Person 029	GS	GS	GS	GS						GO
Person 030							GS	GS	GS	OTS
Person 032							GS	GS	GS	SAR
Person 035	GS	GS	GS							ED
Person 039					GS	GS				PE
Person 041								GO	GO	SR
Person 043		MDCA	GO	GO	ED					SEP
Person 045								GO	GO	CPS
Person 049	GO	GO	GO							PS
Person 056				GO	GO	GO	GO			HPH
Person 058	GO	GO								ORNS
Person 060					GO	GO	GO			ENS
Person 061							OTS	OTS	OTS	HNS
Person 071							OTS	OTS		OGNS
Person 073								OTS	OTS	PH
Person 074	OTS	OTS								LT
Person 077			OTS	OTS	OTS	OTS				RT
Person 078					OTS	OTS				ORNA
Person 079	OTS	OTS	OTS	OTS						HNSA
Person 081	SAR	SAR								PT
Person 085	SAR	SAR	SAR							
Person 094			MDCA	SAR	SAR					

Source: Authors' own creation

Table 6 Optimisation performance

	I	*C*	*A*	*G*	*SO*	*GP*1	*GP*2	*CP*
$\underline{z}$	0	262417	−2	−8.39	−15.88	0.00	0.12	0.30
$\bar{z}$	0	262417	−2	−8.39	−16.21	0.00	0.00	−0.03
t	121	246	136	*7200*	*7200*	2578	*7200*	*>7200*

Source: Authors' own creation

The mission may require the selection of appropriate health personnel to manage the operation, with several positions to be filled. The agencies responsible for this management often apply rigid rules for staff planning or prioritise the cost of the mission. However, it is important to consider the other stakeholders involved in such interventions: the health workers and the end users.

This study presents a mathematical optimisation model that takes into account the interests of all three stakeholders: the cooperation agency (minimising costs), the health personnel (maximising their availability) and the end users (maximising the qualifications of the personnel deployed). To the best of our knowledge, this is the first model with these characteristics.

From a managerial point of view, this study highlights the importance of staff planning, especially when the personnel is made up of volunteers, whose limitations should be taken into account as much as possible. The use of multi-criteria optimisation makes it possible to plan efficiently, taking into account the costs of deployment and balancing the interests of all stakeholders.

From a theoretical point of view, this study presents a novel multi-criteria model and introduces new efficiency measures expressed as averages (average grade and average availability) on the selected personnel. These measures are non-linear because they refer to a model variable (the personnel selected for the mission). In this study, they were linearised using binary auxiliary variables. Various multi-criteria analyses were also carried out, which show that the solutions obtained offer a better balance between the objectives than other approaches.

The model has been validated using the information available from the deployment of the START field hospital in Turkey and the simulation of personnel characteristics. These data have been made available to the interested scientific community (together with the implemented code). The results obtained and the code implemented allow the organisation to have the desired planning ready in a few hours. It is also possible to change the weighting of the criteria (even setting some to zero if the criterion is not relevant to the mission) and to define the desired goals of the mission.

As a future line of research, an in-depth multi-criteria analysis could be carried out from a mathematical point of view and heuristics/metaheuristics should be developed to improve the quality of the solution obtained and to reduce the computational time, facilitating also the use of non-proprietary software. In addition, further case studies could be considered and other methodologies proposed based on the characteristics of the deployment under consideration.

8. Executive summary

The international response to disasters and public health emergencies may include the deployment of field hospitals in cases where local medical capacities are exceeded. In those cases, the hospital and the related personnel must be airlifted, and both the transport and the shifts must be planned.

The aim of this work is to help a cooperation agency manage and plan the deployment of a field hospital. In particular the paper is concerned with the management of the medical emergency staff (both doctors and nurses) from a roster of volunteers with different characteristics. The authors propose a mathematical optimisation model that selects the necessary profiles of the roster according to several criteria, and provides travel planning taking into account the total cost of the operation.

This study uses multi-criteria optimisation to take into account the preferences of the three main stakeholders involved in the deployment of the field hospital: the cooperation organisation, the staff and the end users. The model considers the possibility of using commercial or chartered flights, allows staff to indicate their preferred availability, considers the grading of volunteers according to their skills and training, and provides a final flight schedule for all the medical personnel needed to operate the field hospital during the required planning horizon. Different solutions are proposed comparing several multi-criteria techniques (Weighted Sum, Goal Programming and Compromise Programming).

The use of the proposed multi-criteria model allows to provide more flexibility to the real operation by taking into account the availability and personnel shifts, and can be used in real operations to plan the different shifts and flight combinations to attend the emergency with efficiency reducing associated travel costs. The data needed to run the model is either introduced by the personnel when filling in for the roster or collected by the agency before the start of the mission, but it is not different from the one needed to plan the operation without an optimisation model.

The model has been validated using data from the operation in a case study of the deployment of the Spanish START hospital in Turkey 2023 and simulating from realistic distributions the non-available parameters. The study generalises the current procedures of the Spanish Agency for International Development by introducing more flexibility in the management of the roster, but considers the real actuation of the agency as a particular case, showing the practical utility of the model in similar operations.

References

AECID (2023), "El hospital del START, el equipo médico de emergencia español desplegado en turquía, estará operativo este lunes en iskenderun", available at: www.aecid.es/w/el-hospital-del-start-el-equipo-medico-de-emergencia-espanol-desplegado-en-turquia-estara-operativo-este-lunes-en-iskenderun (accessed 15 July 2024).

Ahadian, S., Pishvaee, M.S. and Jahani, H. (2023), "Reorganization of a medical service network to manage pandemic waves: a real case study", *Operations Research for Health Care*, Vol. 39, p. 100410, doi: 10.1016/j.orhc.2023.100410.

Burke, E.K., De Causmaecker, P., Berghe, G.V. and Van Landeghem, H. (2004), "The state of the art of nurse rostering", *Journal of Scheduling*, Vol. 7 No. 6, pp. 441-499, doi: 10.1023/b:josh.0000046076.75950.0b.

Causmaecker, P. and Vanden Berghe, G. (2010), "A categorisation of nurse rostering problems", *Journal of Scheduling*, Vol. 14 No. 1, pp. 3-16, doi: 10.1007/s10951-010-0211-z.

Charnes, A., Cooper, W.W. and Ferguson, R.O. (1955), "Optimal estimation of executive compensation by linear programming", *Management Science*, Vol. 1 No. 2, pp. 138-151, doi: 10.1287/mnsc.1.2.138.

Cochrane, J. and Zeleny, M. (1973), *Multiple Criteria Decision Making*, University of SC Press, Columbia.

Dolinskaya, I., Besiou, M. and Guerrero-Garcia, S. (2018), "Humanitarian medical supply chain in disaster response", *Journal of Humanitarian Logistics and Supply Chain Management*, Vol. 8 No. 2, pp. 199-226, doi: 10.1108/jhlscm-01-2018-0002.

Ernst, A.T., Jiang, H., Krishnamoorthy, M. and Sier, D. (2004), "Staff scheduling and rostering: a review of applications, methods and models", *European Journal of Operational Research*, Vol. 153 No. 1, pp. 3-27, doi: 10.1016/s0377-2217(03)00095-x.

Falasca, M. and Zobel, C. (2012), "An optimization model for volunteer assignments in humanitarian organizations", *Socio-Economic Planning Sciences*, Vol. 46 No. 4, pp. 250-260, doi: 10.1016/j.seps.2012.07.003.

Fortet, R. (1960), "L'algebre de boole et ses applications en recherche operationnelle", *Trabajos de Estadistica*, Vol. 11 No. 2, pp. 111-118, doi: 10.1007/bf03006558.

Gurobi Optimization, LLC (2024), "Gurobi optimizer reference manual", available at: www.gurobi.com (accessed 15 July 2024)

Ignizio, J. (1985), *Introduction to Linear Goal Programming*, Sage Publishing, Beverly Hills.

Kreiss, Y., *et al.* (2010), "Early disaster response in Haiti: the Israeli field hospital experience", *In: Annals of Internal Medicine*, Vol. 153 No. 1, p. 45, doi: 10.7326/0003-4819-153-1-201007060-00253.

Martín-Campo, F.J., Ortũno, M.T. and Ruiz-Gonz¨alez, B. (2024a), "Codes used in article "responding to an emergency with the START field hospital. Case study: Turkey-Syria earthquakes 2023", available at: https://github.com/beruizgonz/START

Martín-Campo, F.J., Ortuño, M.T. and Ruiz-Gonz¨alez, B. (2024b), "Set of instances used in article "responding to an emergency with the START field hospital. Case study: Turkey-Syria earthquakes 2023", doi: 10.5281/zenodo.10363838.

Matinrad, N. and Granberg, T.A. (2023), "Optimal pre-dispatch task assignment of volunteers in daily emergency response", *Socio-Economic Planning Sciences*, Vol. 87, p. 101589, doi: 10.1016/j.seps.2023.101589.

Mischek, F. and Musliu, N. (2017), "Integer programming model extensions for a multi-stage nurse rostering problem", *Annals of Operations Research*, doi: 10.1007/s10479-017-2623-z.

Niessner, H., Rauner, M.S. and Gutjahr, W.J. (2018), "A dynamic simulation–optimization approach for managing mass casualty incidents", *Operations Research for Health Care*, Vol. 17, pp. 82-100, doi: 10.1016/j.orhc.2017.07.001.

Oksuz, M.K. and Satoglu, S.I. (2023), "Integrated optimization of facility location, casualty allocation and medical staff planning for post-disaster emergency response", *Journal of Humanitarian Logistics and Supply Chain Management. issn:*, Vol. 14 No. 3, pp. 2042-6747, doi: 10.1108/jhlscm-08-2023-0072.

Özdamar, L., Ekinci, E. and Küçükyazici, B. (2004), "Emergency logistics planning in natural disasters", *Annals of Operations Research*, Vol. 129 Nos 1/4, pp. 217-245, doi: 10.1023/b:anor.0000030690.27939.39.

Paret, K.E., Mayorga, M.E. and Lodree, E.J. (2021), "Assigning spontaneous volunteers to relief efforts under uncertainty in task demand and volunteer availability", *Omega*, Vol. 99, p. 102228, doi: 10.1016/j.omega.2020.102228.

Rezvykh, A.D., Ovcharenko, A.P., Lemeshkin, R.N. and Kovalchuk, S.V. (2022), "Modeling the workflow of a field hospital in earthquake conditions", *Procedia Computer Science*, Vol. 212, pp. 330-339, doi: 10.1016/j.procs.2022.11.017.

Romero, C. (1991), *Handbook of Critical Issues in Goal Programming*, Pergamon Press, Oxford.

Shavarani, S.M., Golabi, M. and Vizvari, B. (2020), "Assignment of medical staff to operating rooms in disaster preparedness: a novel stochastic approach", *IEEE Transactions on Engineering Management*, Vol. 67 No. 3, pp. 593-602, doi: 10.1109/tem.2019.2940352. url: http://dx.doi.org/10.1109/TEM.2019.2940352.

USGS, U.S. Geological Survey (2023a), "M 7.5 – Elbistan earthquake, kahramanmaras earthquake sequence", available at: https://earthquake.usgs.gov/earthquakes/eventpage/us6000jlqa/executive (accessed 15 July 2024).

USGS, U.S. Geological Survey (2023b), "M 7.8 - Pazarcik earthquake, kahramanmaras earthquake sequence", available at: https://earthquake.usgs.gov/earthquakes/eventpage/us6000jllz/executive (accessed 15 July 2024).

Van den Bergh, J., Beliën, J., De Bruecker, P., Demeulemeester, E. and De Boeck, L. (2013), "Personnel scheduling: a literature review", *European Journal of Operational Research*, Vol. 226 No. 3, pp. 367-385, doi: 10.1016/j.ejor.2012.11.029.

Wickert, T.I., Smet, P. and Vanden Berghe, G. (2019), "The nurse rerostering problem: strategies for reconstructing disrupted schedules", *Computers & Operations Research*, Vol. 104, pp. 319-337, doi: 10.1016/j.cor.2018.12.014.

Youn, S., Geismar, H.N. and Pinedo, M. (2022), "Planning and scheduling in healthcare for better care coordination: current understanding, trending topics, and future opportunities", *Production and Operations Management*, Vol. 31 No. 12, pp. 4407-4423, doi: 10.1111/poms.13867.

Zadeh, L. (1963), "Optimality and non-scalar-valued performance criteria", *IEEE Transactions on Automatic Control*, Vol. 8 No. 1, pp. 59-60, doi: 10.1109/tac.1963.1105511.

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