Nguyen *et al.*
Scand J Trauma Resusc Emerg Med (2025) 33:190
https://doi.org/10.1186/s13049-025-01504-1

Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine

RESEARCH

Open Access

Selection of helicopter bases and transport modes to minimize pre-hospital times in Iceland

Phuong Nguyen[1], Sveinbjörn Dúason[2], Björn Gunnarsson[2,3] and Ármann Ingólfsson[1*]

Abstract

Background Models for the optimal location of ambulance bases typically focus on response time, but for some patients (e.g., trauma), the total pre-hospital time may matter more. Iceland's geography and population distribution imply that fixed-wing air ambulances are an important mode for transporting emergency patients to one of the small number of hospitals with capabilities to treat patients with time-sensitive conditions. Helicopter ambulances have the potential to improve service for incidents that occur far from the closest airport.

Methods We formulate models to find optimal helicopter base locations with a primary objective of maximizing incident coverage and secondary objective of minimizing patient transport costs. Our models consider three transport modes (ground, fixed-wing, and helicopter), and evaluate the addition of new helicopter bases to a single existing fixed-wing base, single existing helicopter base, and multiple existing ground ambulance bases.

Results Akureyri and Flúðir are potential locations for a second helicopter base. These locations provide similar overall coverage levels, but effectiveness depends on hospital destination assumptions. Flúðir offers greater benefits if all patients are transported to Reykjavík Hospital, whereas Akureyri performs better if patients are transported to the nearest hospital.

Conclusions The choice of helicopter base locations depends on factors beyond coverage. Our work shows how optimization models can reveal the impact of operational assumptions on optimal base selection and illustrates a methodology that can be adapted for other countries facing similar geographic challenges.

Keywords Emergency medical services, Optimization, Healthcare application, Facility location

Background

Air medical services, particularly helicopter emergency medical services (HEMS), are a crucial component of emergency medical services (EMS) and are increasingly prevalent in pre-hospital settings due to their time-saving benefits and improved access to remote areas. Although ground ambulance EMS (GEMS) can be faster for short-distance transport in urban areas, traffic congestion can lead to significant delays, thus lowering the distance threshold at which HEMS is faster [1]. The time advantage of HEMS becomes clear for long-distance transport due to its greater travel speed and ability to fly in a relatively straight path [2]. In areas that are inaccessible by roads, HEMS is the pragmatic means for transporting critically ill and injured patients to advanced emergency care centers.

The optimal placement of ambulance bases has been extensively studied through models such as the maximal covering location problem (MCLP). Originally proposed by Church and ReVelle [3], MCLP aims to maximize demand coverage within a specified service standard, typically defined by distance or time from a base to an incident. Building on the MCLP, several recent studies

*Correspondence:
Ármann Ingólfsson
aingolfs@ualberta.ca
[1] University of Alberta, Edmonton, Canada
[2] University of Akureyri, Akureyri, Iceland
[3] Akureyri Hospital, Akureyri, Iceland

have developed models for the optimization of air ambulance locations [4–9]. Two common characteristics emerge among these studies.

First, many studies define coverage based on response time. Total pre-hospital time is also important, however, for time-sensitive emergencies or "first-hour quintet" conditions such as cardiac arrest, severe trauma, and acute stroke [10], for whom increased pre-hospital time is associated with higher mortality rates [11, 12] and decreased functional independence [13]. Clinical guidelines reflect this time-critical nature through specific recommendations such as patients with stroke should be transported rapidly to the closest healthcare facility capable of administering intravenous thrombolytics [14]. Another example is the recommended 90-minute window from first medical contact to percutaneous coronary intervention (PCI) for ST-segment elevation myocardial infarction patients [15]. Our work uses total pre-hospital time as the criterion for coverage and investigates target times ranging from 60 to 240 minutes. We aim to identify depot locations that perform well throughout this range of target times.

Second, studies do not always account for multiple transport modes or handovers between modes. For instance, in Norway, the disparity in the level of care offered by GEMS and air medical services may justify a focus exclusively on air ambulance locations [5]. For another example, the trauma resource allocation model for ambulances and hospitals (TRAMAH) [16, 17], which we build on, omits ground ambulance response time from the pre-hospital time calculation, by assuming that every incident occurs close to a GEMS depot. There are exceptions, however, involving optimization models that incorporate multiple modes and handovers between modes, specifically HEMS and GEMS [8, 9, 18] or GEMS and a mobile stroke unit [19]. In most of these studies, the modeling of handovers involves the addition of decision variables to the optimization model [8, 9, 19], as opposed to the computationally simpler approach of modeling handovers through input data preparation, which is used in [18] and by us, for handovers between fixed-wing aircraft and GEMS.

In Iceland, there has been interest in establishing a HEMS base in Akureyri or Flúðir [4, 20]. The primary aim of this study is to determine optimal locations for HEMS bases in Iceland, using an optimal facility location model that accounts for existing fixed-wing air ambulance and road ambulance services. The objective is to maximize incident coverage and minimize patient transport times to definitive care, thereby improving timely access to EMS and definitive care across both urban and rural areas. We illustrate an approach that could be used more generally, particularly for regions or countries with uneven population distribution and rugged terrain. A secondary aim is to develop a web application for engaging stakeholders in scenario exploration and methodology validation.

Methods

Our methodology includes three main components: Defining relevant time intervals for each transport mode, estimating parameters, and solving optimization problems to select base locations and choose transport modes. We estimated parameters using empirical data if available, and otherwise relied on indirect data, simplifying assumptions, published estimates, or aspirational targets. Table 1 lists abbreviations and Tables 2 and 3 show notations for sets and parameters used in the optimization models.

Study setting

There are 38 GEMS stations, responding to an average of 14 thousand emergency calls per year from 2016 to 2022. There is one fixed-wing aircraft ambulance base, in Akureyri, which transported 668 patients on average per year from 2012 to 2020 [21]. There is one helicopter base at Reykjavík Airport, operated by the Icelandic

Table 1 Abbreviations

	Terms		Location
EMS	Emergency medical services	AR	Akureyri
HEMS	Helicopter emergency medical services	BD	Bíldudalur
GEMS	Ground emergency medical services	BL	Blönduós
SAR	Search and rescue	EG	Egilsstaðir
PCI	Percutaneous coronary intervention	FL	Flúðir
MCLP	Maximal covering location problem	GJ	Gjögur
TRAMAH	Trauma resource allocation model for ambulances and hospitals	GS	Grímsstaðir
		HN	Höfn
		HK	Hólmavík
		HZ	Húsafell
		HU	Húsavík
		IS	Ísafjörður
		KL	Kirkjubæjarklaustur
		NF	Norðfjörður
		RK	Reykjavík
		KR	Sauðárkrókur
		SL	Skaftafell
		ST	Stykkishólmur
		TN	Þórshöfn
		VM	Vestmannaeyjar
		VO	Vopnafjörður

Table 2 Sets

Symbol	Description
I	Set of demand nodes
K	Set of travel modes = {F (fixed-wing), G (ground), or H (helicopter)}
J^H	Set of potential helicopter bases
J^k	Set of existing bases for mode k

Coast Guard for search and rescue (SAR) but responding primarily to emergency medical missions. Helicopters responded to 134 emergency calls per year on average from 2018 to 2022 [22], but rarely responded to emergencies in the north or east parts of the country.

Time intervals

In this study, the *pre-hospital time* is the time from receipt of the emergency call to the patient's arrival at the hospital, consisting of response time, scene time, and transport time. The *response time* of a travel mode refers to the period from receipt of the call to the arrival of that mode for patient pickup. For GEMS and HEMS, the response time consists of the activation time, which involves the preparations for dispatching, followed by the time to travel to the incident location (see Fig. 1).

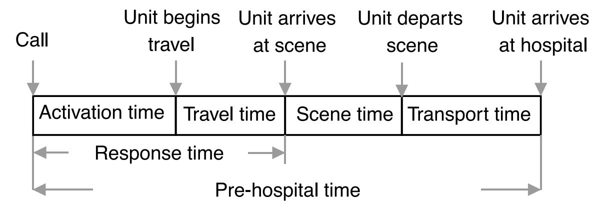

Fig. 1 Events and time intervals for ground ambulance or helicopter

Figure 2 shows a more complex procedure for fixed-wing response time, which involves the response from both a ground ambulance and a fixed-wing aircraft. Upon receiving the call, an aircraft is dispatched from the fixed-wing base in Akureyri to a designated pickup airport, while simultaneously the nearest ground ambulance is dispatched to the incident location. After providing on-site medical assistance and patient preparation (captured as scene time), the ambulance transports the patient to the pickup airport. The fixed-wing response time ends when both the ground ambulance and the aircraft have arrived at the pickup airport.

Figure 3 illustrates the calculation of fixed-wing response time to an incident and the selection of the pickup airport. The activation and flying time from Akureyri to Húsavík is 61 minutes and to Reykjahlíð is 63 minutes (see Sect. Fixed-wing aircraft

Table 3 Parameters

Symbol	Description	Values
Primitive parameters		
d_i	Demand at node i	
$t_{\max}$	Pre-hospital time standard	60, 90, 120, 180, 240 minutes
p	Number of helicopter bases to be located	0, 1, 2, 3
Derived parameters		
a	Acceleration	See Table S10
v_c	Cruising speed	See Table S10
d_c	Distance to reach cruising speed	See Table S10
τ	Degrees of freedom	See Table S10
a_j^k	Activation time of mode k at base j	
s^k	Scene time for mode k	
r_{ji}^H	Total response time from base j to node i, including activation time, using helicopter	
t_{ih}^k	Total transport time from node i to the selected hospital h, using mode k	
r_i^k	Total response time to node i, including activation time, using mode k for $k \in \{F, G\}$	
q_i^k	Total pre-hospital time of node i using mode k for $k \in \{F, G\}$	
q_{ji}^H	Total pre-hospital time of node i using helicopter from base j	
v_i^k	The cost of covering node i using mode k for $k \in \{F, G\}$	
v_{ij}^H	The cost of covering node i using helicopter from base j	
t_{mn}^G	Driving time from location m to location n	Obtained using HERE API
t_{mn}^F	Aircraft flying time from location m to location n	

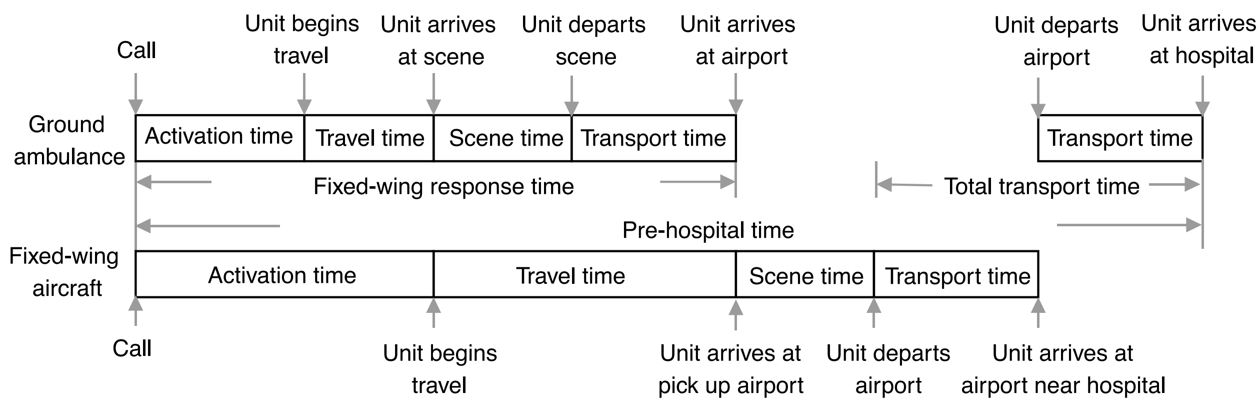

Fig. 2 Events and time intervals for fixed-wing aircraft

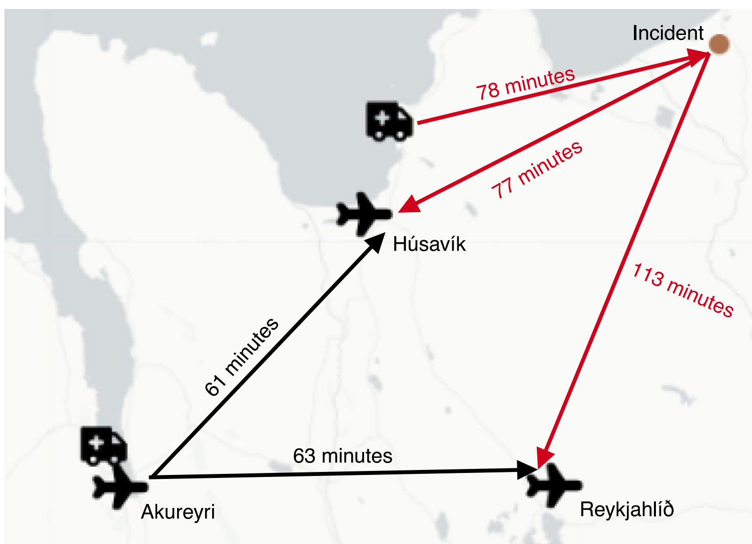

Fig. 3 Illustration of fixed-wing response-time calculation (Black = Fixed-wing aircraft flies, Red = Ground ambulance drives)

transport for information on how the flying times are estimated). The ground ambulance takes a total of $78 + 16 + 113 = 207$ minutes (including activation time and a 16-minute scene time) to travel from the nearest depot in Húsavík to the incident and from the incident to Reykjahlíð whereas the whole process only takes $78 + 16 + 77 = 171$ minutes if the pickup airport is in Húsavík. The resulting fixed-wing response time is $\min\{\max(61, 171), \max(63, 207)\} = \min\{171, 207\} = 171$ minutes, indicating that Húsavík is chosen as the optimal pickup airport.

Upon arrival at the patient's location, each travel mode spends some time for medical support on the scene before proceeding with patient transport, which is the *scene time*. The *transport time* extends from the departure of the travel mode from the scene to the patient's arrival at the hospital. While GEMS and HEMS transport the patient directly to the hospital, fixed-wing aircraft land at the airport closest to the hospital, where an awaiting ground ambulance completes the transfer of the patient to the hospital.

Incidents

The incident data, obtained from Iceland's emergency dispatch center (112 Emergency Line) [23], includes incidents from December 2015 to July 2023, inclusive. A total of 53,522 highest-priority incidents are aggregated into 2,362 one km^2 cells using QGIS [24], whose central point coordinates form the demand nodes.

Hospitals

We focus on the two main healthcare facilities in Iceland, Reykjavík Hospital and Akureyri Hospital. Reykjavík Hospital, with approximately 700 beds, is the country's leading hospital and most advanced trauma center (Level II Trauma Center as per the American Trauma Society classification [25]). Akureyri Hospital, with approximately 115 beds, is the only other alternative for surgical services beyond emergency procedures like Caesarian sections, appendectomies, and other minor surgeries. This hospital has an emergency room and a small intensive care unit, qualifying as a Level IV Trauma Center [25].

It is unclear how to integrate the hospital choice into the optimization model, as merely knowing the call's priority is not sufficient to determine the appropriate hospital. To address this, we solve all models under a worst-case and a best-case scenario. In the worst-case scenario, all patients are transported to Reykjavík Hospital. In the best-case scenario, all patients are transported to the closer of the two hospitals. The best-case scenario results in shorter pre-hospital times. The difference in performance between the worst and best-case scenarios provides insights into the potential benefits of extending the specialized services at Akureyri Hospital.

Ground ambulance transport

We compiled a list of 38 GEMS depot locations in Iceland as of 2023 (see Fig. 4c). The median ambulance activation times for 2022 at each depot were obtained from the emergency dispatch center [23]. We used a median scene time of 16.4 minutes, which was obtained for all GEMS calls in Iceland in 2021 through personal communication. We used generic road driving time estimates, obtained using HERE (see Additional file 1 for details). For any incident that is considered unreachable by HERE, we assigned a driving time of 600 minutes to ensure that these incidents will not be considered as reachable within any of the pre-hospital time standards, by either GEMS or fixed-wing aircraft.

The GEMS response time for node i is $r_i^G = \min\{a_j^G + t_{ji}^G : j \in J^G\}$. The total pre-hospital time is $q_i^G = r_i^G + s^G + t_{ih}^G$, assuming transport to hospital h.

Fixed-wing aircraft transport

A total of 2,130 aircraft flight records from 2020 to 2022 were provided, detailing each stage of the flight from

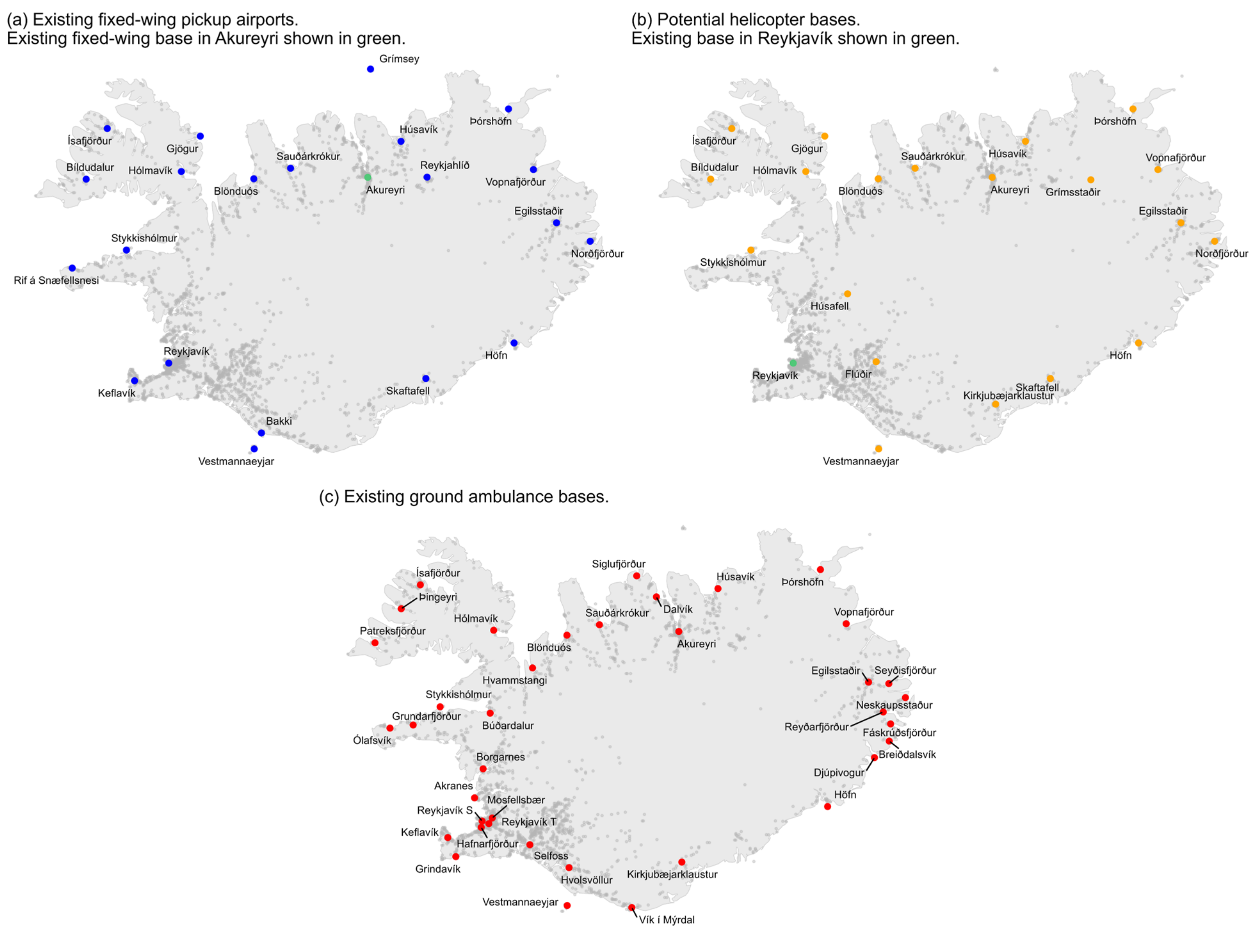

Fig. 4 Existing and potential bases for ground ambulance, fixed-wing aircraft, and helicopters. Locations of one-km squares with nonzero incidents are shown in grey

departure from base to arrival at the patient's location and subsequent transport to hospital. We compiled a list of 22 airports suitable for patient pickup (see Fig. 4a), together with the single existing fixed-wing aircraft base in Akureyri. We obtained a median activation time of 47 minutes and a median scene time of 20 minutes from the aircraft flight records.

We used a robust estimation approach [26], which accounts for acceleration and deceleration effects, to estimate fixed-wing flying times as a function of straight-line distance. This approach has been used to estimate ground ambulance and fire engine driving times [26, 27] and is arguably even more appropriate for estimating fixed-wing and helicopter flying times, because of less traffic congestion in the air than on the ground. See Additional file 1 for further details.

The aircraft response time is the maximum of two durations: (i) the total time for a ground ambulance to travel from the nearest depot $j' \in J^G$ to node i and from i to a pick up airport $j \in J^F$ $(a^G_{j'} + t^G_{j'i} + s^G + t^G_{ij})$, and (ii) the total time for the aircraft to fly to the pickup airport j $(a^F + t^F_j$; we omit a subscript for the fixed-wing base, because there is only one base). Thus, the fixed-wing response time is:

$$r^F_i = \min_{j \in J^F}\{\max(a^G_{j'} + t^G_{j'i} + s^G + t^G_{ij}, a^F + t^F_j)\}. \quad (1)$$

The transport time from patient pickup to arrival at hospital h is $t^F_{ih} = t^F_{jj^*} + t^G_{j^*h}$, where j^* the airport closest to hospital h. The total fixed-wing pre-hospital time for node i is $q^F_i = r^F_i + s^F + t^F_{ih}$.

Helicopter transport

Figure 4b illustrates 21 potential helicopter base locations. The same locations were used in a previous study [4] and they were chosen to span all inhabited parts of the country, but exclude the interior. We assume that the helicopter will pick the patient up at the incident location (thus, we ignore the infrequent situation in which a ground ambulance transports the patient to a suitable helicopter landing site). We use the following estimates from [22]: A 27-minute activation time (median time for the highest-priority missions), a 13-minute scene time (median), and an average speed of 185 km/h (median flight time of 40 minutes divided by median distance of 123 km). We used this average speed and the geodesic distance to estimate helicopter response time and transport time. HEMS pre-hospital time from base j for node i is $q^H_{ji} = r^H_{ji} + s^H + t^H_{ih}$.

The HEMS coverage region given a pre-hospital time standard, assuming straight-line travel over a flat surface, is an ellipse, as noted previously [28].

Optimization models

Our aim is to select one or more HEMS base locations and to assign a transport mode to each demand node. The base location selection is a strategic long-term decision, whereas the transport mode selection is an operational decision, which is contingent on the base locations as well as a variety of factors that are not incorporated in our model, such as weather conditions and real-time ambulance availability. Thus, we use lexicographic optimization – a multi-objective approach that begins by optimizing the highest-priority objective and then optimizes lower-priority objectives without compromising the achieved value of higher-priority ones [29]. We have two objectives: Maximize coverage of incidents and minimize the cost of responding to calls.

First, in Problem 1, we determine the maximum coverage subject to constraints on the number of helicopter bases and on which nodes can be covered by which mode. Problem 1 is a modified version of TRAMAH [16]. As originally formulated, TRAMAH considers two modes (air and ground) and site selection for new aeromedical bases and trauma centers. We include three modes, one of which (F = fixed wing) requires responses from both air and ground ambulances, and we limit site selection to helicopter bases.

Second, in Problem 2, we select HEMS base locations and the transport mode to use for each demand node to minimize response costs while maintaining the maximum coverage obtained from solving Problem 1. We define cost as either estimated pre-hospital time or expenses associated with the selected mode. If cost is quantified as transport expenses, we assume that G is the least costly option, followed by F, and H [30].

Additional file 2 provides mathematical formulations of Problems 1 and 2. We formulated Problems 1 and 2 using the *ompr* optimization modeling language in R [31] and solved using the GLPK, Gurobi, and HiGHS solvers [32–34] across different combinations of parameters: $t_{\max}$ values of 60, 90, 120, 180, and 240 minutes; the two hospital selection scenarios; and the 11 greenfield and brownfield scenarios listed in Table 4, in which the number of bases, p, ranges from 0 to 3. This resulted in a total of $5 \times 2 \times 11 = 110$ problem instances. All three solvers produced the same results and all problems were solved to global optimality. We used the GLPK solver for the app, because its license permits free distribution.

Short computation times are necessary in order to make the app a useful tool for experimentation. With our data, Problem l has 9,449 constraints and 9,469 decision variables, and takes less than 20 seconds to solve using GLPK on a 6-core processor. Problem 2, with cost quantified as estimated pre-hospital time, has 9,471 constraints and 56,709 decision variables, and requires from

Table 4 Greenfield and brownfield scenarios

Number of bases (*p*)	Type	Base 1	Base 2	Base 3
0	N/A	N/A		
1	Greenfield	Any		
	Brownfield	Reykjavík		
2	Greenfield	Any	Any	
	Brownfield 1	Reykjavík	Any	
	Brownfield 2	Reykjavík	Akureyri	
	Brownfield 3	Reykjavík	Flúðir	
3	Greenfield	Any	Any	Any
	Brownfield 1	Reykjavík	Any	Any
	Brownfield 2	Reykjavík	Akureyri	Any
	Brownfield 3	Reykjavík	Flúðir	Any

150 to 210 seconds to solve with the same settings. However, in many instances we can avoid this long computation time for Problem 2 by using a greedy algorithm (an algorithm that makes a locally optimal choice at each stage). If cost is quantified as estimated pre-hospital time, the total time to solve Problems 1 and 2 is less than 80 seconds per instance for the 85 problem instances for which the greedy algorithm can be used. For the 25 problem instances for which Problem 2 must be solved as an integer program, the average total solution time is 250 seconds per instance. All of these instances correspond to $t_{\max} \geq 120$ minutes. If cost is quantified as expense, then the total solution time is less than 20 seconds for all 110 problem instances. Additional file 2 provides detailed information about the greedy algorithm and conditions under which it can or cannot be used.

App development and model testing

To engage stakeholders and validate our model's assumptions, we developed a *Shiny* web application [35] with two main features (see https://aihems.shinyapps.io/Iceland_HEMS/). First, users can visualize how parameters such as number of helicopter bases or pre-hospital time affect coverage and explore location tradeoffs (see Fig. 5a). We used the GLPK solver, because its licensing terms permit distribution of the app. Second, users can click any map location to view detailed pre-hospital time intervals for each relevant transport mode (see Fig. 5b).

Developing the app helped us better understand several model assumptions for special scenarios. For example, our model overlooks wait times for ferries serving Iceland's coastal islands, making the GEMS and fixed-wing pre-hospital time estimates overly optimistic for incidents that occur on these islands. Neither GEMS nor fixed-wing aircraft are appropriate options for incidents that are inaccessible by road, so we adjusted the app to show only HEMS pre-hospital time for these cases. Similarly, fixed-wing aircraft would not be used for an incident that is close to one of the two hospitals. We proved that when the pickup airport is the same as the hospital's nearest airport, our model will never assign fixed-wing aircraft to cover the incident (see Additional file 2). We also ensured that the app does not display fixed-wing aircraft pre-hospital times for these circumstances.

We contacted potential end users in Iceland including emergency number dispatch managers, paramedics, physicians, nurses, and government professionals and asked them to try the app and complete the survey (see Additional file 3 for the survey questions).

Results

Model results

Tables 5, 6, 7, 8, and 9 show the incident coverage (obtained by solving Problem 1) and the selected HEMS bases (obtained by solving Problem 2) for all problem instances. We organize the discussion of the results around three questions of practical interest: (1) What is the impact of having the existing SAR helicopter base in Reykjavík respond regularly to medical calls; (2) what is the impact of having two helicopter bases; and (3) what could be the impact of being able to transport more patients to Akureyri Hospital, rather than Reykjavík Hospital? These three questions operationalize our study's main aim by translating it into concrete, testable scenarios.

The impact of having the existing helicopter base in Reykjavík respond to medical calls ranges from a high of 3.9 pecentage points (pp) for a 120-minute time standard to a low of 0.2 pp for a 240-minute time standard. For certain time standards, the greenfield solution for a single HEMS base does not select Reykjavík. For example, the greenfield solution for a 90-minute standard selects Vestmannaeyjar, which increases coverage by 3.5 pp, compared to 1.8 pp if the base is restricted to Reykjavík.

For the second question, we consider the greenfield and the three brownfield scenarios separately.

For the greenfield scenario, the impact of adding a second base is greatest (3.1 pp) for the 120-minute standard under the closest hospital scenario. This solution involves locating HEMS bases in Reykjavík and Neskaupstaður. For the other solutions corresponding to a 90- or 120-minute time standard, the impact ranges from 1.3 to 1.7 pp, and Reykjavík is not one of the two selected bases. In all other cases, the impact is 0.3 pp or less.

If the first base is restricted to Reykjavík (Brownfield 1), the impact of adding a second base ranges from 1.5 to 3.1 pp for the 90- and 120-minute standards. In all other cases, the impact is 0.3 pp or less.

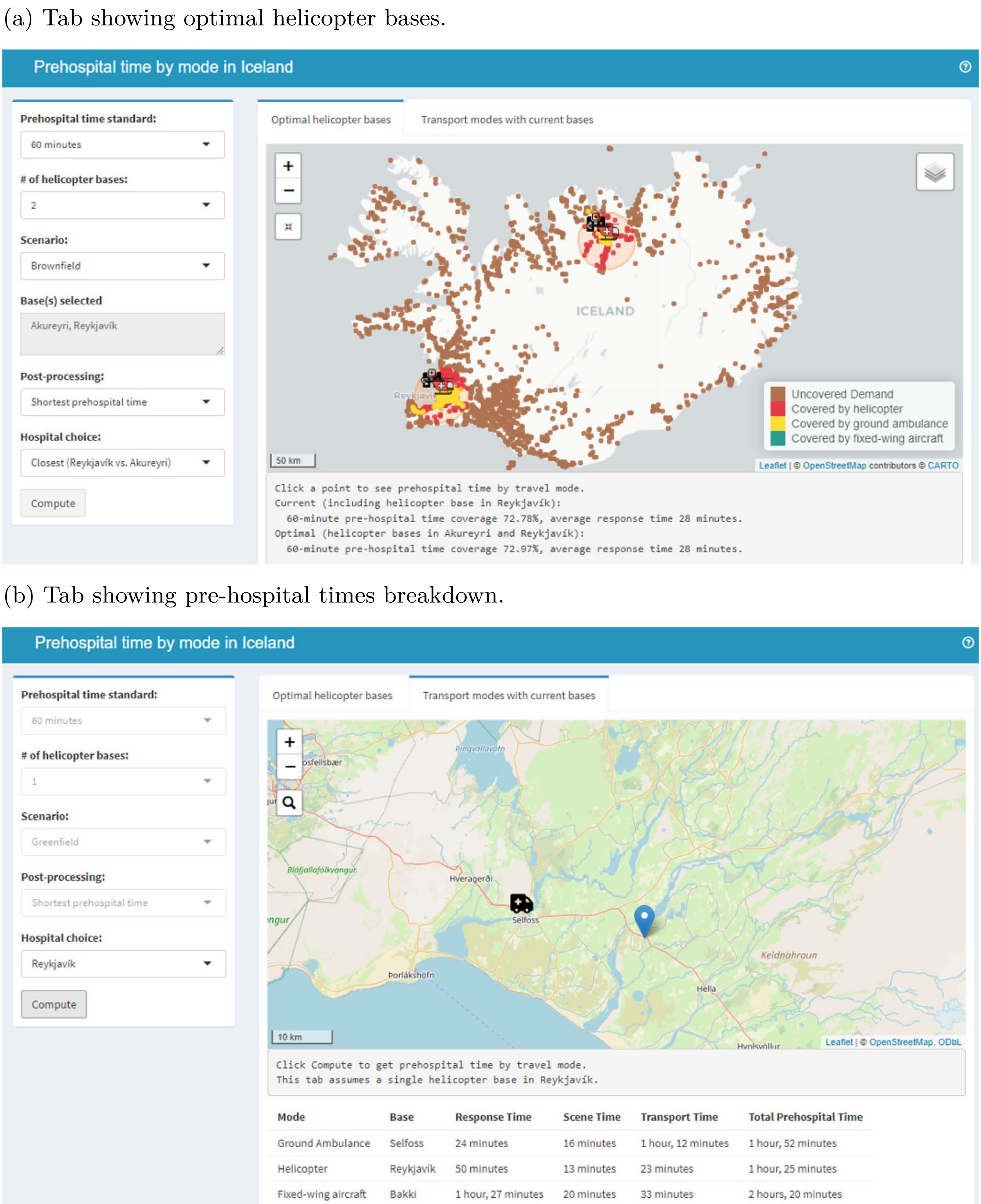

Fig. 5 Screenshots of the *Shiny* web app

Table 5 Coverage of incidents by different scenarios and hospital choices for a 60-min pre-hospital time. Brownfield fixed locations are in bold

Scenario	Hospital choice	Bases located at:			Percent coverage with:			
		1 base	2 bases	3 bases	0 bases	1 base	2 bases	3 bases
Greenfield	Closer	RK	RK, HU	RK, HU, AR	70.4	72.8	73.1	73.2
Brownfield 1	hospital	**RK**	**RK**, HU	**RK**, HU, AR	70.4	72.8	73.1	73.2
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, HU	70.4	72.8	73.0	73.2
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, HU	70.4	72.8	72.8	73.1
Greenfield	Reykjavík	RK	RK, BD	RK, BD, BL	64.2	66.6	66.6	66.6
Brownfield 1	Hospital	**RK**	**RK**, AR	**RK**, AR, BD	64.2	66.6	66.6	66.6
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, BD	64.2	66.6	66.6	66.6
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, AR	64.2	66.6	66.6	66.6

Table 6 Coverage of incidents by different scenarios and hospital choices for a 90-min pre-hospital time. Brownfield fixed locations are in bold

Scenario	Hospital choice	Bases located at:			Percent coverage with:			
		1 base	2 bases	3 bases	0 bases	1 base	2 bases	3 bases
Greenfield	Closer	VM	VM, KR	VM, KR, HZ	85.2	88.7	90.4	91.6
Brownfield 1	hospital	**RK**	**RK**, VM	**RK**, VM, KR	85.2	87.0	89.4	91.1
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, VM	85.2	87.0	88.4	90.8
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, KR	85.2	87.0	88.5	90.2
Greenfield	Reykjavík	VM	VM, HZ	VM, ST, FL	77.7	81.1	82.4	83.1
Brownfield 1	Hospital	**RK**	**RK**, VM	**RK**, VM, ST	77.7	79.5	81.9	82.6
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, VM	77.7	79.5	79.5	81.9
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, VM	77.7	79.5	81.0	82.4

Table 7 Coverage of incidents by different scenarios and hospital choices for a 120-min pre-hospital time. Brownfield fixed locations are in bold

Scenario	Hospital choice	Bases located at:			Percent coverage with:			
		1 base	2 bases	3 bases	0 bases	1 base	2 bases	3 bases
Greenfield	Closer	RK	RK, NF	NF, IS, KL	89.0	92.9	96.0	97.9
Brownfield 1	hospital	**RK**	**RK**, NF	**RK**, NF, IS	89.0	92.9	96.0	97.6
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, NF	89.0	92.9	93.5	96.4
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, NF	89.0	92.9	93.3	96.3
Greenfield	Reykjavík	RK	IS, KL	IS, KL, KR	85.9	89.8	91.4	92.9
Brownfield 1	Hospital	**RK**	**RK**, BL	**RK**, IS, KR	85.9	89.8	91.3	92.6
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, BL	85.9	89.8	89.8	91.3
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, BL	85.9	89.8	90.1	91.6

If the first base is restricted to Reykjavík and the second base is restricted to Akureyri (Brownfield 2), the impact of adding the base in Akureyri is greatest (1.4 pp) for a 90-minute standard under the closest hospital scenario. The impact is 0.6 pp for a 120-minute standard under the closest hospital scenario. In all other cases, the impact is 0.3 pp or less.

If the first base is restricted to Reykjavík and the second base is restricted to Flúðir (Brownfield 3), the impact of adding the base in Flúðir is greatest (1.5 pp) for a

Table 8 Coverage of incidents by different scenarios and hospital choices for a 180-min pre-hospital time. Brownfield fixed locations are in bold

Scenario	Hospital choice	Bases located at:			Percent coverage with:			
		1 base	2 bases	3 bases	0 bases	1 base	2 bases	3 bases
Greenfield	Closer	AR	EG, HZ	EG, FL, ST	99.3	100.0	100.0	100.0
Brownfield 1	hospital	**RK**	**RK**, EG	**RK**, EG, VM	99.3	99.8	100.0	100.0
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, EG	99.3	99.8	100.0	100.0
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, AR	99.3	99.8	99.9	100.0
Greenfield	Reykjavík	HU	HU, NF	AR, NF, TN	99.1	99.7	99.8	99.9
Brownfield 1	Hospital	**RK**	**RK**, TN	**RK**, TN, NF	99.1	99.5	99.8	99.9
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, TN	99.1	99.4	99.7	99.9
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, TN	99.1	99.4	99.5	99.8

Table 9 Coverage of incidents by different scenarios and hospital choices for a 240-min pre-hospital time. Brownfield fixed locations are in bold

Scenario	Hospital choice	Bases located at:			Percent coverage with:			
		1 base	2 bases	3 bases	0 bases	1 base	2 bases	3 bases
Greenfield	Closer	FL	FL, EG	FL, EG, ST	99.7	100.0	100.0	100.0
Brownfield 1	hospital	**RK**	**RK**, EG	**RK**, EG, VM	99.7	100.0	100.0	100.0
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, EG	99.7	100.0	100.0	100.0
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, EG	99.7	100.0	100.0	100.0
Greenfield	Reykjavík	HU	HU, FL	HU, RK, VM	99.7	100.0	100.0	100.0
Brownfield 1	Hospital	**RK**	**RK**, HU	**RK**, HU, VM	99.7	99.9	100.0	100.0
Brownfield 2		**RK**	**RK**, **AR**	**RK**, **AR**, TN	99.7	99.9	100.0	100.0
Brownfield 3		**RK**	**RK**, **FL**	**RK**, **FL**, HU	99.7	99.9	99.9	100.0

90-minute standard under both hospital choice scenarios. In all other cases, the impact is 0.4 pp or less.

For the third question, the upper limit on the impact of being able to transport some patients to Akureyri rather than Reykjavík is highly dependent on the time standard and weakly dependent on the number of HEMS bases. The impact is highest (8.9 pp) for a 90-minute standard and at least two HEMS bases, with the first two bases restricted to Reykjavík and Akureyri. The impact is at least 3.1 pp for time standards of 120 minutes or less and at most 0.4 pp for time standards of 180 minutes or more.

Figures 6, 7, 8 and 9 illustrate transport mode selection (based on the Problem 2 solutions), both spatially and overall. These figures are for time standards of 120 and 180 minutes, two HEMS bases (the first restricted to Reykjavík and the second in either Akureyri or Flúðir), and both hospital choice scenarios. In general, we see that GEMS covers incidents close to one of the available hospitals and HEMS covers incidents that are further away but still within the ellipses that define the HEMS coverage areas. Adding a HEMS base in Akureyri if all patients must be transported to Reykjavík Hospital provides no benefit for time standards of 120 minutes or less (see top-left panel of Fig. 6), because it takes longer than 120 minutes to get a patient to Reykjavík if the helicopter starts in Akureyri. Fixed-wing begins to provide coverage for a 120-minute time standard (Fig. 6), for incidents that are close to one of the pickup airports, and fixed-wing coverage expands to the remote northwestern and eastern parts of the country as the time standard increases to 180 minutes (Fig. 8).

App feedback

We shared the app and the accompanying survey with 19 professionals involved in prehospital care and emergency services in Iceland. We received 10 responses, for a 52.6% response rate. Additional file 3 provides the survey questions and detailed numerical results. Respondents included paramedics, emergency dispatch personnel, and healthcare professionals familiar with rural emergency logistics.

Overall, the app was well-received. Most participants found it intuitive and easy to navigate, with 60% reporting that they were able to obtain results in under one minute, and the remaining 40% requiring between one and two minutes. Importantly, no testers experienced crashes,

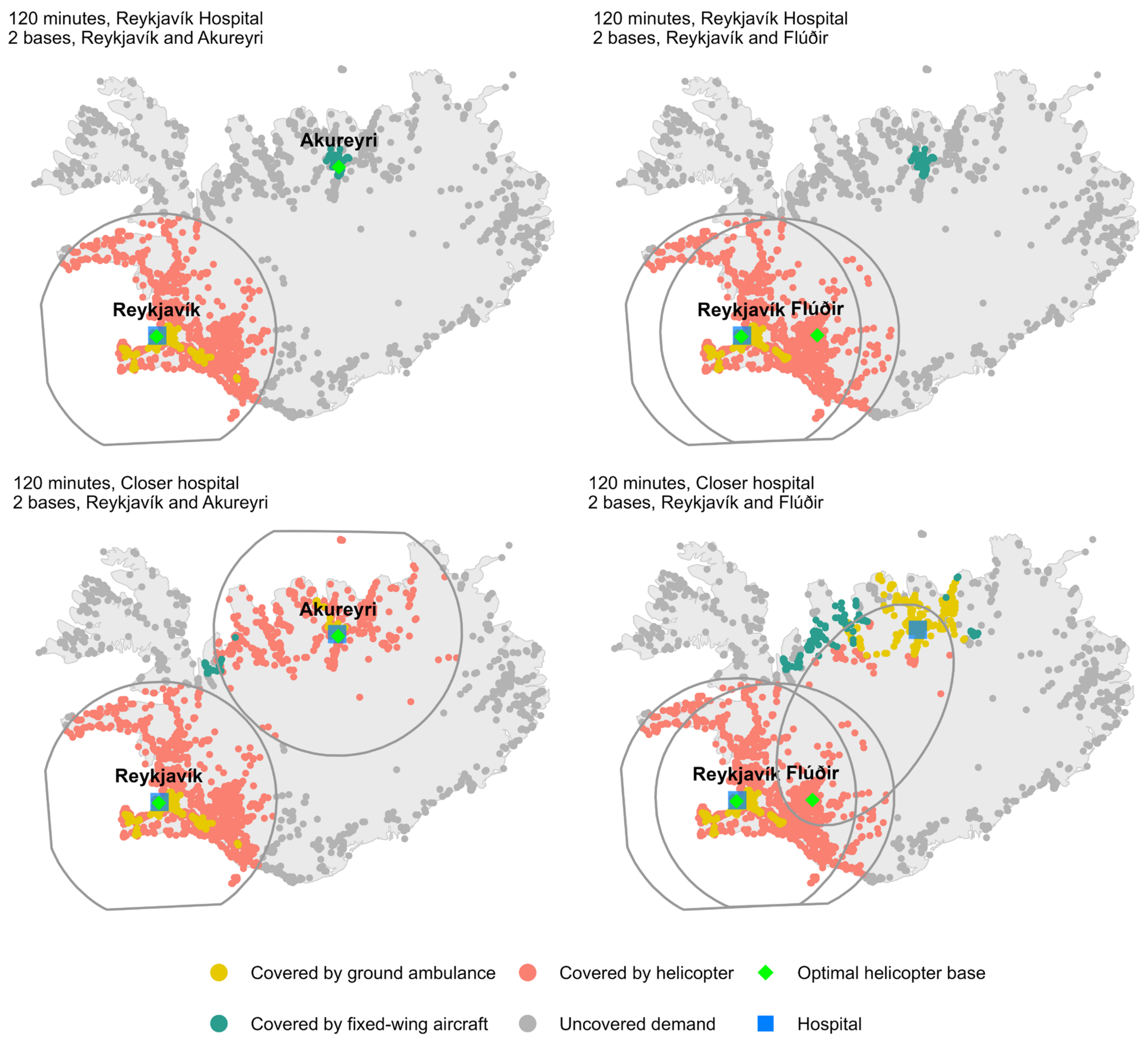

Fig. 6 Impact of the addition of a second helicopter base for 120 minutes

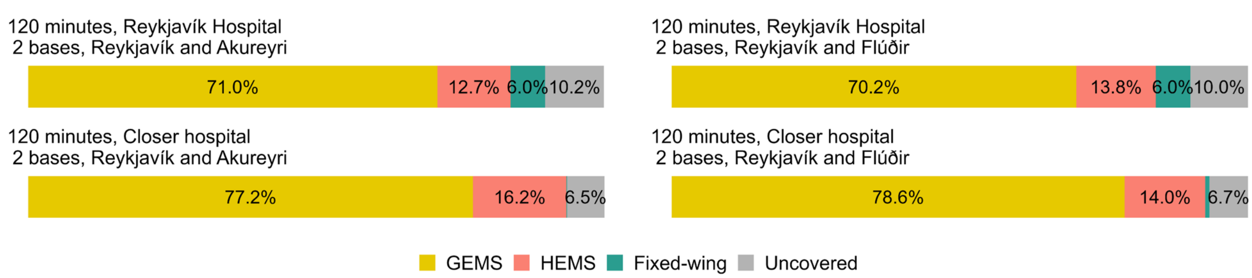

Fig. 7 Proportion of calls covered by each mode for 120 minutes

technical errors, or usability barriers during testing, suggesting a strong foundation for reliability and robustness in operational settings.

However, several participants raised concerns regarding the accuracy of the travel time estimates. Three respondents (30%) expressed that the app might

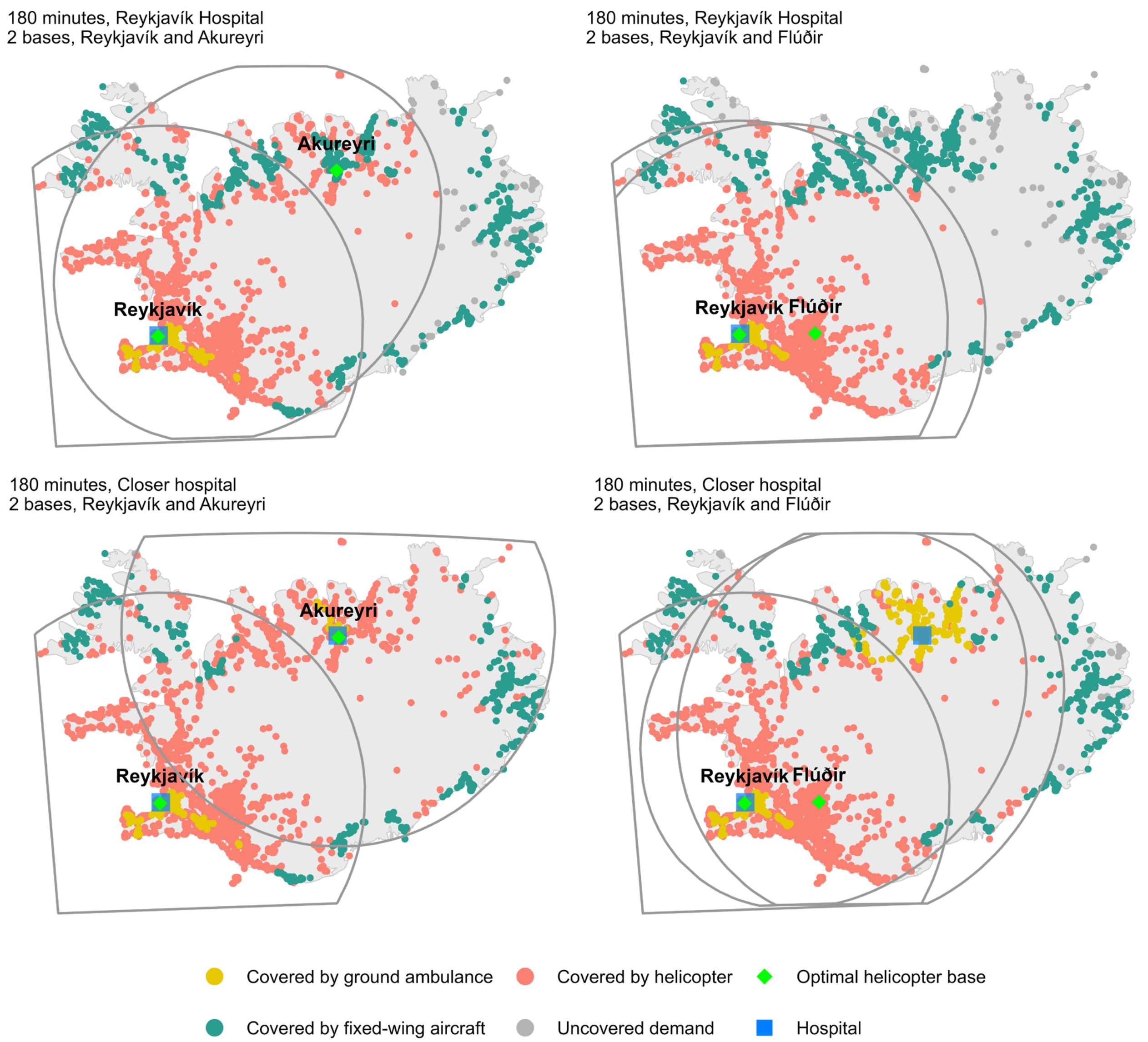

Fig. 8 Impact of the addition of a second helicopter base for 180 minutes

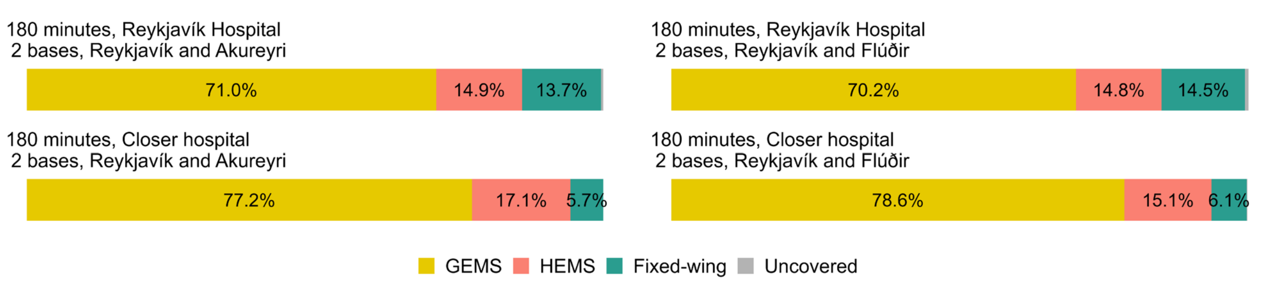

Fig. 9 Proportion of calls covered by each mode for 180 minutes

underestimate travel durations, especially if ambulances are unavailable due to concurrent missions or if severe weather delays dispatch or travel. These concerns are valid, particularly in the Icelandic context, where emergency service capacity is limited and weather can significantly affect travel times. This feedback highlights the need to incorporate dynamic data sources—such as real-time weather and vehicle availability—into future versions of the app to enhance prediction accuracy and reliability.

Despite these limitations, participants noted several potential use cases that demonstrate the app's practical value. Respondents emphasized its utility within emergency dispatch and coordination centers, where fast comparative estimates for different transport modes can support rapid decision-making. Hospital staff, particularly those in urban centers managing patient discharges to remote locations, could benefit from the app's overview of transport options—especially if unfamiliar with rural infrastructure or availability constraints. The app's ability to compare transport modes (GEMS, HEMS, and fixed-wing aircraft) was viewed as particularly beneficial in rural areas where availability varies due to weather or concurrent operations. In such contexts, the app offers an evidence-based method for selecting the most efficient and context-appropriate transport option.

Discussion

A strength of this study is the quality of the data regarding incident locations and travel times. We obtained a nationwide incident dataset with minimal spatial aggregation, using 1 km^2 squares. This approach should scale reasonably for countries like Norway, which is approximately four times Iceland's area. For larger countries, increased aggregation might be necessary to reduce computational complexity. We used fixed-wing aircraft flying time data to estimate realistic flying times and we used the HERE mapping service to estimate driving times that incorporate road distances and speed limits. This level of detail allows us to avoid assumptions made in previous studies, such as estimating travel times based on assumed average speeds for ground and air ambulances [4, 8, 36]. Furthermore, some previous research either analyzed coverage solely with HEMS [7, 36] or used an ad-hoc approach to omit incidents near hospitals, assuming that they could be covered by GEMS [4]. Our study's inclusion of GEMS, HEMS, and fixed-wing aircraft better reflects the situation in Iceland, where fixed-wing aircraft play a significant role. Another strength of this study is the focus on total pre-hospital time. Most prior studies prioritize response time, but both response time and total pre-hospital time play crucial roles in patient outcomes. Response time is vital for quick patient retrieval in SAR missions and for rapid arrival of medical expertise and equipment for interventions like field intubation. Pre-hospital time is crucial for patients who require swift transport to a hospital.

The data that we use has some limitations. Our incident data does not provide sufficient information to determine the most appropriate hospital for each patient, which led us to use a best-case vs. worst-case approach to model hospital choice. We note that in reality, the most appropriate hospital could vary across incidents that occur at the same location. The median fixed-wing activation time that we used exceeds a 35-minute performance target, and we suspect that fixed-wing activation time data might be unreliable. The HEMS activation time that we use omits the interval from a call reaching the 112 emergency number until assistance from the Coast Guard is requested [22]. We assumed that HEMS can transport patients directly to Reykjavík Hospital. However, Reykjavík Hospital has two campuses and only one of them has a helipad, meaning patients requiring treatment at the campus without a helipad must first land at Reykjavík Airport and then transfer by GEMS, which can cause treatment delays (6-minute driving time, according to Google Maps, and 37 minutes in total until coronary intervention started, according to [22]).

Our modeling of hospital choice raises the question of whether the real situation is closer to the worst case, in which each patient must be transported to Reykjavík Hospital, or to the best case, in which each patient is transported to the closer of the two hospitals. Our fixed-wing aircraft data indicates that of 409 patients of the two highest priority levels, 86.3% were transported to Reykjavík and 13.7% to Akureyri. For HEMS, of 578 patients transported by helicopter from 2015 to 2022, 91.6% were transported to Reykjavík and 2.9% to Akureyri [22]. Using the location information in our incident data and our estimated GEMS driving times, we find that 87.0% of the incidents are closer to Reykjavík and the remaining 13.0% are closer to Akureyri. To compare these statistics to our model results, we analyzed one problem instance, in which patients were transported to the closest hospital, the time standard was 180 minutes, and there were two HEMS bases, in Reykjavík and Akureyri. Based on the solutions to Problems 1 and 2, the split between transport to Reykjavík vs. Akureyri, by transport mode, was 31.4% vs. 68.6% for fixed wing, 84.5% vs. 15.5% for HEMS, and 91.3% vs. 8.7% for GEMS. Although this is not a comprehensive analysis, with the exception of fixed-wing transport, these observations suggest that reality is closer to the best case than the worst case. Therefore, the benefits of providing more services in Akureyri Hospital are are likely to be smaller than we have estimated.

There are important differences between SAR and HEMS. The current helicopter service based in Reykjavík is a SAR service, but it responds to medical emergencies as well. In our modeling, we assume that if additional helicopter bases are established, the activation time, scene time, and flying speed will be the same as for the current SAR base. The cost of establishing a second helicopter base includes the cost of purchasing (or leasing) and operating a helicopter, base infrastructure, and crew expenses. The cost depends on whether the delivery model is closer to SAR or to HEMS. A motion in 2025 to the Icelandic Parliament [37] proposed that one of the Coast Guard's three SAR helicopters be operated out of Akureyri, and estimated the startup cost (building a new hangar) to be 200–300 million ISK (1.4–2.1 million Euros) and the annual operating cost to be 500 million IKR (3.5 million Euros). These costs would be higher if a new SAR or HEMS helicopter were to be purchased or leased.

We assume that all vehicles (ground or air) are always available at their base. In reality, they could be unavailable because of weather, concurrent missions, maintenance, or other reasons. Regarding concurrency, a recent study [38] of Norwegian HEMS base locations reported an overall average busy fraction of 4.4% across 14 HEMS units responding to 4,280 calls per year, which corresponds to an average mission duration of 1.26 hours. Using this mission duration, with approximately 134 HEMS calls per year [22], the busy fraction of Icelandic HEMS would be only 1.9%. The number of HEMS calls per 100,000 population is about 37 in Iceland [22] and 82 in Norway [38]. Even if the introduction of a second HEMS base in Iceland were to more than double the number of HEMS calls, the estimated busy fraction would remain below that in Norway. The Norwegian study [38] found that because of the low busy fraction, the impact of concurrency on optimal base locations was small. The even smaller estimated busy fraction for Iceland suggests that not incorporating concurrency conflicts into our optimization model is an acceptable simplification.

Our model ignores multi-patient transport and interfacility transfers. We incorporate the combined use of GEMS and fixed-wing, but we ignore other combinations of transport modes that are sometimes used in practice and were mentioned by some of the app survey respondents. One example is the combined use of GEMS and HEMS, in which a ground ambulance and a helicopter travel towards a rendezvous point, from which the helicopter transports the patient to a hospital. Another example is the combined use of HEMS and fixed-wing, in which HEMS transports a patient from an incident location that is not reachable by GEMS (e.g., a hiker in a wilderness area) to a pickup airport, from which a fixed-wing aircraft transports the patient to a hospital (because the fixed-wing aircraft travels faster than the helicopter).

To put the coverage increase from adding a second HEMS base in perspective, our models suggest that for the current situation, HEMS is the fastest way to bring 8.7% of the 6,984 highest-priority incidents per year, or 608 incidents per year, to a hospital within 90 minutes. If a base were to be established in either Akureyri or Flúðir, an additional 1.4–1.5 pp, corresponding to 98 to 105 incidents, would be added.

In addition to coverage, other factors should be considered in selecting helicopter base locations. It is important for the base to have access to nearby infrastructure and essential services. In this regard, locating the base at Akureyri's international airport has significant advantages over the the small landing strip in Flúðir. Its proximity to Akureyri Hospital not only allows for better access to healthcare services but also enables staff members to work at both the hospital and for the air medical services. Akureyri is an urban area with more amenities and facilities than Flúðir, making it a more attractive place for crew members to live. These factors should make recruitment and retention of staff easier. The weather is another major factor as it determines the availability and effectiveness of helicopter ambulances. Flúðir is likely to experience similar weather patterns to Reykjavík, which can limit flight availability during adverse conditions. In contrast, Akureyri might experience different weather conditions, which means that when bad weather prevents helicopter flights from Reykjavík, Akureyri might still be operational, and vice versa. These operational capabilities support locating a second helicopter base farther from Reykjavík, such as in Akureyri rather than in Flúðir, as the location can provide comprehensive emergency medical services to a greater part of the country. Incident frequency is another important factor. The south of Iceland experiences higher rates of severe traffic accidents, which could justify a base there to provide timely medical response. Furthermore, there are many summer cottages around Flúðir, which increases the area's population during vacation periods, underscoring the potential demand for EMS.

User testing highlighted both the feasibility and practical relevance of the app for real-world prehospital decision making. The user feedback underscores the importance of contextual awareness (e.g., weather, resource constraints) in time prediction models and points toward valuable directions for future development. We view this initial round of user testing as a crucial validation step that informs both short-term improvements and longer-term integration with national emergency services.

Conclusions

Akureyri and Flúðir are representative options for a second helicopter base location that have been discussed in Iceland in recent years. Our findings show that the increase in coverage provided by these two bases is similar across a range of pre-hospital time standards, and is greatest, at 1.4–1.5 pp, for a 90-minute standard. The choice between Flúðir and Akureyri is not clear, due to important tradeoffs including coverage, fairness, and surrounding infrastructure. Our study provides information that helps clarify the nature of the tradeoffs and presents a methodology that can be adapted for other countries aiming to select optimal helicopter base locations.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13049-025-01504-1.

Additional file 1. Driving time and flying time estimation

Additional file 2. Algorithms and proofs

Additional file 3. Detailed survey results

Acknowledgements

Not applicable.

Clinical trial number

Not applicable.

Authors' contributions

All authors read and approved the final manuscript.

Funding

We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) [funding reference number RGPIN-2019-04355], a Francis Winspear Fellowship from the Alberta School of Business, University of Alberta, and RANNÍS (The Icelandic Centre for Research).

Data availability

We do not have permission to share our data. We will share our R code upon request.

Declarations

Ethics approval and consent to participate

We applied to the Icelandic national bioethics committee, for study permission, which determined that ethics approval was not required (referral number 22-125).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 13 June 2025 Accepted: 28 October 2025
Published online: 27 November 2025

References

1. Chen X, Gestring ML, Rosengart MR, Peitzman AB, Billiar TR, Sperry JL, et al. Logistics of air medical transport: when and where does helicopter transport reduce prehospital time for trauma? J Trauma Acute Care Surg. 2018;85(1):174–81. https://doi.org/10.1097/TA.0000000000001935.
2. Diaz MA, Hendey GW, Bivins HG. When is the helicopter faster? A comparison of helicopter and ground ambulance transport times. J Trauma Acute Care Surg. 2005;58(1):148–53. https://doi.org/10.1097/01.TA.0000124264.43941.41.
3. Church R, ReVelle C. The maximal covering location problem. Pap Reg Sci. 1974;32(1):101–18. https://doi.org/10.1111/j.1435-5597.1974.tb00902.x.
4. Gunnarsson B, Björnsdóttir KM, Dúason S, Ingólfsson Á. Locating helicopter ambulance bases in Iceland: efficient and fair solutions. Scand J Trauma Resusc Emerg Med. 2023;31(1):70. https://doi.org/10.1186/s13049-023-01114-9.
5. Røislien J, van den Berg PL, Lindner T, Zakariassen E, Aardal K, van Essen JT. Exploring optimal air ambulance base locations in Norway using advanced mathematical modelling. Inj Prev. 2017;23(1):10–5. https://doi.org/10.1136/injuryprev-2016-041973.
6. Røislien J, van den Berg PL, Lindner T, Zakariassen E, Uleberg O, Aardal K, et al. Comparing population and incident data for optimal air ambulance base locations in Norway. Scand J Trauma Resusc Emerg Med. 2018;26(1):1–11. https://doi.org/10.1186/s13049-018-0511-4.
7. Garner AA, van den Berg PL. Locating helicopter emergency medical service bases to optimise population coverage versus average response time. BMC Emerg Med. 2017;17:31. https://doi.org/10.1186/s12873-017-0142-5.
8. Erdemir ET, Batta R, Rogerson PA, Blatt A, Flanigan M. Joint ground and air emergency medical services coverage models: a greedy heuristic solution approach. Eur J Oper Res. 2010;207(2):736–49. https://doi.org/10.1016/j.ejor.2010.05.047.
9. Bozorgi-Amiri A, Tavakoli S, Mirzaeipour H, Rabbani M. Integrated locating of helicopter stations and helipads for wounded transfer under demand location uncertainty. Am J Emerg Med. 2017;35(3):410–7. https://doi.org/10.1016/j.ajem.2016.11.024.
10. Krafft T, Castrillo-Riesgo LG, Edwards S, Fischer M, Overton J, Robertson-Steel I, et al. European emergency data project (EED Project) EMS data-based health surveillance system. Eur J Public Health. 2003;13(suppl_1):85–90. https://doi.org/10.1093/eurpub/13.suppl_1.85.
11. Chen X, Guyette FX, Peitzman AB, Billiar TR, Sperry JL, Brown JB. Identifying patients with time-sensitive injuries: association of mortality with increasing prehospital time. J Trauma Acute Care Surg. 2019;86(6):1015–22. https://doi.org/10.1097/TA.0000000000002251.
12. Eisenberg MS, Bergner L, Hallstrom A. Cardiac resuscitation in the community: Importance of rapid provision and implications for program planning. JAMA. 1979 05;241(18):1905–1907. https://doi.org/10.1001/jama.1979.03290440027022.
13. Mulder MJ, Jansen IG, Goldhoorn RJB, Venema E, Chalos V, Compagne KC, et al. Time to endovascular treatment and outcome in acute ischemic stroke: MR CLEAN registry results. Circulation. 2018;138(3):232–40. https://doi.org/10.1161/CIRCULATIONAHA.117.032600.
14. Powers WJ, Rabinstein AA, Ackerson T, Adeoye OM, Bambakidis NC, Becker K, et al. Guidelines for the early management of patients with acute ischemic stroke: 2019 update to the 2018 guidelines for the early management of acute ischemic stroke: a guideline for healthcare professionals from the American Heart Association/American Stroke Association. Stroke. 2019;50(12):e344-418. https://doi.org/10.1161/STR.0000000000000211.
15. O'Gara PT, Kushner FG, Ascheim DD, Casey DE Jr, Chung MK, de Lemos JA, et al. 2013 ACCF/AHA guideline for the management of ST-elevation myocardial infarction: executive summary. Circulation. 2013(4). https://doi.org/10.1161/CIR.0b013e3182742c84.
16. Branas CC, MacKenzie EJ, ReVelle CS. A trauma resource allocation model for ambulances and hospitals. Health Serv Res. 2000;35(2):489–507.
17. Branas CC, Wolff CS, Williams J, Margolis G, Carr BG. Simulating changes to emergency care resources to compare system effectiveness. J Clin Epidemiol. 2013;66(8):S57–64. https://doi.org/10.1016/j.jclinepi.2013.03.021.

18. Zhang M, Zhang Y, Qiu Z, Wu H. Two-stage covering location model for air–ground medical rescue system. Sustainability. 2019. https://doi.org/10.3390/su11123242.
19. Markhorst B, Jagtenberg C, Hov MR, van der Mei R, Larsen K. Optimizing mobile stroke unit deployment: A strategic case study in the greater Oslo area. Eur Stroke J. 2025;Advance online publication. https://doi.org/10.1177/23969873251329862.
20. Magnússon V. Sjúkraflutningar með þyrlum [Medical transport by helicopter]; 2017. In Icelandic, published by the Icelandic Ministry of Health. https://www.stjornarradid.is/gogn/rit-og-skyrslur/stakt-rit/2017/06/27/Sjukraflutningar-med-thyrlum/. Accessed 3 Nov 2025.
21. Gunnarsson B, Björnsdóttir KM, Dúason S. Air ambulance service from Akureyri, Iceland 2012-2020. Laeknabladid. 2022;108(3):137–42. https://doi.org/10.17992/lbl.2022.03.682.
22. Stefansson SO, Magnusson V, Sigurdsson MI, Helicopter emergency medical services in Iceland between,. and 2022-A retrospective study. Acta Anaesthesiol Scand. 2018;2024. https://doi.org/10.1111/aas.14509.
23. Neyðarlínan. The Emergency Line. 2023. https://www.112.is. Accessed 6 Oct 2023.
24. QGIS Development Team. QGIS Geographic Information System. 2023. https://www.qgis.org. Accessed 7 Sep 2023.
25. American Trauma Society. Trauma center levels explained. 2024. https://www.amtrauma.org/page/traumalevels. Accessed 26 Mar 2024.
26. Budge S, Ingolfsson A, Zerom D. Empirical analysis of ambulance travel times: the case of Calgary Emergency Medical Services. Manage Sci. 2010;56(4):716–23. https://doi.org/10.1287/mnsc.1090.1142.
27. Kolesar P, Walker W, Hausner J. Determining the relation between fire engine travel times and travel distances in New York City. Oper Res. 1975;23(4):614–27. https://doi.org/10.1287/opre.23.4.614.
28. Dodds N, Emerson P, Phillips S, Green DR, Jansen JO. Analysis of aeromedical retrieval coverage using elliptical isochrones: an evaluation of helicopter fleet size configurations in Scotland. J Trauma Acute Care Surg. 2017;82(3):550–6. https://doi.org/10.1097/TA.0000000000001335.
29. Fishburn PC. Exceptional paper–lexicographic orders, utilities and decision rules: a survey. Manage Sci. 1974;20(11):1442–71. https://doi.org/10.1287/mnsc.20.11.1442.
30. Taylor CB, Stevenson M, Jan S, Middleton PM, Fitzharris M, Myburgh JA. A systematic review of the costs and benefits of helicopter emergency medical services. Injury. 2010;41(1):10–20. https://doi.org/10.1016/j.injury.2009.09.030.
31. Schumacher D. ompr: Model and solve mixed integer linear programs. 2023. R package version 1.0.4. https://github.com/dirkschumacher/ompr. Accessed 5 July 2023.
32. Makhorin A. GNU Linear Programming Kit. 2023. http://www.gnu.org/software/glpk/. Accessed 5 July 2023.
33. Gurobi Optimization, LLC. Gurobi Optimizer Reference Manual. 2023. https://www.gurobi.com. Accessed 5 July 2023.
34. Huangfu Q, Hall JJ. Parallelizing the dual revised simplex method. Math Program Comput. 2018;10(1):119–42. https://doi.org/10.1007/s12532-017-0130-5.
35. Chang W, Cheng J, Allaire J, Sievert C, Schloerke B, Xie Y, et al. Shiny: web application framework for R. 2024. R package version 1.8.1.9001. https://github.com/rstudio/shiny. Accessed 5 Jan 2023.
36. Jagtenberg CJ, Uleberg O, Waaler Bjørnelv GM, Røislien J. Utopia for Norwegian helicopter emergency medical services: estimating the number of bases needed to radically bring down response times, and lives needed to be saved for cost effectiveness. PLoS One. 2023;18(3):e0281706. https://doi.org/10.1371/journal.pone.0281706.
37. Friðbertsson NT. Tillaga til þingsályktunar um fasta starfsstöð þyrlu Landhelgisgæslunnar á Akureyri. [Proposal for a Coast Guard helicopter base in Akureyri]. 2025. In Icelandic, motion proposed to the Icelandic Parliament. https://www.althingi.is/altext/156/s/0041.html. Accessed 3 Nov 2025.
38. Røislien J, van den Berg PL, van Essen JT, Uleberg O, Jagtenberg C. The impact of concurrency conflicts on optimal location of air ambulance bases in Norway. Scand J Trauma Resusc Emerg Med. 2025;33:57. https://doi.org/10.1186/s13049-025-01324-3.