Selection of rural villages as volunteer centers for emergency response

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ABSTRACT

Rural areas are typically sparsely populated, and coverage from emergency services is weak. In some such areas in Sweden, professional emergency services train civilian volunteers in providing help for certain types of emergencies. In case of an emergency, they are alerted on their mobile phones and are primarily expected to provide help in the vicinity of their homes. Due to limited resources, it is impossible to include all villages in the volunteer initiative, making the selection of the most beneficial villages for emergency response important. However, this decision is not always trivial to make. Therefore, we propose an optimization model to determine which villages should be included in this initiative to achieve the best possible emergency response coverage. The model is used in a case study for a large Swedish fire and rescue service organization, and based on the results, they have started volunteer centers in two villages.

Keywords

Volunteers, Civilian first responders, Optimization, Coverage, Emergency response.

INTRODUCTION

Emergency services have a pivotal role for managing emergencies ranging from daily emergencies (frequent events that have low consequences such as traffic accidents (Quarantelli, 1995)) to disasters, which happen seldomly but have high level of consequence. To manage any type of emergency, these organizations use different resources, including personnel, physical equipment, and information. However, the availability of these resources plays an important role in their service delivery (Matinrad, 2022). In recent years, emergency services have been facing different challenges, including cost pressures and budget cutbacks as well as long distances to sparsely populated areas (Yousefi Mojir & Pilemalm, 2016). The occurrence of the COVID-19 pandemic also showed how these challenges could be exacerbated under extreme situations. Shortage of resources and longer travel distances translate to longer response times, especially for rural and sparsely populated areas. Longer response times can lead to higher rate of damage to the properties and the environment, harm to human health, and higher mortality rates, for example in cases of cardiac arrest (Waalewijn et al., 2001) and fires (Jaldell, 2004 & 2017). Consequently, emergency services in recent years have tried to use additional resources that will not incur additional cost but can help them improve their response times. One such resource is civilians, who volunteer to help in case of emergencies in their vicinity.

In collaboration with the municipal fire and rescue services (FRS), volunteers in some villages in Sweden, where the emergency coverage is poor, are trained (and potentially equipped) for first response to a selected set of emergency types. The civilians in this initiative receive training in cardiopulmonary resuscitation (CPR), first aid, extinguishing of small fires, and required actions when a person first arrives at some emergencies (e.g., a fire or a traffic accident) (Hallström et al., 2017). These trained civilians are, simultaneous with the dispatch of emergency services, notified of an emergency through a short message service (SMS) or an application on their mobile phones. Training and potentially equipping civilians in rural areas requires monetary and time investment from the emergency services. However, as the FRS have budget (and personnel) restrictions, it is not possible to include a large number of civilians and villages in such a volunteer initiative, especially not in the first round. While a major part of the cost is setup, there are also running costs for maintaining the volunteer centers, including costs for continuous training, and possibly equipment. It is therefore important to initially select a number of villages that both meet a few minimum requirements for inclusion and gives the best improvement for the emergency response system. However, it is not always trivial to determine which villages will give the most benefit. A possible solution for this problem is to use optimization and develop a model that can take into account the required factors. However, such a model also needs to be comprehensible for the practitioners, which means that a simpler model that can fulfill the purpose might be more suitable than a very complex one.

The aim of the paper is to develop an optimization model to determine which rural villages should be included in a volunteer first response initiative, so that the population in the region receive the best possible emergency coverage from FRS and the volunteer initiative.

The rest of this paper is organized as follows. In the next section, we provide a brief overview of the related literature and positioning of this work with respect to the literature. In the following section, we present the problem description as well as the proposed optimization model. Then, we describe the numerical experiments, detailing the case study, where we help an FRS organization to select rural villages to use as volunteer centers, and the results. Finally, in the last section, we present conclusions and future research directions.

PREVIOUS STUDIES

Emergency response coverage in rural areas in many countries, including Sweden, is weak. As Pilemalm et al. (2013) pointed out, most of Sweden can be considered rural, given that population centers are sparsely located and driving time (by a car) to the nearest town with more than 3000 residents takes more than 45 minutes from many areas. Therefore, strengthening the emergency response for rural areas becomes even more crucial. In the following, we briefly discuss some of the literature that are most relevant to this study.

Volunteer initiatives have emerged and increased in numbers over a relatively short amount of time as a potential solution to enhancing emergency response time and coverage, especially in rural areas. In some initiatives, volunteers respond to only a specific type of emergency (e.g., out-of-hospital cardiac arrest - OHCA). Examples include SMS lifesavers in Sweden (https://heartrunner.com/) and HartslagNu in the Netherlands (https://hartslagnu.nl/), but more examples can be found in several reviews such as Oving et al. (2019), Scquizzato et al. (2020), and Valeriano et al. (2021). In other initiatives, a wider range of emergency types is considered; examples are the enhanced neighbors project (Ramsell et al., 2017) and civilian response persons (Stenberg et al., 2014; Hallström et al., 2017) in Sweden. Here, volunteers respond to selected medical emergencies as well as small fires and traffic accidents. There are also initiatives in Germany for responding to medical emergencies (e.g., Gross et al. (2019)) and in Finland (Tamminen et al., 2019). Several studies, especially within the medical area, have examined the impact of volunteer responses on the outcome of the cases, showing that volunteers can reduce response times (see e.g., Auricchio et al. (2019), Berglund et al. (2018), Ringh et al. (2015), and Stroop et al. (2020)). Svensson et al. (2024) compared emergency service response times between rural and urban areas, showing a notable difference. They also showed that volunteers had the shortest median response times to OHCA compared to emergency medical services (EMS) and FRS. Similarly, Lapidus et al. (2023) showed that volunteers had shorter response times than EMS, especially in sparsely populated areas.

Two crucial aspects for being able to start and maintain volunteer initiatives, are to attract and motivate volunteers. Thus, it is important to understand which factors lead to the involvement of civilians in volunteer initiatives and why they might leave. Cowlishaw et al. (2008) raised family issues as a factor with direct impact on the decrease of the number of volunteers in rural areas. Timmons and Vernon-Evans (2013) as well as Barry et al. (2019) showed that one of the motivating factors for people to volunteer comes from a personal level, their "ideas of altruism and sense of community" and personal experiences of emergencies or illness. Choudhury (2010) stated that local government agencies are important bodies for attracting and managing volunteers.

In many volunteer initiatives, volunteers are alerted through their mobile phones, for example by SMS or specific mobile phone applications (Matinrad & Granberg, 2023). Initiatives such as the enhanced neighbors project relied on SMS for sending notifications to volunteers (Ramsell et al., 2017). SMS lifesavers also started using SMS, but later switched to a mobile phone application (Jonsson et al., 2020), while other initiatives, HartslagNu for example, use both SMS and a mobile phone application (Slaa, 2020). All these initiatives use some type of geographical positioning of the volunteers so that they can send the notification to the volunteers in the vicinity of the incident site. This geographical positioning can be static (i.e., registered addresses) or dynamic using Global Navigation Satellite Systems (GNSS). All these initiatives need some type of decision-making logic, which can be embedded in a decision support system (DSS). The underlying logic in an emergency DSS can be a simple rule such as the one used in SMS lifesavers initiative (Granberg et al., 2022) or it can be more advanced models (see e.g., Matinrad and Granberg (2023) and Frigstad et al. (2023)).

For rural areas, determining which villages that should be included in a volunteer first response initiative relies on different factors, where one crucial factor is the geographical distribution of the villages. While the literature on volunteer location studies is scarce, there are many studies to be found on the location of emergency service stations (see for example, van den Berg and Aardal (2015), Røislien et al. (2016), van den Berg et al. (2016), Garner and van den Berg (2017), and Jagtenberg and Mason (2020)) or public emergency equipment such as automated external defibrillators (AEDs) (e.g., Chan et al. (2013), Bonnet et al. (2015), and Yang et al. (2021)). The majority of these studies use a type of covering location model, such as the maximal coverage location problem (MCLP) (Church & ReVelle, 1974) or the maximum expected coverage location problem (MEXCLP) (Daskin, 1983). In some studies, such as Bonnet et al. (2015), a MCLP model is extended to incorporate more factors, including temporal aspects (e.g., accessibility of candidate locations across different times for AED locations) and amount of used resources (e.g., number of deployed devices).

In this paper, we address the problem of determining which rural villages that should serve as volunteer centers and present an optimization model that aims to maximize the population coverage, with regards to both volunteer and FRS response. To the best of our knowledge, this is the first optimization model for such a problem. Given the simplicity of the model, it is easily comprehensible for practitioners. Results from the model are currently being utilized in an ongoing volunteer initiative in Sweden for creating volunteer centers across rural areas in order to improve the emergency response system.

PROBLEM DESCRIPTION AND MATHEMATICAL MODEL

In this section, we will first briefly describe the problem statement as well as assumptions that we have made, and then, we will present the optimization model.

Problem Statement and Assumptions

The problem, Selection Of Rural Villages as Volunteer centers for Emergency response (SORVIVE), deals with *determining which rural villages should be included in the volunteer response initiative, aiming to improve the emergency response coverage, considering the current professional emergency service system*.

In this problem, we have made a few assumptions:

- The candidate villages are known and have at least five people that are willing to volunteer and respond to emergencies if they are notified. It is hypothetically possible to consider all villages as candidates, but since one person will not always be able to respond, more than one volunteer is needed to get any effect. Furthermore, in these kinds of initiatives, the volunteers prefer not to be the only one responding to an incident (Ramsell et al., 2017). Thus, it is preferable that the candidate villages have at least five residents willing to volunteer.
- Volunteers in the selected villages are assumed to primarily respond to emergencies within their own villages. However, if their neighboring villages are within a reasonable distance, they can receive help as well.

In Figure 1, we show a schematic representation of the SORVIVE problem, with two FRS stations in the area, and four selected villages that will function as volunteer centers. Note that in this schematic representation, we have considered different coverage radius for different villages, given the size of the villages and their geographical position, and a 20-minute coverage radius for the FRS stations. Each of these volunteer centers will cover a subset of villages and towns (population centers) that can be divided into population squares.

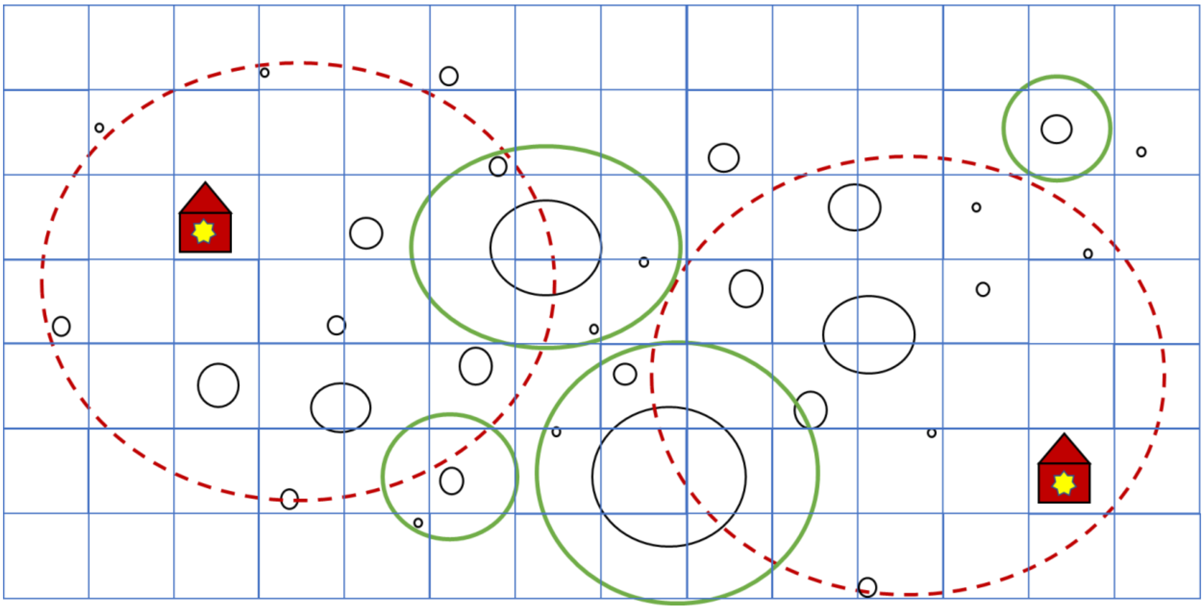

Figure 1. Schematic representation of the problem.
The small black circles represent rural villages, and the blue squares represent population squares; the dashed red circles show the coverage radius of FRS with the red houses representing the FRS stations, and the solid green circles show the coverage area of selected population squares anchored around a village.

Model Formulation

As input to the mathematical formulation of the SORVIVE problem, we know where the FRS stations as well as candidate volunteer centers across a specific region are located. We can also divide the whole region into squares where we know the resident population in each square, and calculate all distances between stations, centers, and squares. We also know the coverage radius for volunteer centers (either individually based on their size and location or a common radius for all of them) and the maximum service time to reach a population center from an FRS station. It is also known how many volunteer centers are planned to be established. The model determines which candidate volunteer centers that are selected, and which population squares they cover.

We have used the following notation in the mathematical formulation of the SORVIVE problem:

Sets and indices

$I = \{1, \dots, m\}$	Set of candidate volunteer centers, indexed by $i \in I$
$K = \{1, \dots, o\}$	Set of population squares, indexed by $k \in K$
$J = \{1, \dots, n\}$	Set of FRS stations, indexed by $j \in J$

Parameters

s_k	Total number of people in population square *k*
z_{jk}	Equals to 1 if FRS station *j* covers population square *k*; otherwise, 0
df_{kj}	(Shortest) response time (i.e., preparation time plus travel time) between FRS station *j* and population square *k*
dp_{ik}	(Shortest) response time between volunteer center *i* and population square *k*
P	Maximum number of volunteer centers
D_i	Coverage radius of volunteer center *i*
L_j	A predefined maximum service time to reach a region from FRS station *j* within a given time

Decision variables

y_i	Equals to 1 if volunteer center is established in *i*; otherwise, 0
x_k	Equals to 1 if population square *k* is covered; otherwise, 0
w_{ik}	Equals to 1 if volunteer center at village *i* covers population square *k*; otherwise, 0

The SORVIVE problem is thus formulated as an integer programing (IP) model:

$$max \sum_{k \in K} s_k x_k \quad (1)$$

$$\sum_{i \in I} y_i \leq P \quad (2)$$

$$D_i y_i \geq dp_{ik} w_{ik} \qquad \forall i \in I, k \in K \quad (3)$$

$$\sum_{i \in I} w_{ik} \leq 1 \qquad \forall k \in K \quad (4)$$

$$x_k \leq \sum_{i \in I} w_{ik} + \sum_{j \in J} z_{jk} \qquad \forall k \in K \quad (5)$$

$$y_i, w_{ik}, x_k \in \{0,1\} \qquad \forall i \in I, j \in J, k \in K \quad (6)$$

The objective function (1) maximizes the weighted coverage of the population squares, where the weight is the population. Constraint (2) is defined to limit the number of the selected volunteer centers to P. Constraint set (3) determines which population squares a selected volunteer center covers; coverage is possible if the travel time between a center and a square is shorter than the predefined coverage radius for the volunteer center. Constraints (4) ensure that each square is covered by a maximum of one volunteer center. Constraint set (5) determines whether a square is covered or not, where the coverage can be by FRS stations, by a volunteer center, or by both FRS stations and a volunteer center. Constraints (6) are the binary constraints for the variables.

NUMERICAL EXPERIMENTS

In the following, we first present a short description of the case study that we used to test and validate the model and then, we present the numerical results.

Case Description

We used the area of a large FRS organization (Räddningstjänsten Östra Götaland, RTÖG) in Östergötland county in Sweden as our use case. Östergötland is located at the south-east of Sweden with a population of over 470 000 inhabitants and an area of 9 979 square kilometers, leading to a population density of approximately 47.1 inhabitants per square kilometers. Östergötland is divided into 13 municipalities, and RTÖG is responsible to provide FRS in five of these, that together have about 341 140 (72.6% of the county total) inhabitants and spans an area of 5 270 square kilometers (53% of the county). In RTÖG's area of responsibility, there are a total of 120 populations centers, including cities, towns, and villages. A subset of these (the ones where we expect to be able to recruit at least five volunteers) are used as potential volunteer centers. The area is also divided into a set of 6084 population squares, with a known number of permanent residents. This is done to get a detailed view of the expected coverage from fire stations and volunteers centers.

RTÖG currently has 20 fire stations: four fulltime stations, 12 part-time stations, and four volunteer stations. At the fulltime stations, there is always at least one unit (typically consisting of four firefighters and one commander) present. They have a preparation time (i.e., the time from when the alert comes to the station until the resources leave the station) of 90 seconds. At the part-time stations, the firefighters have preparedness at home or at their regular job. When there is an alert, they will go to the station to prepare and leave in an appropriate vehicle. Thus, their preparation time is longer than for the fulltime firefighters, being 300 seconds (five minutes). Volunteer firefighters do not have preparedness and are thus not obligated to respond when there is an alert (although many will do so). Otherwise, a volunteer station is much like a part-time station. There is no set preparation time, since response is voluntary, but for calculation purposes, we use 300 seconds. Volunteer firefighters, and volunteer FRS stations, are different from the civilian volunteer centers that we locate in this case study. While the volunteer firefighters have training, clothes, vehicles and a fire station to which they go before responding, the civilian first response volunteers that are to be trained at the volunteer centers, will have much more limited training and equipment, and will typically respond directly from where they are when they get the alert.

RTÖG plans to start some volunteer centers across the county, and as their starting goal, they plan to begin with initiating two centers. Thus, our initial target for locating volunteer centers is $P = 2$. As previously indicated, the location of all population centers as well as FRS stations are known, and thus, travel times between each pair of these locations can be easily calculated. We used ArcGIS 10.6.1, utilizing the Network Analyst module to calculate these, based on the Swedish national road database, and using shortest path calculations with the speed limit and link length to estimate the time it takes to travel on a link.

We considered the service radius for all FRS stations (fulltime, part-time, and volunteer) to be 1200 seconds (20 minutes) and for the volunteer centers to be 600 seconds (10 minutes). The preparation time for the fulltime stations was set to 90 seconds, while this time for part-time and volunteer FRS stations was set to 300 seconds.

We considered two scenarios where volunteers had either 90 seconds or 300 seconds preparation time, since real preparation times for volunteers are difficult to estimate. In one additional setting, as a verification, we excluded the volunteer FRS stations from the set of FRS stations, which resulted in a total of 16 stations (rather than the original 20).

In Figure 2, we show the primary coverage areas for the 20 FRS stations, where the border is reached within 20 minutes of driving from a station; the volunteer FRS stations are shown with the red triangles and the remaining are fulltime and part-time FRS stations.

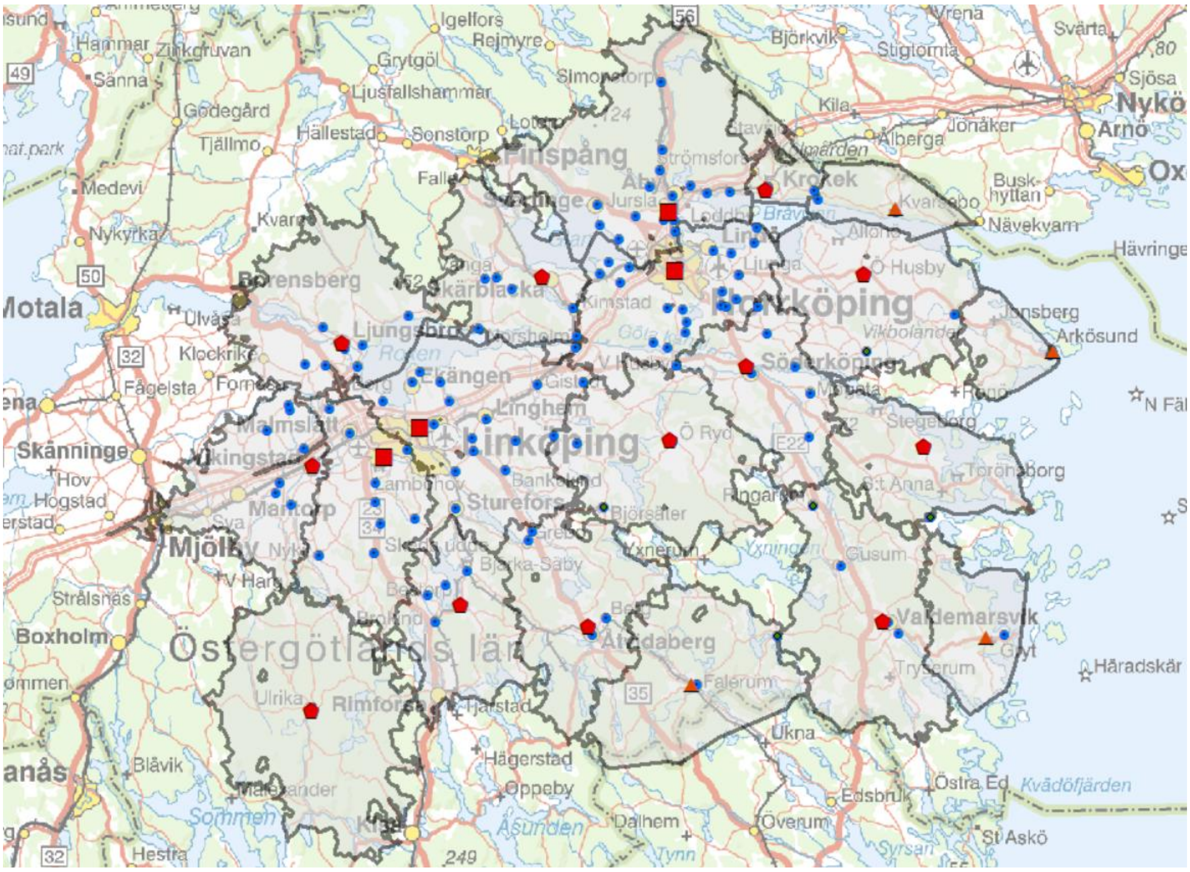

Figure 2. All FRS stations in RTÖG, with 20 minutes service areas.
The red squares represent full time stations, the pentagons part time stations, and the triangles are volunteer FRS stations. The small blue circles are potential locations for volunteer centers

Numerical Results

First, we ran the model with a dataset in which the four volunteer FRS stations were not included as FRS stations, for different values of the parameter P, ranging from 2 to 5. When the model was run for $P = 2$, the selected volunteer centers overlapped with two of the existing volunteer FRS stations, which validates both the existing location of the volunteer FRS stations, and the usefulness of the model.

In Figure 3, we show the results of the model, where $P = 5$ and volunteers have 90 seconds preparation time. Three of the selected volunteer centers overlap with existing volunteer FRS stations and another center is relatively close to the fourth volunteer station in the southern part of the county. In this figure, volunteer center allocation to population squares are shown with brown lines, to squares they can reach within 10 minutes.

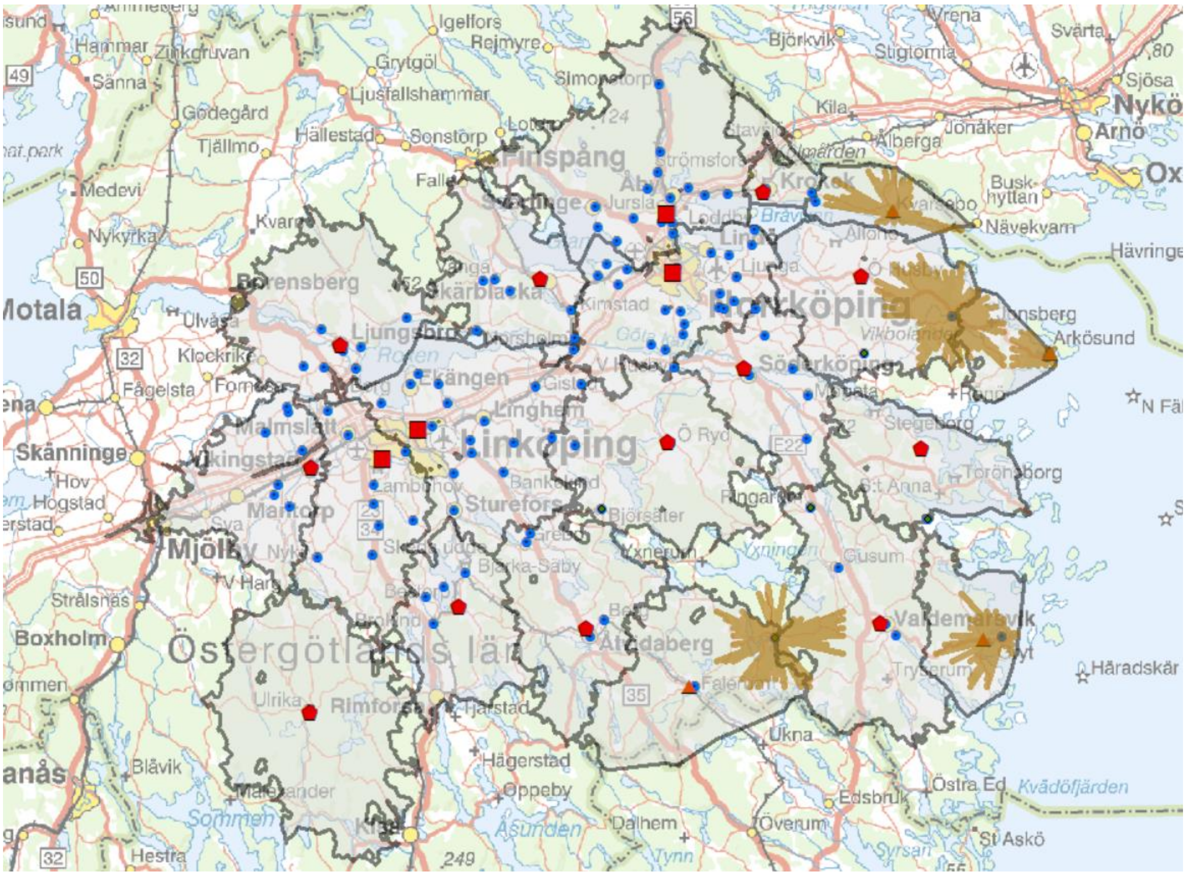

Figure 3. Location of five volunteer centers with 90 seconds preparation time, not considering volunteer FRS stations

Then, we wanted to compare output of the model when including all stations (20 stations) and investigate how different preparation times might affect the coverage. In Table 1, we present results for $P = 2$ but for different setups where volunteers had 90 seconds or 300 seconds as their preparation time. For both setups, the model produces the same optimal locations, indicating stability of the model in producing the results, that is, the variability in preparation time does not affect which centers that are opened, and has only a marginal impact on the coverage. As expected, with the longer volunteer preparation time, a slight decrease in the total coverage rate can be seen as the response time (preparation time plus travel time to the scene) becomes longer. The decrease can, however, be considered fairly small.

Table 1. Comparison of coverage for different data setups, $P = 2$

Row	Data setup	Total number of covered people	Total coverage
1	90 seconds, 20 stations	335 381	98.3%
2	300 seconds, 20 stations	335 293	98.3%

Finally, we ran the model with all 20 FRS stations included, volunteers had 90 seconds preparation time (and 10 minutes coverage radius), and for different values of P. The result of this test for $P = 5$ is visualized in Figure 4. The solid, red circle (Ringarum) shows one of the first selected volunteer centers by the model (i.e., when the model was run for $P = 2$); according to RTÖG, the FRS used to have a part-time fire and rescue service station there, that was closed down in recent years. However, as we can see, parts of the Ringarum area receives a poor coverage from the closest FRS stations, which was also confirmed by RTÖG. Consequently, locating a volunteer center in that region, as shown in Figure 4, was considered reasonable by RTÖG. The dashed, blue circle in Figure 4 is around Ramsdal, the second village which was selected by RTÖG to be a volunteer center, and the second village selected by the model for $P = 2$. Ringarum had a population of 606 residents in 2020 and Ramsdal had 50, but together they cover a total of 3003 inhabitants within 10 minutes. After the selection of these two villages, RTÖG started recruitment and training of volunteers in these two locations.

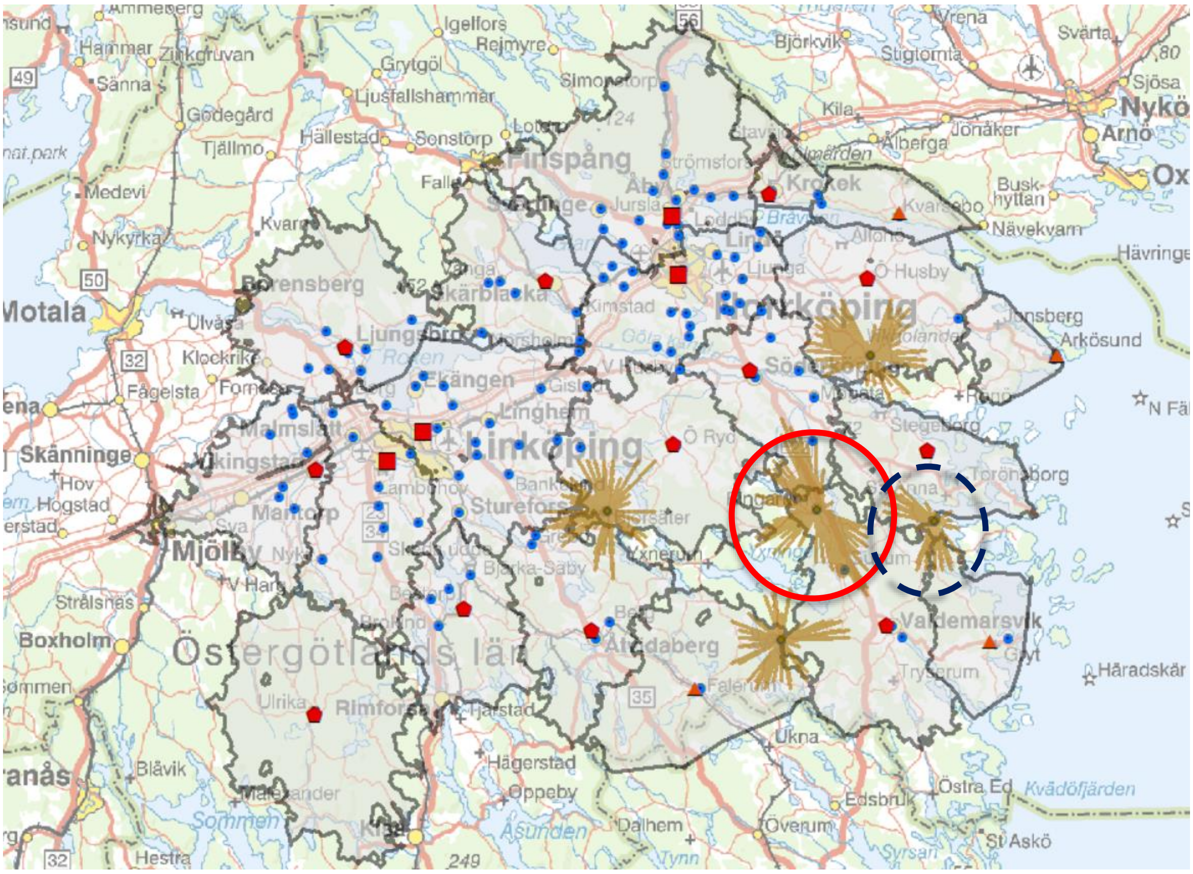

Figure 4. Location of five volunteer centers with 90 seconds preparation time, considering all 20 FRS stations

CONCLUSIONS AND FUTURE STUDIES

In this work, we proposed a simple coverage model for the selection of rural villages as volunteer centers to improve emergency response coverage. The model showed promising results, which were acceptable for practitioners (i.e., the largest FRS organization in Östergötland), and the simplicity of the model makes it easy for them to understand and utilize it. Thus, they picked a solution from the model, and have started volunteer centers in two new villages in Östergötland. This shows that the model is useful as a practical decision support tool. We are now following the implementation process, and when the volunteer initiative has matured, and the volunteers in these two villages have responded to enough events, we will evaluate the practical effects of the initiative. This should give valuable insight into how information system facilitated volunteerism, combined with operations research-based techniques can help improve the emergency response system.

The optimization model can be further extended by considering additional aspects, such as minimizing response times, incorporating uncertain elements, and including budget constraints. However, this must be done carefully, so that the comprehensibility of the model is not lost. Moreover, further research directions related to the volunteer initiative can include studies aimed at assessing the effectiveness of volunteer response and other aspects that should or could be incorporated.

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