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FROM POLITICS TO MATHEMATICS

Exploring optimal air ambulance base locations in Norway

In Norway the nationwide physician-manned air ambulance service is considered essential in order to achieve the desired equality in healthcare. Yet, the location of the air ambulance bases has rarely been approached by the scientific community. A collaboration between mathematicians in the Netherlands and medical researchers in Norway is exploring the optimal location of air ambulance bases using mathematical modelling. The research has produced numerous novel insights, demonstrating that population coverage could be increased by moving existing bases, and that openly available population data might not be a reasonable proxy for actual incident data.

Jo Røislien

On May 12, 2014, Norwegian national broadcaster NRK published a news story that created a stir: "166,000 people do not receive help from a medical helicopter within 45 minutes." Placing a pair of compasses at each of the existing 12 air ambulance bases in Norway and drawing circles, combined with openly available population data from Statistics Norway, the journalists could simply count how many Norwegians could be reached by a medical helicopter within 45 minutes – and how many could not. The areas outside the circles were termed 'the black holes' on the map. More news stories followed. "Cardiac arrest in the black hole" and "Mayors demand better helicopter coverage". Interviews, radio, television.

Unfair?

The news story sparked a debate, but did the health service really perform poorly? A Norwegian Government white paper from 2001 states that "90 percent of the country's population should be reached by a physician manned ambulance within 45 minutes". As the news stories surfaced in 2014 the Norwegian population was about 5.1 million. The 166,000 living in 'the black holes' thus make for only 3.3% of the population. The medical helicopter service was not only performing due to government regulations: they were performing significantly better, covering almost 97% of the population within the target time.

While NRK was quick to point this out in editorial revisions, the debate was rooted in something bigger. Equality is a strong ideal in Norway. Equal opportunities. Equal pay. Equality for the law. Equality in health care. A famous photo in Norway shows King Olav taking the tram in 1973 during the petroleum shortage (Figure 1). So when there is indication that health services are unevenly distributed, that some people don't get something that others do, there's bound to be reactions.

Delft calling

Born in Norway professor Karen Aardal at Delft University of Technology (TU Delft) still follows the news from her home country regularly. And the news stories about the air ambulance caught her eye. Aardal is a professor of applied mathematics specializing in operations research and logistics, and she and her team have been working on various base location problems for emergency vehicles in The Netherlands, including ground ambulance allocation, and the location of fire trucks in Amsterdam. Aardal sent an e-mail to the Norwegian Air Ambulance Foundation (SNLA), a non-profit charity organization working to improve pre-hospital critical care. The e-mail initiated a collaboration between Aardal and a team of mathematicians at TU Delft and professor of medical statistics Jo Røislien and a team of medical researchers in Norway, aimed at exploring the optimal base locations for the Norwegian helicopter emergency service (HEMS).

This is Norway

Norway is a long-stretched country to the far North of Europe, covering 323,000 km^2. With a population

Figure 1. The Norwegian King Olav (right) riding the tram in 1973 during the petroleum crisis

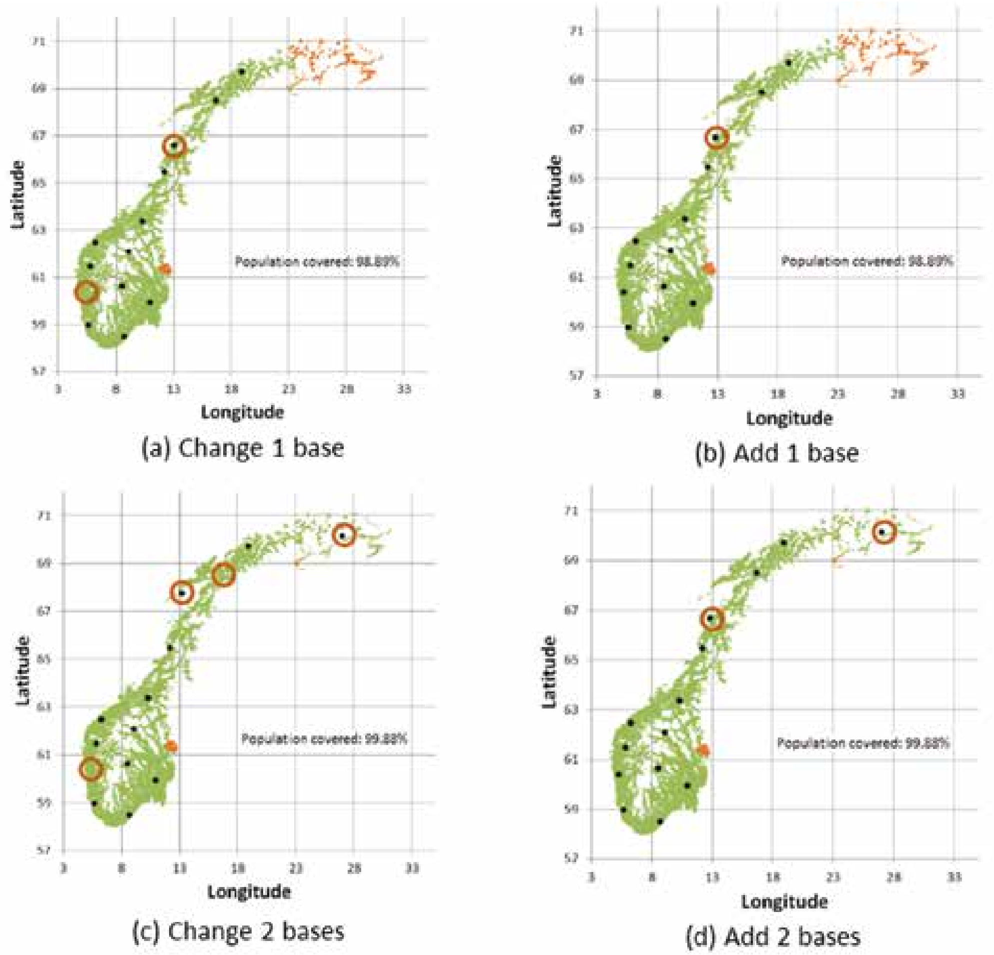

Figure 2. Optimizing air ambulance base locations conditioned on the existing base structure: Moving or adding one base (upper row), and moving or adding two bases (lower row)

of about 5.1 million, the average is only 16 inh/km². For comparison the Netherlands has 411 inh/km², the mountainous Switzerland has 203 inh/km², and Europe's largest country Ukraine has 73.6 inh/km². The Norwegian population is also unevenly distributed, with large urban-rural differences. In the capitol Oslo the population density is 1132 inh/km², while in Northern Norway it is 1.5 inh/km²: less than in Mongolia. Yet, potential inequalities in health care services make headline news.

With large geographical distances and large uninhabited areas the nationwide physician manned HEMS is considered essential in order to achieve the desired equality in health care in Norway. Yet, the question of how to localize HEMS bases has rarely been approached by the scientific community. The 12 helicopter ambulance bases in Norway providing HEMS are established through historical local engagement from the late 1970s.

From news to maths

The journalists' approach gave a good estimate of the current population coverage. The main shortcoming of their approach was the lack of a mathematical model, and the added flexibility provided by that. A mathematical model is like a laboratory: It allows for experimentation. It allows for looking beyond the current situation, with its 'black holes', and whether – and how – it might be improved. Also, pre-hospital critical care time is an important factor, and it is of significant interest to explore the consequences of lowering the target threshold of 45 minutes. It was time to let mathematics get to work.

We collected official population statistics for Norway on a fine grid with cells of dimension 1km x 1km from Statistics Norway. For possible base locations we used a coarser 10km x 10km grid. Helicopter ground speed depends on wind direction and strength, and varies according different helicopter types and speeds used dur-

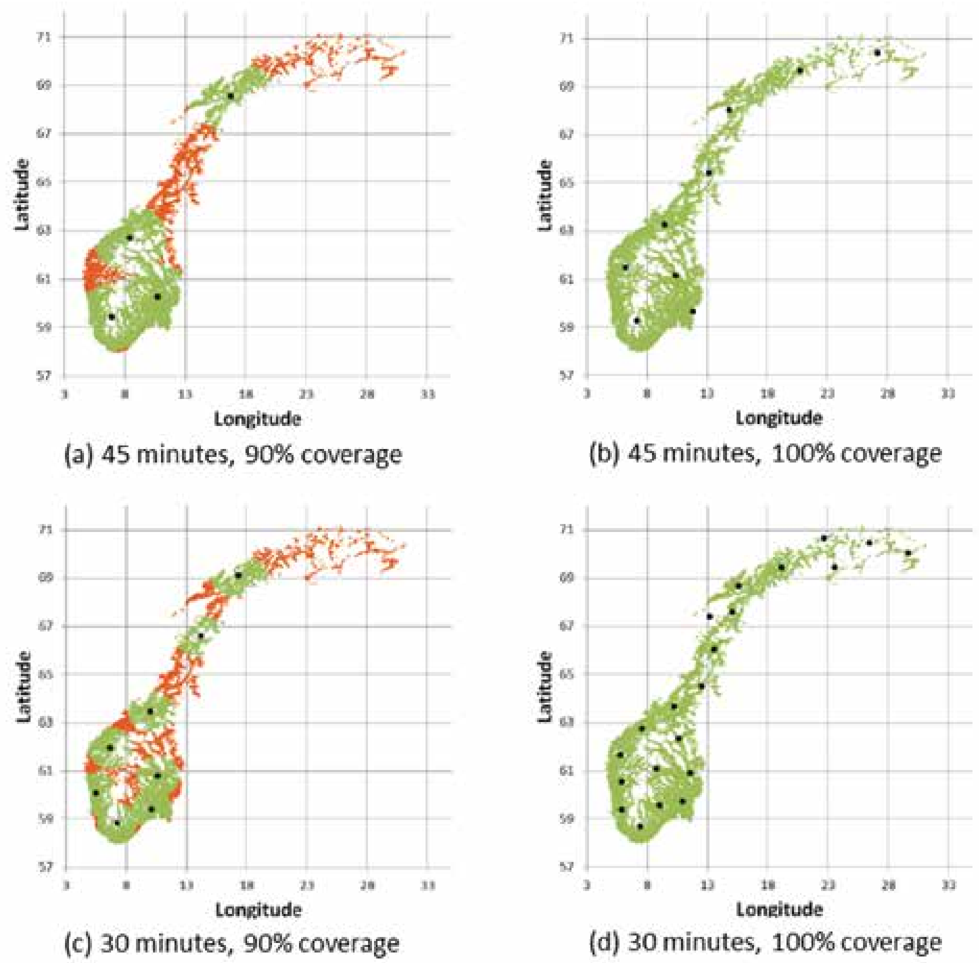

Figure 3. Optimal air ambulance locations in greenfield analyses for 90% and 100% population coverage: 45 minute target time (upper row), and 30 minute target time (lower row)

ing missions. As an overall average number we used 220 km/h. The empirical average pre-flight preparation time of 5.5 minutes for air ambulances in Norway was also entered into the calculations.

Several mathematical models can be used to optimize the location of emergency vehicles in order to maximize coverage, one being the Maximal Covering Location Problem (MCLP). The MCLP maximizes the weighted number of demand locations covered within a desired service distance, or time, from a facility by allocating a fixed number of facilities. Conversely, the model can be used to determine the least number of bases needed in order to guarantee a certain pre-specified coverage.

Population coverage

Using a 45 minute threshold the existing 12 bases cover an estimated 97.84% of the population. By moving the base in Bergen, Norway's second largest city, further north (Figure 2a) or adding a new base at this northern location (Figure 2b) coverage increases to 98.89%. Moving or adding two bases further north (Figure 2c and 2d) increases coverage further to 99.88%. With minor adjustments to the existing base structure almost full population coverage is within reach.

Performing greenfield analyses demonstrates that with a 45 minute threshold 90% of the population can be covered with only four bases (Figure 3a), and the whole population with nine (Figure 3b). Reducing the target time to 30 minutes increases the number of bases needed markedly. It takes eight bases to cover 90% of the population (Figure 3c) and 21 bases to cover the whole population (Figure 3d). The greenfield numbers are shockingly low. Chances they might ever be implemented are slim to none. In Norway the air ambulance is a symbol of safety, and removing an existing base will not be taken lightly.

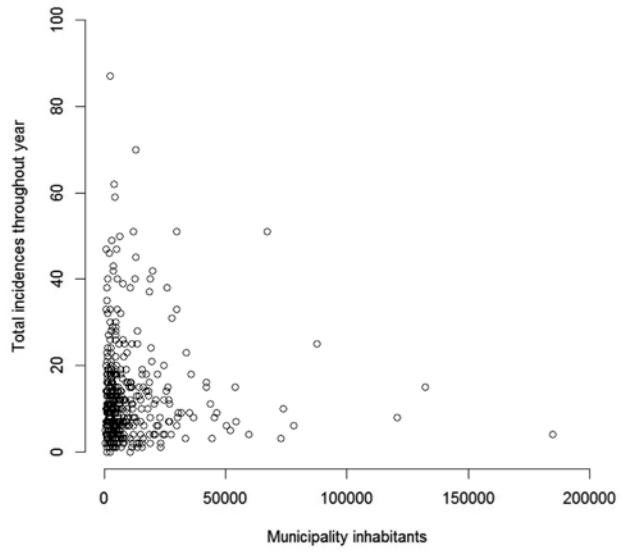

Figure 4. Municipality inhabitants and yearly total of incidences

It's all about the data

Government regulations are with regards to population coverage. But the main concern of the air ambulance is not where people live. After all, it is not a postal service. The main interest is the incidents for which HEMS is needed. Basing the analyses on population data is only meaningful if population density data is a reasonable proxy for actual incidents.

Norway is a country of large distances and changing weather. In winter Norwegians flock to the snow covered mountains, and in summer they spend time along the coast. The Norwegian air ambulance service already has seasonal bases, for example one in Hovden in southern Norway during Easter. "The location is essential with regards to the mountain tourism", says regional head Arild Sørensen.

The variation in the number of municipality incidents per 1000 inhabitants is substantial, with the higher numbers in Northern Norway, where the population density is the lowest. Indeed, the correlation between municipality population and yearly number of incidents is only -0.0027 (Figure 4). It's a common saying that 'people get injured where they live', but for incidents for which HEMS is needed this does not seem to be the case. We decided to redo the analysis, comparing results using both population density and incident data.

Where we live and where we are

Using population density data and a 45 minute threshold coverage can be increased by moving the Bergen base further north (Figure 5). Using incident data the Bergen base is still the least contributive, but in order to increase coverage the base should be moved significantly further north (Figure 5).

Reducing the target time to 30 minutes, the difference between the two data types remain. Using population data a base in northern Norway should be moved to the larger Oslo region to increase coverage (Figure 5). Using incident data it's more beneficial to move one of the bases along the southern coast further up the mountain – closer to the location of the Hovden seasonal base (Figure 5).

Where we live and where we spend our time is not the same thing.

It's all about the model

In our work on the location of HEMS bases in Norway (Røislien et al., 2017 and 2018) we have used the MCLP model. While regarded as a robust model for estimating optimal base locations for emergency vehicles, it has a major flaw: it assumes that there is always a vehicle available at a base whenever needed. This is rarely the case in practice. The model is thus suitable for exploring the optimal location of bases, but it cannot answer how to best distribute the available vehicles across these bases. For this a more advanced mathematical model is needed. Several such models exist that take the busy fraction into account, the fraction of the time emergency vehicles are busy with concurrent tasks, but there is no simple, well-established such model that can model Norway's uneven distribution of inhabitants and incidents. Newer theoretical results exist, but these are not readily available. We are currently working on testing and comparing various models.

When we published our first article, 153 of the thousands of articles in the journal contained the search term 'HEMS'. Ours was the first to contain the term 'MCLP'. Searching for the term 'EMS' (emergency medical service) in the extensive library of medical research literature PubMed returns about 15,000 search results. Searching for 'EMS AND busy fraction': Zero.

Mathematics is a cornerstone in modern medical research, and in 2000 the *New England Journal of Medicine* highlighted statistical analysis as one of the 11 most important medical developments of the last 1000 years. The

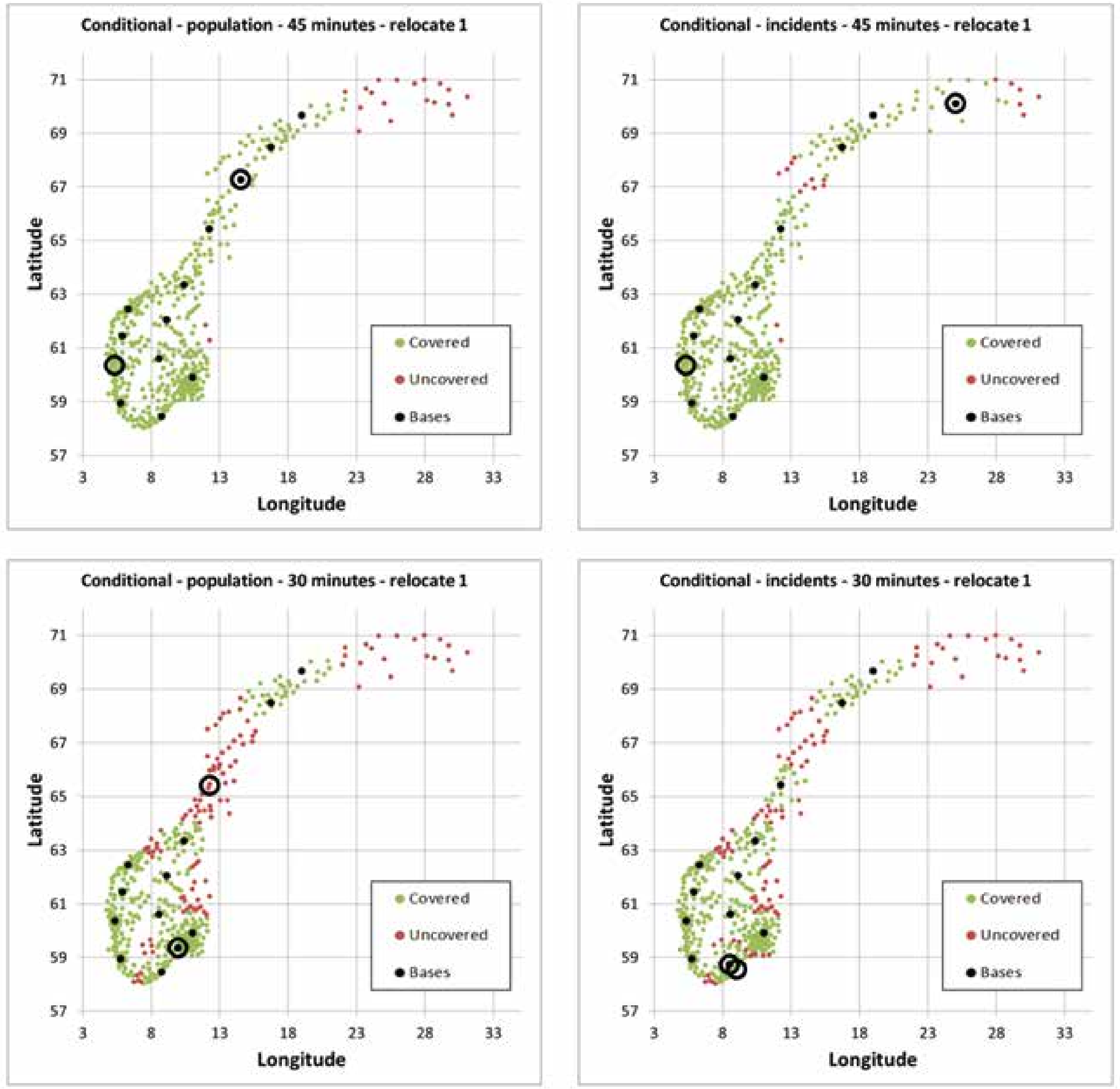

Figure 5. Optimal air ambulance locations in Norway comparing population and incident data for 45 minute threshold (upper row), and 30 minute threshold (lower row)

mathematical literature holds numerous results potentially of great value for medical researchers, and more advanced mathematical modelling is slowly finding its way into medical research. But if not applied to real world problems – problems that healthcare personnel actually care about – this mathematics will remain hidden in plain sight, read only by the few. This would be unfortunate. Healthcare is too important to be left to health personnel alone.

References

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