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DISCUSSION PAPER

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Locating fire-stations: an integrated approach for Belgium

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Abstract

This paper demonstrates the potential of a decision-support system developed for Belgium by a consortium of universities and a private firm, in the framework of a public call by the Ministry of the Interior. The system is designed to provide the Belgian emergency management administration with a complete decision-aid tool for the location of fire-stations. The originality of the project is that it includes a risk-modeling approach developed at a national scale. This analysis involves a multiscale GIS system which includes a thorough representation of the physical, human and economic spatial realities, a risk modeling approach, an adequate optimal location and allocation model (taking into account both queuing and staffing problems). The final result is an interactive operational tool for defining locations, equipment allocations, staffing, response times, the cost/efficiency trade-off, etc. which can be used in an assessment as well as a prospective context. It has numerous functionalities including rapid modification of the modeling conditions to allow for quick scenario analysis, multiscale analysis, and prospective analysis.

Keywords: location-allocations, GIS, fire-stations, Belgium.

JEL Classification: C61, R53

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Introduction

The fire service plays a key role in any country. Its operations are high profile since the public is acutely aware of its own vulnerability and possibly vital reliance on the service one day. Firemen and women are rightly admired, particularly as their intervention may carry a risk to their own lives. More generally, this service comes at a considerable cost. In a small country like Belgium (10 million inhabitants, 30 000 sq. km) the fire service involves about 17 000 people (including about 12 000 volunteers) and an annual budget of about 400 million euros. The efficient utilization of these resources is a big responsibility and can have a considerable impact on the quality of the service provided.

In most countries, the network of fire-stations has historically grown one station at a time as new needs and means for prevention and protection emerged. This paper deals with the development of an optimal location-allocation strategy for fire-stations in Belgium. It describes the organization and main results of a research project financed by the Ministry of the Interior (Home Office) aimed at developing an operational and interactive decision-support tool related to the spatial management of the disaster and emergency fire services: the location of brigades, design of service areas, staffing and equipment etc. (Janssens et al., 2006). The fundamental question underlying this research is: given a time norm (e.g. 8 minutes) within which 90% of fires must be reached, what is the lowest-cost solution that can achieve this? The main decision variables are the location and staffing of fire-stations, and the proposed approach is intended to guide retrospective assessment as well as prospective planning. It was designed to answer questions such as: is the present spatial organization efficient and homogeneous? is it reasonable to consider a reorganization? how much would such a reorganization cost? how can the steps of a reorganization be planned sequentially? This project consisted of developing a user-friendly decision aid tool that would help the public authorities to implement solutions that were both efficient and feasible.

The problem is quite complex due to its dimensions and constraints (see e.g. Tillander, 2004). Since fires are the core task of the service, we call the sites to be optimally located 'fire-stations' and the service the 'fire service'. However it must be remembered that the service does not only respond to fires, but also to other emergencies (such as road accidents and floods) as well as to less urgent missions, such as eliminating wasp nests. It thus faces several types of risk that require different types of equipment and skills. As these risks vary over space (physical, social, economical, historical, environmental, etc.), location planning should rely on local as well as global risk assessment. For emergencies, the delay between the brigade's departure and arrival on the scene is a key determinant of operational efficiency. This delay not only depends on the distance to be traveled, but also on the peculiarities of space (road network, environment, etc.) and time (congestion, meteorological conditions, etc.). A long delay may have a large impact on the consequences of the fire/accident in terms of victims and damage. The national administration of the service must manage large geographical differences that lead to equity/efficiency trade-off considerations, but also to a multiscale problem (the spatial accuracy should be greater in large cities and less in rural areas). Moreover, the occurrence of simultaneous calls cannot be ignored. Nation-wide decisions might have dramatic local consequences.

Modeling the spatial organization of emergency facilities such as fire-stations has led to an impressive amount of literature since the seminal papers of Guild and Rollin (1968), Toregas et al. (1971) or Hogg (1971). The objective of this paper is not to review them (see therefore a recent review made by Goldberg (2004) for fire-stations, or less service specific publications such as those of Hansen et al. (1987), Daskin (1994), Drezner and Hamacher (2004) or ReVelle et al. (2008)). The objectives of the approach proposed here are the following: to define clear criteria representing the location problem realistically, to develop an operational and interactive tool, to determine optimal locations, to design optimal service areas, to assign staff and equipment (optimal size of the brigades), to manage intervention time at the scale of the country (Belgium) and consequently to test the extent to which spatial reorganization improves on the current situation. Hence, this paper fits well into the existing literature (see e.g. Goldberg, 2004 or Yang et al., 2006 for a literature survey): there is a severe need for modeling real-world complexities and suggesting sustainable solutions.

This paper starts with an overview of the architecture of the project. Data input and other pre-processing functions are then described, followed by the location-allocation methods. Data output, and the interpretation of results are illustrated by means of a case study. The paper concludes with a summary of the model's potentialities and limitations, as well as plans for future work.

Architecture of the project

The objective is to construct an architecture coupling an adequate database management system (DBMS) to a location-allocation model (LAM) to provide an operational spatial decision-support system (SDSS) (Figure 1). DBMS refers to software that collects, manipulates, queries, and retrieves tabular data. It is a prerequisite to an operational model as data collection is the basis of the application developed in the project. Here data were here collected about the service itself: what are the tasks to be provided? what are the service level requirements of the Ministry? what are the costs of running the services? etc. These are all basic management questions which do not always find clear-cut answers as we are dealing with a multifaceted public service in a quite multifaceted country.

The optimal location of emergency facilities has a long history in management sciences and operations research literature (see e.g. Goldberg, 2004 for a review). However, operational location-allocation models (LAMs) have to be specifically developed to take into account the specificities of the problem of defining the location, the service areas, the size of the fire-stations (staff, building, cars, etc.), the intervention times, and queuing aspects for all types of emergency services.

The LAM is coupled with a geographical information system (GIS) to provide an operational decision tool. GIS is an information technology used to maintain and analyze geographic data; it organizes data into layers and relates sets to space. It allows relationships and operational trends to be conveyed in a spatial context. The use of GIS for providing spatial decision-support systems is nowadays well-known (Longley et al., 2005). GISs provide most inputs to LAMs. GISs are used for storing and analyzing geographically distributed data in a multiscale perspective (data about the road network, the distribution of potential and present risk factors, the characteristics of the geographical space, the environmental risks, the current and potential location sites, etc.).

The GIS also supports the visual interface of the spatial decision support system (SDSS). Hence, the originality of this project consists of adopting a risk-modeling approach developed at a national scale without ignoring local specificities. In an SDSS the complexity of the service as well as its organizational and geographical constraints is coupled with the modeling process to develop a user-friendly interface where the decision maker can select various combinations of criteria for evaluating current locations or for predicting the impact of changes in location.

This mission was entrusted to an interdisciplinary team with expertise in data management, statistics, risk modeling, geography and operations research. Such expertise was found in a consortium of scientists and Experian Business Strategies, a private firm which was also in charge of the 3-year follow-up. Given the severe time pressures on the project, an achievable balance had to be sought between a sophisticated scientific approach and a feasible, fast and user-friendly solution.

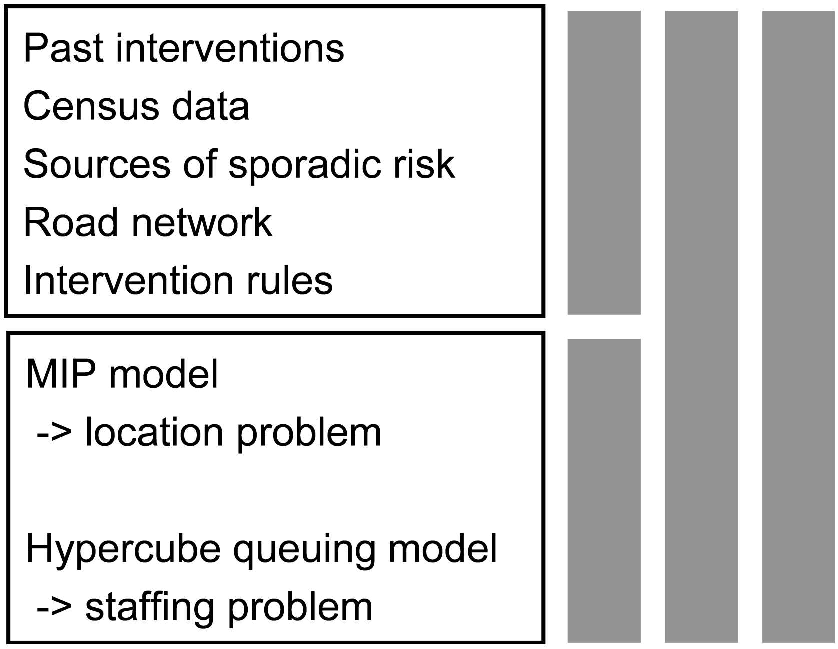

Figure 1: The architecture of the project

Data input and processing

Study area and scale of analysis

The model was developed at the scale of one country, Belgium, a small but highly urbanized European country (10 million inhabitants spread over 30 000 sq. km.). The population density varies from less than 20 inhabitants per km² in rural regions to more than 20,000 in highly urbanized areas (see Appendix 1). The country is varied in its topography (rather flat in the north, with a much more rugged landscape in the south), urbanization, and historical networks of towns, as well as in economic, social, political, cultural and environmental features. The country is dominated by Brussels, which is centrally located and sprawls out across its administrative borders into Wallonia and Flanders. Belgium has approximately 17 000 firefighters, including some 12 000 volunteers.

We used the NUTS principles (nomenclature of territorial units for statistics, Eurostat, 2005) for aggregating spatial data. Belgium (*Nuts0* level of aggregation) is administratively divided into three partially autonomous administrative regions (*Nuts1* regions), and into 10 provinces (*Nuts2*). *Nuts1* and *Nuts2* borders are seldom crossed by the disaster and emergency services. *Nuts* regions smaller than *Nuts2* are purely administrative divisions for fire organization.

While *Nuts5* regions (called 'communes') might have been sufficient for studying national locations of fire-stations, they are still too coarse for intra-urban locations and would have led to unacceptable aggregation errors in the modeling solutions. Hence we chose 'statistical wards' as are our basic spatial unit (BSU): the 19,781 statistical wards correspond to the finest aggregation level for which official data are available in Belgium. However, they vary widely in shape and size leading to well-known aggregation problems (see Goldberg (2004) for a review or Grubesic (2008) for a recent discussion). These wards are officially defined in terms of internal homogeneity. In this project each BSU is used as both a demand point and a potential location for a fire-station. Information relating to each BSU is summarized at its centroid. Given the size of a BSU, travel time within a BSU is always less than 2 minutes.

Without accurate and realistic travel times, location models would have little value. Shortest distances were computed in travel time between the centroids of the BSUs along the road network, using the MultiNet database from TeleAtlas, with computation being undertaken by Experian Business Strategies. Average speed and traffic conditions were taken into consideration. Average speeds were attributed to each type of road segment, and speed-reduction factors were taken into consideration within urban areas as well as for crossroads. Speed conditions range from 15 km/h at intersections to 80 km/h on highways (see Janssens et al., 2006, p. 13). They were defined by a workgroup of experienced firefighters from various fire-stations. No specific traffic regulation measures or congestion situations were included in the present computation but the tool could easily be updated.

Demand: risk modeling

Risks were divided into two types: recurring risks and sporadic risks. *Recurring risks* are events that occur with a frequency that can be estimated from historical data. *Sporadic risks* are events that are very rare or unlikely (e.g. a major Chernobyl-like event) for which it is not possible to determine a probability of occurrence based on the direct observation of historical data. However, the magnitude of their possible consequences is such that they have to be taken into account in planning emergency services. Consequently, the procedure for estimating the two types of risk is very different. The recurring risks were forecast by regression models using historical intervention data, while the sporadic risks were evaluated by gathering exhaustive lists of locations associated with potential causes of catastrophic events.

In order to estimate recurring risks, a survey was conducted in all 251 existing fire-stations over an 11-year period (1993–2004). Not all fire-stations could provide full data, but sufficient information was gathered on about 839 000 incidents, including 157 000 fires (the yearly average for Belgium is about 30 000 fires and 150 000 “other incidents”). A statistical model linked these data to (complete) statistics on risk factors, which allowed – under certain assumptions – risk levels to be predicted for the entire country. The explanatory variables (characteristics of the resident population, working, shopping, visiting, etc. in the ‘commune’, as well as land-use characteristics) of the statistical model were mostly drawn from the 2001 national census.

Several models were built to estimate the recurring demand in a prospective way and to fill in the gaps in our geographical representation (missing data due to the fact that not all fire-stations answered the survey). The emergencies were divided into five categories: fires related to a dwelling, fires not related to a dwelling, medical emergencies, non-medical emergencies and non-urgent tasks. A separate model was built to estimate the local rate of calls for each category of emergency (see Goetghebeur et al., in preparation). Specifically, a log-linear model was fitted to estimate the yearly numbers of type-specific events per square kilometer in the BSUs. The input to the model was based on predictor values from census information available for all BSUs, but outcomes were missing for BSUs covered by fire-stations that did not submit event data. The models aimed to estimate the spatial variation of events despite the missing data, but did not attempt to yield causal explanations.

As expected from the literature, population density is a key determinant of fire hazards (see Richard et al. 1991, Beguin et al 1992, Peeters and Thomas 2001). The estimated spatial information is illustrated for one type of risk in Figures 2 and 3. For confidentiality reasons, the results are mapped at the level of the communes (*Nuts5*). Both maps demonstrate the strong influence of the urbanization level and the population density (see Appendix 1).

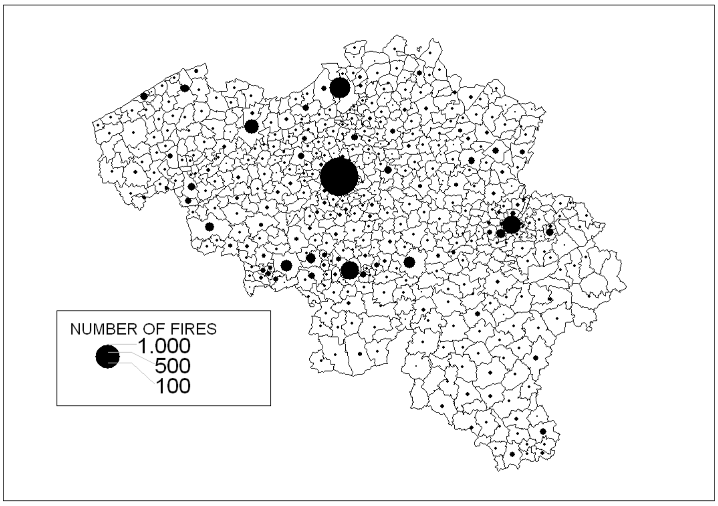

Figure 2: Estimated number of fires in dwellings by commune and by year

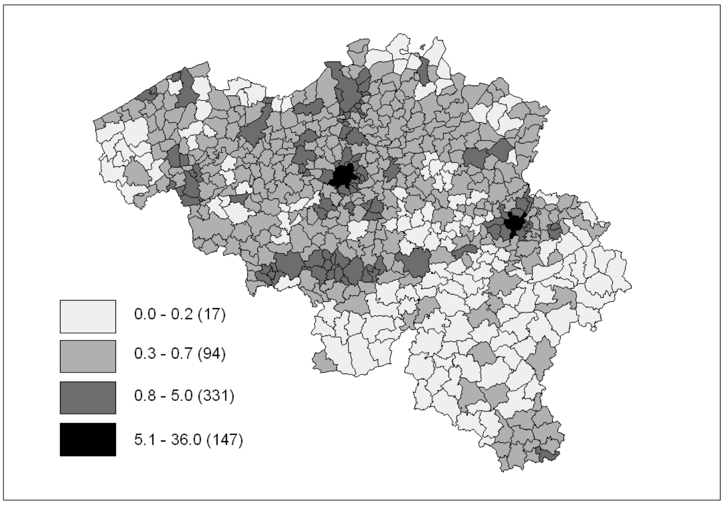

Figure 3: Estimated density of fires in dwellings (number of fires by year and by square kilometer)

N.B. Numbers in brackets give the number of communes in each class

The estimates of sporadic risks are based on the potential causes of catastrophic events, which are mainly linked to places where people gather (e.g. health care centers, education centers, shopping centers, entertainment centers, large office buildings, etc.) or to places whose infrastructure presents potential dangers (e.g. high rise buildings, industrial complexes with hazardous materials (Seveso-type sites), tunnels, pipelines, etc.). A database was built containing all the locations corresponding to nine categories of sporadic risk.

Supply: intervention rules

As well as the enquiry into the history of interventions, another survey was conducted on rules for intervention and their application. It is clear that a large variety of interpretations was observed, and the application of the rules is far from being uniform. Two types of information were collected: the choice of the fire-station that sends a team, and the composition of that team. The project-team collaborated with representatives of the firefighters to establish standards for the composition of the response teams for each category of emergency (team + equipment). Standards also had to be established for the escalation scheme when reinforcements were needed. These standards depend on the location of the emergency; they can be translated into parameters and costs at a later stage. The definitions are a useful by-product of this project, but they are highly dependent upon the decision maker.

Optimization heuristic

The optimal-dimensioning problem consists of finding the minimum cost configuration for the emergency services which will enable them to arrive on the scene of a given proportion of emergencies within a given time (for example, 90% of emergencies within 8 minutes), and ensuring that there is a fire-station within a given time radius of each sporadic risk (for example there is a fire-station within 10 minutes of each location with a sporadic risk). The cost of a configuration depends on the number of fire-stations as well as on the number of vehicles and crews present in each station. The time to arrive at an emergency includes the time for a vehicle and crew to get ready and the time to drive to the site of the emergency. Our model only considers the latter component.

Given the complexity of the location-allocation problem at the scale of a country, two sub-problems were approached sequentially. The location problem was solved first, and then the staffing problem was tackled. For the location problem we assume that a crew is always available in each station, and we seek the minimum number of stations (and their locations) needed to achieve the desired service level. This problem is modeled as a mixed-integer programming (MIP) optimization problem. A brief description of the formulation appears in Appendix 2. Eiselt and Marianov (2009) examine different formulations to take into account the notion of quality of service rather than a strict covering function. This was not pursued here as the size of our problem makes these models too difficult to solve.

In the staffing problem we take the locations as fixed and we optimize the number of crews in each station for the desired service level. A specific development of the hypercube queuing model is used.

When the locations of the fire-stations are fixed, the staffing of each station is optimized to meet the required service level at a minimum cost. If each BSU could only be reached by a single fire-station within the required service time, the staffing problem would consist of a series of independent problems for each station. In practice, the geography of the country means that, if we aim to cover, let us say, 90% of the country within a specified time interval, there are relatively large overlap regions where teams from more than one fire-station could reach the scene of an emergency within the prescribed time. As the frequency of incidents is only relevant for recurrent risks, the staffing part of the model does not consider sporadic risks.

This leads to a spatial queuing model. For a given emergency call, we assume that, if the closest fire-station has an adequate crew available, it will deal with the situation. If not, we look for such a crew at the second-nearest fire-station, and so on until an adequate crew is found. The hypercube queuing model (Larson and Odoni 1981) is used to evaluate the waiting times and the service level for each type of call according to the rate of arrival of demands and the staffing level of each fire-station. A local search heuristic is then used to optimize the staffing of each station in order to meet the overall service level.

The notion of 'service level' is slightly modified in this part of the model. Since there might be portions of the country that are not reachable within the specified time limits, the optimization model completely neglects these areas: no matter how many crews are used, the calls to such locations cannot be answered in time. Our metric is the fraction of situations where the team arrives on the scene within the specified time limit where this is possible given the location, or as fast as technically possible when the location is outside the specified time limit for any fire-station. This implies that a crew must always be available at the closest fire-station.

As mentioned above an escalation scheme was defined to send reinforcements when emergencies require more resources than a single response team. In the decision aid tool, two levels of reinforcement are considered, each level having its own time limit and coverage requirement. The same optimization approach is used for the staffing of reinforcement crews at each level (the reinforcement must be based in a fire-station).

Decision aid tool

The decision aid tool provides a flexible and user-friendly interface for quick modification of the parameters (e.g. the fraction of recurrent risk to cover, the list of sporadic risks, the list of potential locations for fire-stations, the specifications of acceptable time-distances for each type of emergency/risk).

Nowadays, the territory covered by a fire service is usually a commune or, in some cases, a group of communes. A service can also be called in to reinforce other stations. A first analysis revealed the dramatic impact these boundaries have on performance. It would thus seem advantageous to consider the problem at the national level, ignoring further territorial constraints. The national scale was however considered too large, for both administrative and computational reasons. Our computations showed that, operating within each province (*Nuts2*), causes little loss of efficiency but gives better control of the service level. This is due to the diversity in Belgium, where some provinces are much more densely populated than others. The 'optimal' solution at the national level strongly favors more densely populated areas when trying to meet an overall service level. It is easier to manage the service level and/or to get a good coverage of the whole population at the provincial level. The number of fire-stations needed increases with the percentage of risk covered (Figure 4). By this we mean the percentage of the expected number of emergencies (as given by the estimated occurrence rates of all five categories or risk) that lie within an acceptable time-distance of a fire-station. The standard time-distance used here was 8 minutes for all categories of recurrent risk.

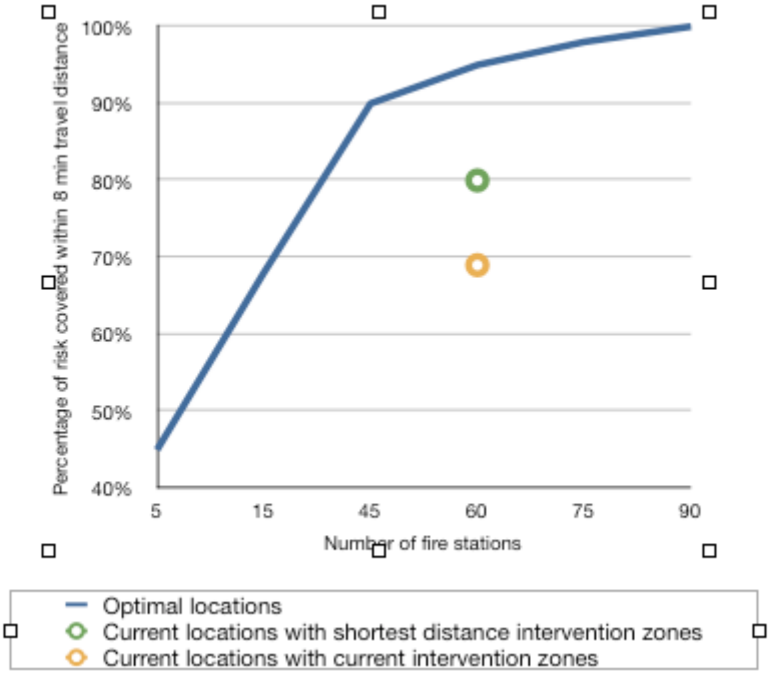

Figure 4: Trade-off between the number of fire-stations and the percentage of risk covered in a province

These results confirmed the Ministry's assumption that sending the crew that can reach the scene the soonest would have a direct beneficial effect. Although this conclusion is quite intuitive, being able to evaluate it precisely and objectively was of great value for the Federal Emergency Management agency. It showed that the relocation/removal/addition of fire-stations might be advantageously considered. This formed a second important set of results of the study.

Data output and interpretation of results

The final product takes the form of a software package. The user is faced with choices related to the modeling rules and conditions:

(1) the area studied: should the location problem be considered for the entire country (*Nuts0*), or just one region (*Nuts1*) or province (*Nuts2*), or even a set of communes corresponding for instance to an urban agglomeration (bearing in mind that the model relies on detailed spatial information at the level of the statistical wards or BSUs)?

(2) the types of sporadic risks: the user can choose which sporadic risks are considered in the modeling process and the associated time thresholds;

(3) the types of recurring risk: the application can be restricted to a particular kind of recurring risk or it can consider all five types;

(4) the time threshold: the user decides, for instance, that each BSU should be reached within an 8-minute intervention time; the simulations can then be repeated with 9, 10 or 12-minute deadlines to test and measure the impact of changing the threshold; the threshold can also be varied as a function of the local population density;

(5) the fraction of risk 'covered': the fraction of emergencies (according to the estimated rate of occurrence of the recurrent risks) that lie within the time threshold can be manipulated; all the sporadic risks must lie within the corresponding intervention time threshold.

(6) locations for a fire station: the user can choose to list the BSUs that are /are not potential sites for a fire-station; some BSUs may be ruled out, while others may be definitely included;

(7) existing fire-stations: moving a fire-station from one location to another is quite expensive, and the user can weight the inertia of the existing system, depending on the available budget and the willingness to change;

(8) staffing: what fraction of expected callouts should be able to be responded to within the special rules for staffing calculations;

(9) time taken to handle each category of emergency: this is used in the staffing part of the model to compute the (non)availability of crews ('busy-time').

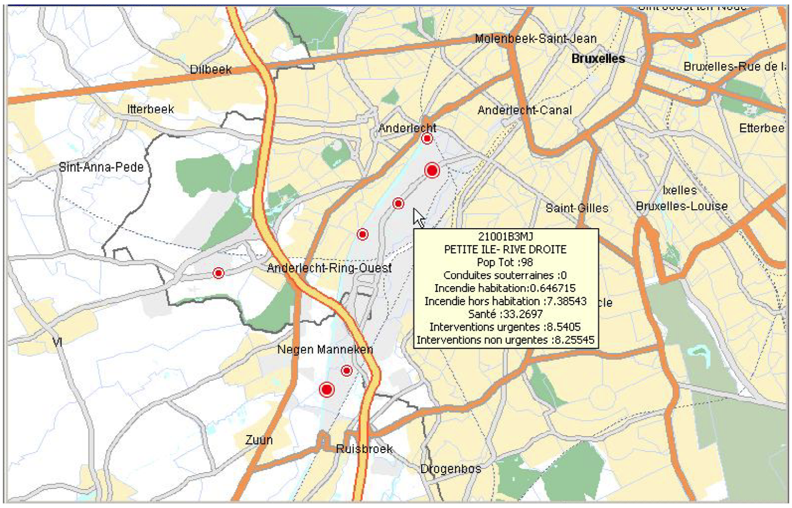

Figure 5: Example of screenshot I: by clicking on any BSU, it is highlighted and the relevant risk information is displayed

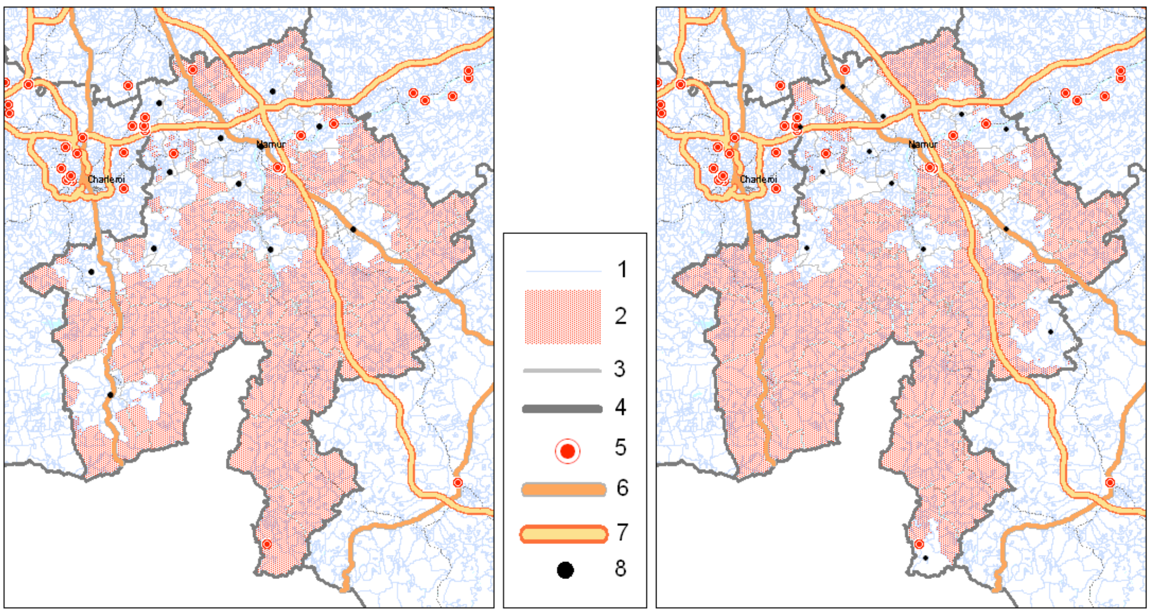

Figure 6: Example of screenshot II: optimal locations of fire-stations when 70% of the emergencies lie within 10 minutes of a fire-station

N.B. Sporadic risks are ignored for the left hand map. The map on the right includes the requirement that all locations with a sporadic risk are within 10 minutes of a fire-station.

Conclusion

The tool developed in this project has resulted in an efficient and flexible decision tool that not only assists decision makers, but also helps them to achieve a better understanding of the functioning of the Belgian fire services. It is important to stress the fact that the quality of the results is highly dependent on the quality of the empirical data. Given the many data sources, fruitful collaboration with all the data organizations proved to be a real challenge. An additional difficulty for such an endeavor is that many countries have decided not to continue with population censuses, which will make the estimation of the spatial variation in risk much more difficult.

One of the key benefits of this project is that it provides a clear and objective basis for discussion between the many stakeholders involved with planning the fire service (in Belgium these include the communes, the federal emergency service agency and the firefighters' unions). Using this tool, it is much easier to asses the impact of various planning decisions. It is notable that at the end of the project, a national reform of the fire service started, motivated in part by several findings of the project, most notably the necessity to pool services across large intervention zones. The tool developed is systematically used for all decisions related to this national reorganization plan of emergency services. The direct benefit is hard to asses as such a national reorganizations involving the building of new facilities and the closing of some existing facilities takes a lot of time. Nevertheless the fact that the tool is systematically used shows that it brings some value for the decision makers.

In order to improve the value of the tool, a process should be built in order for the data to be kept upto date with the latest statistics collected. It would also be valuable to have tools to build future scenarios based on the current data and some indicators of the anticipated evolution of the main data. The tool does not provide ‘the ultimate solution’; however it does make an important contribution to the rational, evidence-based, informed decisions which will necessarily involve political choices.

Acknowledgements. This paper summarizes a fruitful collaboration between Adhoc Solutions (a private company located in Louvain-la-Neuve and now part of the Experian Group) and a consortium of scientists from several universities and disciplines (Chevalier P., Crémer L., Geraets D., Goetghebeur E., Janssens O., Plastria F., Peeters D., Thomas I., Vandaele. N., Voisin O.) as well as the Ministry of the Interior represented by Mrs Breyne and Mr Looze. A special thanks goes to the firefighters and their commanders for many fruitful discussions and for the data. They all contributed to the success of this research.

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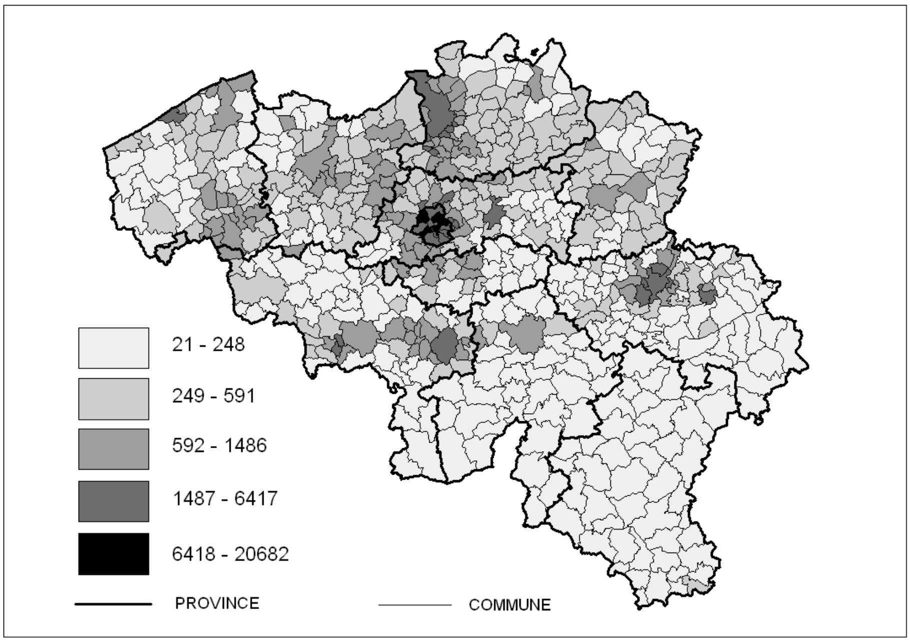
APPENDIX 1



Population density in Belgium (inhabitants per square kilometer)

Source: I.N.S., 1 January 2002

APPENDIX 2

The recurrent risk associated with each BSU is represented by 5 rates, corresponding to the 5 categories of emergencies. A 0-1 variable was defined, indicating the presence inside each BSU of a sporadic risk that requires the presence of a fire-station within a specific time radius.

The location problem is modeled as follows:

$$
\begin{aligned}
& Min \sum_i y_i \\
\text{s.t.} \quad & \sum_i a_{ij} y_i \geq z_j \ \forall j \\
& \sum_j w_j z_j \geq P \sum_j w_j \\
& \sum_i b_{ij} y_i \geq 1 \quad \forall j \in S \\
& y_i \in \{0,1\} \qquad \forall i \\
& z_j \in \{0,1\} \qquad \forall j
\end{aligned}
$$

where

- $i = 1, \ldots, n$ is an index of the possible locations (BSUs);
- y_i indicates whether there is a fire-station at BSU i;
- w_j quantifies the expected recurrent yearly event rate at BSU j;
- z_j indicates whether BSU j is within an acceptable distance of a fire-station for recurrent risks;
- a_{ij} indicates whether the potential location i for a fire-station is within an acceptable distance of BSU j for recurrent risks;
- P is the fraction of the recurrent risk that must be covered by fire-stations within an acceptable range;
- S is the set of BSUs that contain a source of sporadic risk and which must therefore be within a special acceptable range of a fire-station;
- b_{ij} indicates whether the potential location i of a fire-station is within an acceptable distance of the site of a sporadic risk j.

We started by implementing the problem for an exact solution with a commercial MIP (mixed-integer programming) solver. As the solution times with the best available commercial solvers were often quite long (several hours), even when applied at a provincial level, we chose to implement a mean-field-feedback neural network approach (Ohlsson et al, 2001). This heuristic has a reliably short running time and led to solutions that were almost as good as the optimal ones.

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