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Philippe Chevalier, Isabelle Thomas, David Geraets,
Els Goetghebeur, Olivier Janssens, Dominique Peeters
and Frank Plastria

CORE
Voie du Roman Pays 34, L1.03.01
B-1348 Louvain-la-Neuve, Belgium.
Tel (32 10) 47 43 04
Fax (32 10) 47 43 01
E-mail: corestat-library@uclouvain.be
http://www.uclouvain.be/en-44509.html

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Locating fire stations: An integrated approach for Belgium

Philippe Chevalier [a,b,*], Isabelle Thomas [a,c], David Geraets [d], Els Goetghebeur [e], Olivier Janssens [d], Dominique Peeters [a,f], Frank Plastria [g]

[a] Center for Operations Research and Econometrics (CORE), Université catholique de Louvain, Voie du Roman Pays, 34, 1348 Louvain-la-Neuve, Belgium
[b] Louvain School of Management, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[c] School of Geography and Fund for Scientific Research, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[d] Experian Business Strategies SA, Louvain-la-Neuve, Belgium
[e] Department of Applied Mathematics and Computer Science and Center for Statistics, Ghent University, Ghent, Belgium
[f] School of Geography, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[g] INVE and MOSI, Vrije Universiteit Brussels, Belgium

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ABSTRACT

This paper illustrates 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 made 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 that 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. This flexible tool can be used in an assessment as well as a prospective context. It has been used to draw a national reorganization plan for fire stations that started being implemented in 2010.

1. Introduction

The fire service plays a key role in any country. Its operations have a high visibility since the public is 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 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. [14]. The fundamental question underlying this research is: given a time norm (e.g. 8 min) 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 spatial reorganization? How much would such a reorganization cost? How can the steps of a reorganization be planned sequentially? This project consisted in developing a user-friendly decision-aid tool that would help public authorities to implement solutions that are both efficient and feasible.

The problem is quite complex due to its dimensions and constraints (see, e.g. [26]). Since fires are the core task of the service, we call the sites to be optimally located 'fire stations' and

* Corresponding author. Center for Operations Research and Econometrics (CORE), Université catholique de Louvain, core – LSM, Voie du Roman Pays, 34, 1348 Louvain-la-Neuve, Belgium. Tel.: +32 10478396; fax: +32 10478324.
E-mail address: philippe.chevalier@uclouvain.be (P. Chevalier).

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the service '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 or floods) as well as to less urgent missions, such as eliminating wasp nests. Therefore, it faces several types of risks 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 characteristics 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 Belgian 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 than 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 [11], Toregas et al. [29], Hogg [13] or Plane and Hendricks [20]. The objective of this paper is not to review them (see therefore reviews made by Badri et al. [1] or Goldberg [9] for fire stations, or less service specific publications such as those of Hansen et al. [12], Daskin [4], Drezner and Hamacher [6] or ReVelle et al. [21]). The objectives are here: 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 (intervention zones), 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. [9] or [30] 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.

2. 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). Fig. 1 presents the global architecture of the system that was developed. The plain lines show the flow of data used, the dashed lines show the data that can be visualized, the dotted lines show data that comes from the user interface, when the dashes are mixed the data can be visualized and modified through the user interface.

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. Data were 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. Many meetings with different stakeholders were needed in order to gather and organize this data.

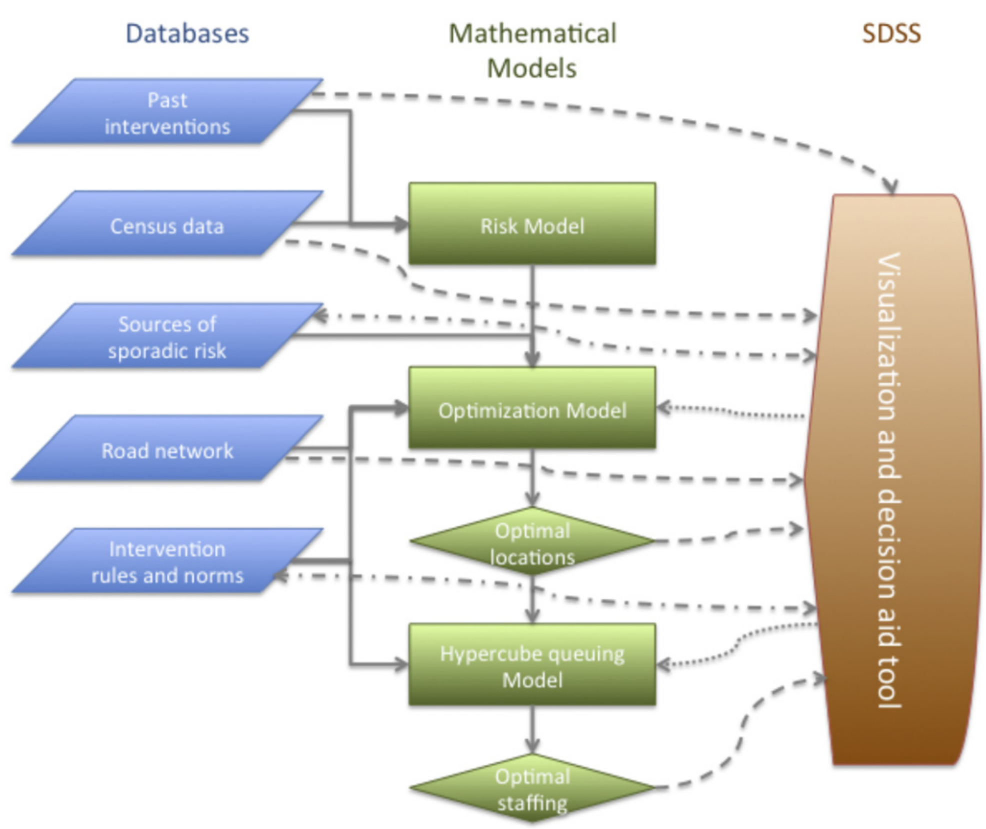

Fig. 1. Architecture of the complete system.

The optimal location of emergency facilities has a long history in management sciences and operations research literature (see, e.g. [9] 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 (see, e.g. [5,16]). GISs provide most inputs to LAMs (see, e.g. [22] or [17]) and especially for fire services (see, e.g. [24]). The GIS software *MapInfo* was used to store, analyze and visualize geographically distributed data in a multi-scale 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 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 (see Section 5.1).

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 that 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.

3. Data input and processing

3.1. 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 sq km in rural regions to more than 20,000 in highly urbanized areas (see Fig. 2). 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 urban hierarchy is dominated by Brussels, which is centrally located and sprawls out across its administrative borders into Wallonia and Flanders [25]. Belgium counts approximately 17 000 firefighters, including some 12 000 volunteers.

Spatial scale is an important issue for the organization of fire fighting services as well as for their modeling. The choices to be made are not straightforward and a trade-off must be sought between data availability and operational or modeling constraints. We used the NUTS principles (Nomenclature of Territorial Units for Statistics, [8]) for aggregating spatial individual data. Belgium is administratively divided into three partially autonomous administrative regions (*Nuts1* regions), and into 10 provinces (*Nuts2*).

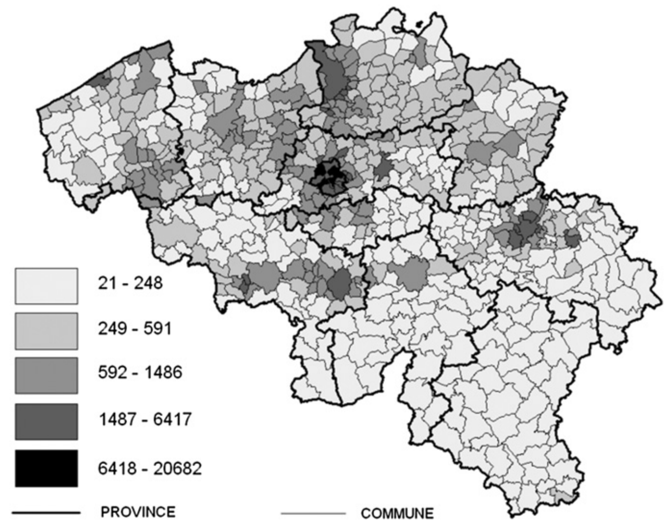

Fig. 2. Population density in Belgium (inhabitants per sq. km) Data source: I.N.S., 1 January 2002.

Nuts1 and *Nuts2* limits are seldom crossed by emergency services. Finer spatial units such as communes (corresponding to Eurostat lower Local Administrative Unit: LAU2 level) are hence considered here as purely administrative divisions for fire organization (they are mainly a remnant from the past and should not be considered for future optimal organization).

While the 589 municipalities ('communes') might have been sufficient for studying national locations of fire stations, they appeared to be too coarse for intra-urban locations and would have led to unacceptable aggregation errors in the modeling solutions. Hence we chose 'statistical wards' as the 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 [9] for a review or [10] for a recent discussion). These wards are officially defined in terms of internal homogeneity. In this project, each BSU is used as a demand point and as 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 min.

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 [14, p. 13]). They were defined and validated 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.

3.2. 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 about interventions. *Sporadic risks* are events that are very rare (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 procedures for estimating the two types of risks are 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, etc. in the 'commune', as well as land-use characteristics) of the statistical model were mostly drawn from the 2001 national census or other official Statbel data.

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. Specifically, a log-linear model was fitted to estimate the yearly numbers of type-specific events per square kilometer in all BSUs by a set of over 50 explanatory variables. The models aimed at estimating the spatial variation of events of type k despite the missing data, but did not attempt to yield causal explanations. The spatial variation of Y_i was estimated by means of over 50 variables mainly issued from the official census and land cover data sources. The numbers of incidents (Y_i) were first statistically estimated for all BSUs for which intervention of type k were known (fire stations gave the event data); these estimated numbers were hence compared to actual numbers for each existing fire station having made statistics available. Results were fully satisfactory. It was then easy to estimate the missing Y_i values by means of observed and known X_i values and the equation parameters. We hence obtained a complete covering of the territory: the real numbers for communes were interventions Y_i were known, and estimated numbers for missing data (see Figs. 3 and 4).

As expected, population density is a key determinant of fire hazards (see [2,19,23]). The estimated spatial information is illustrated for one type of risk in Figs. 3 and 4. For confidentiality reasons, the results are mapped at the level of the communes (*LAU2*). Both maps demonstrate the strong influence of the urbanization level and the population density (see Fig. 2).

The estimates of the 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 the nine categories of sporadic risk.

3.3. Supply: intervention rules

As well as the enquiry into the history of interventions, another survey was conducted on the rules for intervention and their application. It is clear that a large variety of interpretations were observed, and the application of the rules is far from uniform. Two types of information were collected: the choice of the fire station that sends a team, and the composition of that team. The co-authors of this paper 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. Most of these "rules" are either included in the model itself, or considered as options in the software (see Fig. 6).

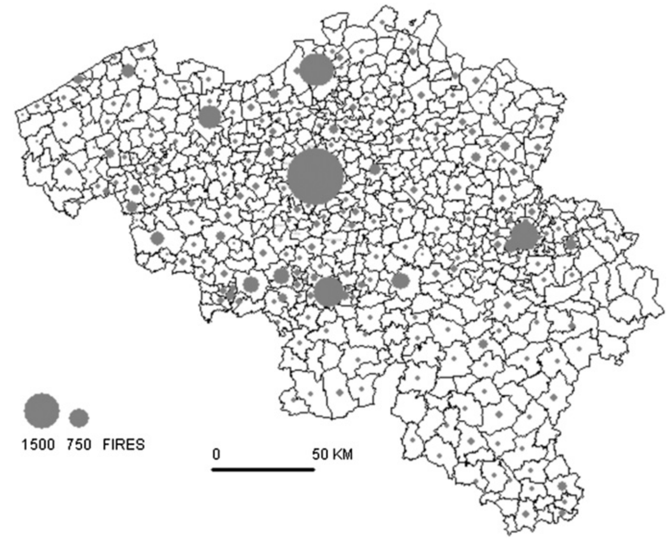

Fig. 3. Estimated number of fires in dwellings by commune per year.

4. Optimization heuristic

The optimal-dimensioning problem consists in finding the minimum cost configuration for the emergency services which will

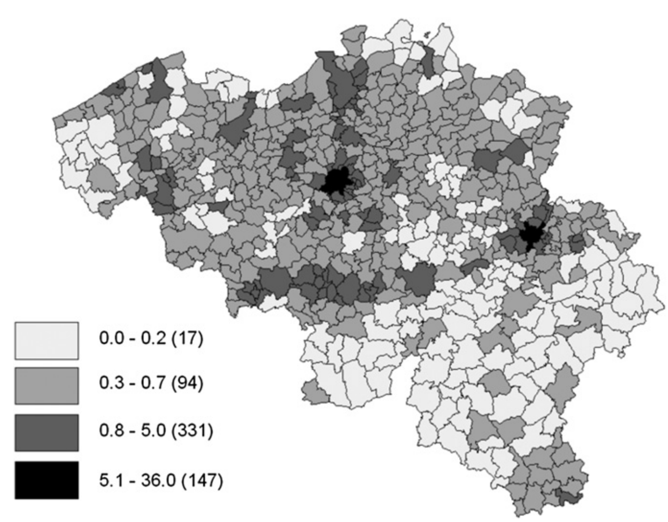

Fig. 4. Estimated density of fires in dwellings (number of fires per year and per square kilometer). Note: between brackets: number of communes in each interval.

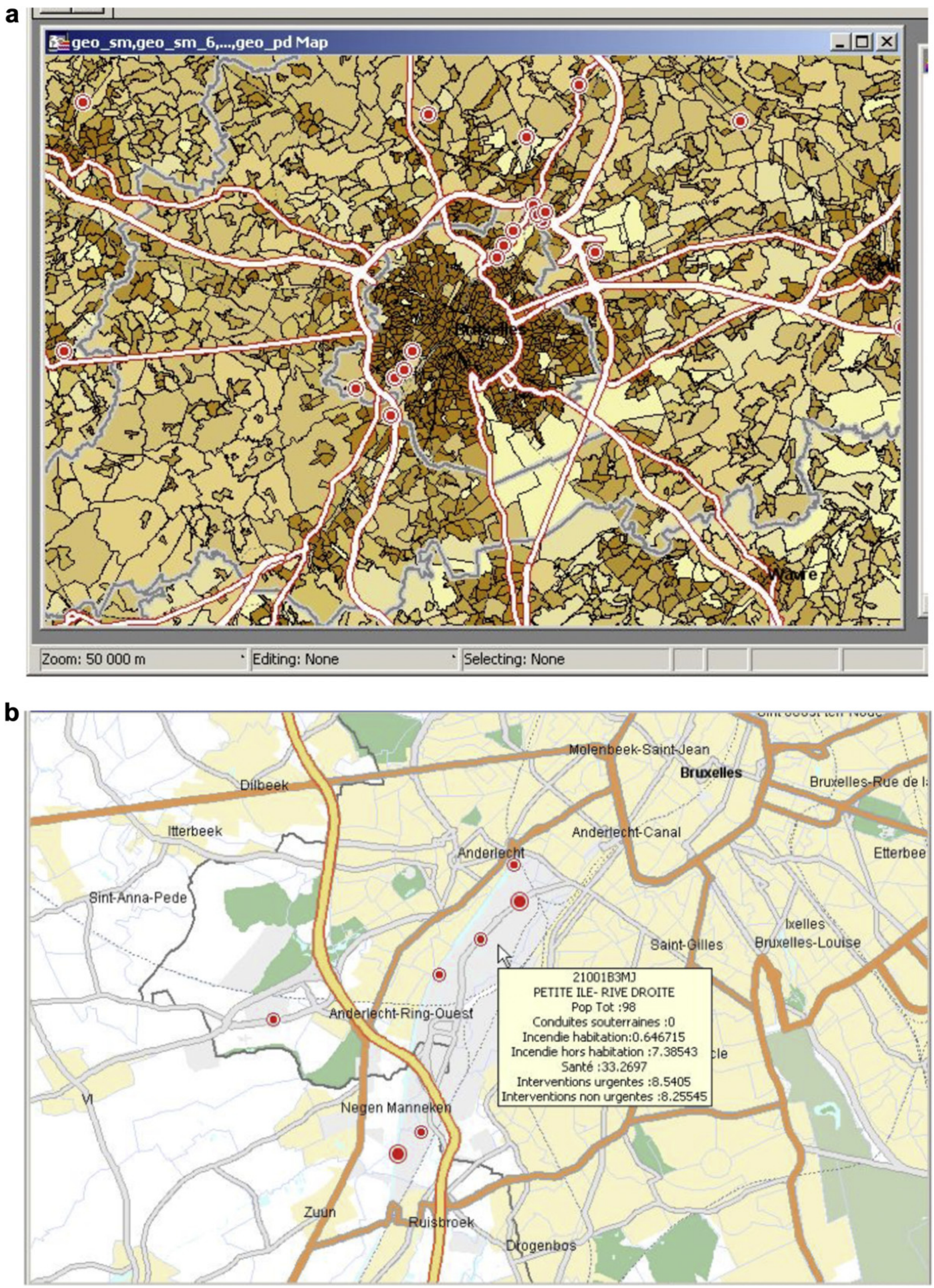

Fig. 5. (a): System window showing the population density and sporadic risk sources. (b) Example of interactive window: by clicking on any BSU, it is highlighted and the relevant risk information is displayed.

enable them to arrive on the scene of a given proportion of emergencies within a given time (for example, 90% of emergencies within 8 min), 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 min 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 travel time for arriving at the 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 1. Eiselt and Marianov [7] examine different formulations for taking the quality of service into consideration 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; more details are given in Appendix 2.

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 a crew is available in the closest fire station, it will deal with the situation. If not, we look for such a crew in the second-nearest fire station, and so on until a crew is found. The calls are divided in two categories: medical emergencies for which an ambulance is dispatched, and "other emergencies" for which a fire brigade is dispatched. This standard intervention rule depends on the location of the fire station to reflect the local risk types (facility of access to water, terrain type, construction type, etc.). The hypercube queuing model [15] 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 (see Appendix 2). A local search heuristic is then used to optimize the staffing of each station to meet the overall service level. By staffing we mean the number of ambulances and the number of fire brigades (consisting of several vehicles), with their respective crews. For highly specialized equipment, the location was only based on a covering approach, the frequencies being too low to warrant a queuing type approach.

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 in which 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

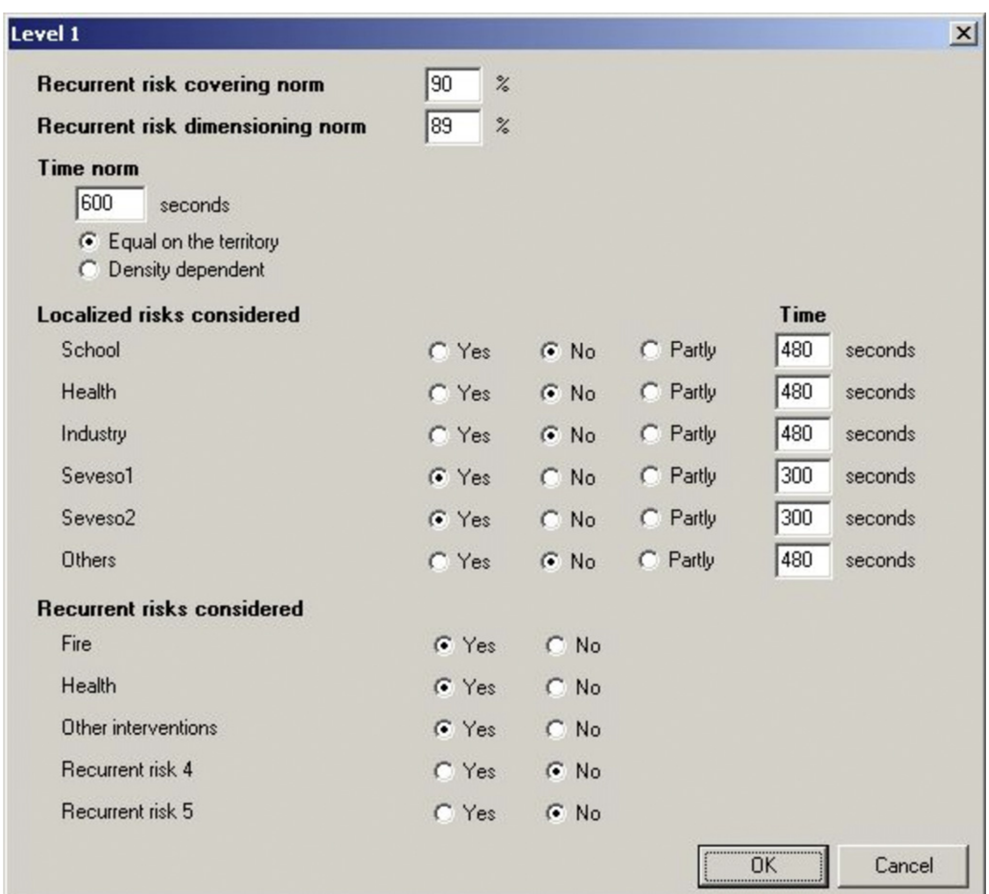

Fig. 6. System window presenting the options for the parametrization of risk to be considered for the optimization.

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).

5. Implementation and utilization of the decision aid tool

5.1. Implementation

The application was built on top of the Mapinfo GIS software; all optimization routines were coded in C++ by the implementation partner Adhoc Solutions (now part of the Experian Group).

The application consists of three parts. In the first part, the user can define scenarios and visualize the data corresponding to the scenario (location and distribution of the different types risks). An example is shown in Fig. 5.

The second part is the optimization model, where the user can define 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). As shown in Fig. 6, with a single click the user can then run the optimizer to find the best solution either for the entire country or for some part of it.

Finally, the application provides several visualization tools to analyze the proposed solution (expected intervention speed at each point of the territory, localization of fire stations, etc.). An example is shown in Fig. 7.

5.2. Utilization of the tool

To show the potential of the tool, let us now provide an illustration of the first studies realized with the tool. The prevailing situation is that the service area of each fire service corresponds to one or several communes. A first analysis revealed the dramatic impact these boundaries have on service performance. It would thus seem interesting 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 and also politically not possible. Our computations showed that operating within each province (*Nuts2*) causes little loss of efficiency but gives better control of the service level. This is mainly due to the intra-national diversities, where some provinces are much more densely populated than others. The 'optimal' solution at the national level strongly favors 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; by

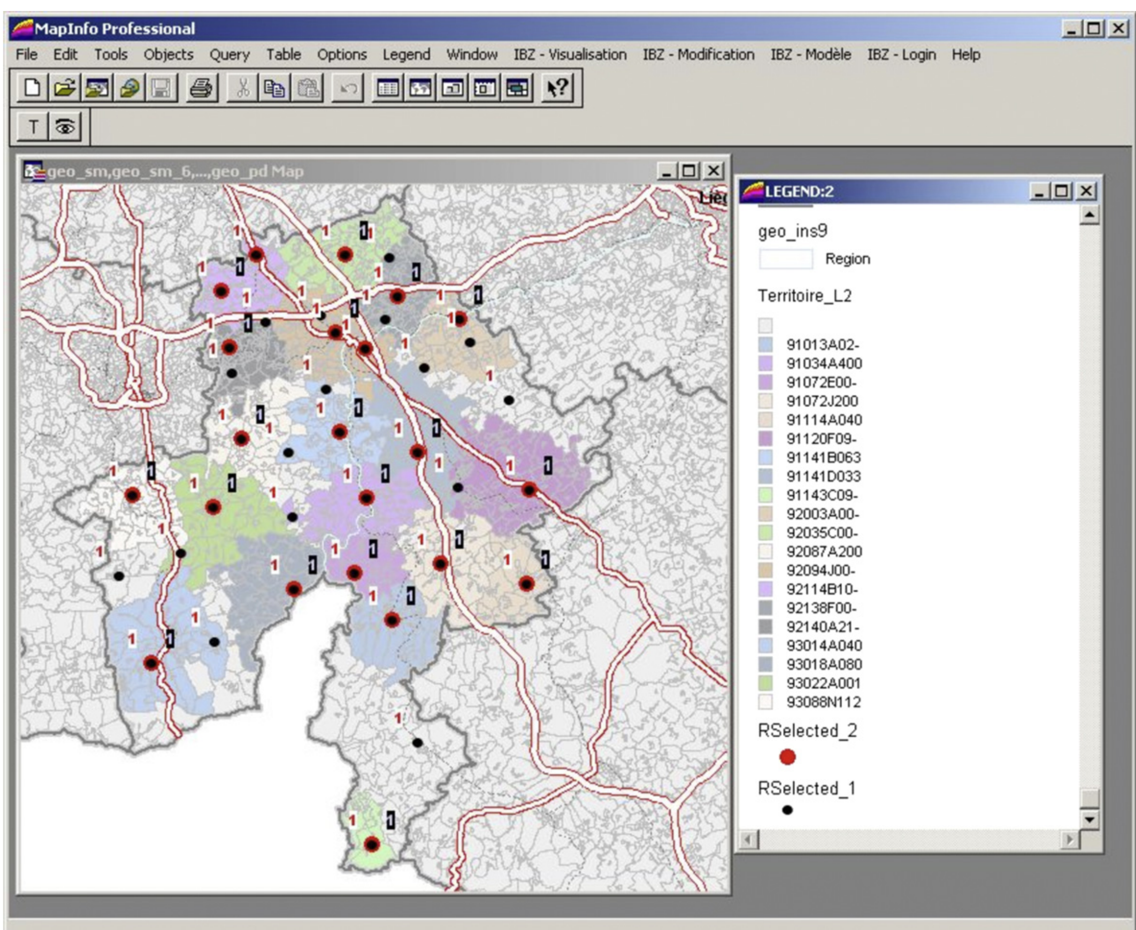

Fig. 7. Results window: little black dots represent level 1 fire stations, while red dots represent level 2 fire stations. The number above left represents the number of level 1 crews in the station, and the number above right represents the number of level 2 crews (for confidentiality reasons these results are based on fictitious data and the legend has been coded). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

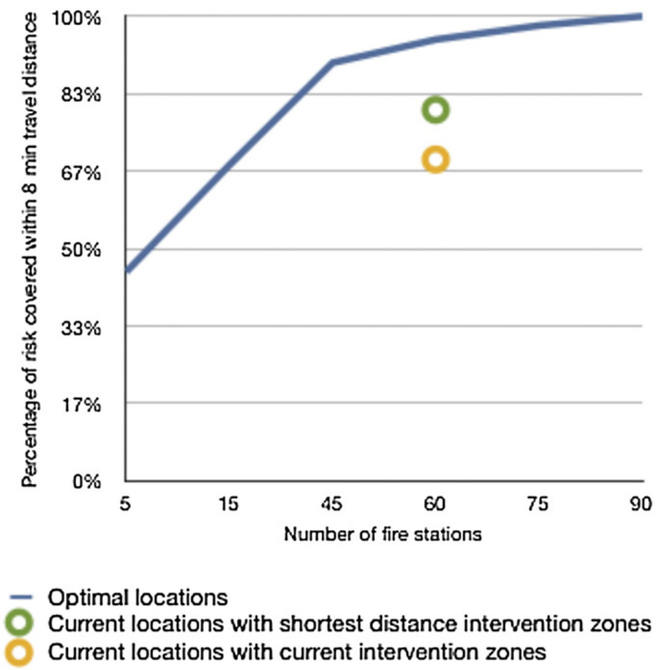

Fig. 8. Trade-off between the number of fire stations and the percentage of risk covered in a province.

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 min for all categories of recurrent risk. Fig. 8 shows the results obtained for one province. There are currently 60 locations in this province. With the current intervention rules (the brigade sent is based on the commune where the emergency is located) about 69% of emergencies can be reached within 8 min. Determining the intervening brigade based on the closest location increases the proportion of emergencies that can be reached within 8 min to 80%. Finally, by relocating stations to optimal locations, 95% of the emergencies could be reached within 8 min with the same number of fire stations.

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.

The tool has been used extensively for different purposes. First, a few new fire stations were built and the tool helped identify the best locations based not only on the current situation, but also on scenarios of possible evolutions (relocations of other stations, etc.). The tool also evaluates the number of crews necessary at each location. The availability of the tool enabled the Ministry to run a large number of what-if scenarios. This in turn made the dialog with the local authorities much easier.

6. Conclusion

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 fire services (in Belgium these include the communes, the federal emergency service agency and the firefighters' unions). Using this tool, it is much easier to assess the impact of various planning decisions and to avoid power struggles. 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 and to take into consideration the variety of tasks and spatial behaviors.

The project presented in this paper resulted in an efficient and very flexible decision-support method that has really assisted Belgian decision makers, and also helped them to achieve a better understanding of the functioning of the Belgian fire services. It is important to stress that the quality of the results depends upon the quality of the empirical data. Given the many data sources consulted, fruitful collaboration with all the data organizations proved to be a real challenge, especially for getting spatially disaggregated national data. 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 in the future.

The tool developed is systematically used for all decisions related to this national reorganization plan of emergency services. The direct benefit is hard to assess as such a national reorganization involving the building of new facilities and the closing of some existing facilities takes a lot of time (the first phase of the reorganization was only implemented in 2010). Nevertheless the fact that the tool is systematically used shows that it brings some value for the decision makers.

To enhance the value of the tool, a process should be built for the data to be kept up to date with the latest statistics collected. It would also be valuable to have tools to build future scenarios based not only on current data but also on the anticipated evolution of the main data. The tool does not provide 'the ultimate solution'; however it does make an important contribution to rational, evidence-based, informed decisions that 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.

Appendix 1

The recurrent risk associated with each BSU is represented by five rates, corresponding to the five 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:

$$\min \sum_i y_i$$

$$\text{s.t.} \quad \sum_i a_{ij} y_i \geq z_j, \quad \forall j \tag{1}$$

$$\sum_j w_j z_j \geq P \sum_j w_j \tag{2}$$

$$\sum_i b_{ij} y_i \geq 1, \quad \forall j \in S \tag{3}$$

$$y_i \in \{0,1\} \quad \forall i$$
$$z_j \in \{0,1\} \quad \forall j$$

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.

Constraint (1) expresses that a BSU j can only be considered as "covered" if there is a fire station located within acceptable distance. Constraint (2) imposes that a fraction P of all events are located in BSU's that are covered within the acceptable distance. Constraint (3) says that there must be a fire station within the acceptable distance of all sporadic risks. This formulation is similar to that proposed by Toregas et al. [29], Church and ReVelle [3] and Tong and Murray [27]. 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 [18]. This heuristic has a reliably short running time and led to solutions that were almost as good as the optimal ones. Tong et al. [28] follow a similar approach.

Appendix 2

Hypercube model

The staffing problem was solved using a hypercube queuing model [15] that represents geographically dispersed servers. The model was run for two types of servers, the ambulances and the fire brigades. The model is run for one province at a time, as the province roughly corresponds to the maximum size of that a unit could travel in an emergency condition. The hypercube queuing model is based on nine key assumptions:

1. *Geographical atoms*: the area of service is divided into a finite number of points, in our case BSUs.
2. *Independent Poisson arrivals*: service requests are supposed to follow independent Poisson processes with a fixed arrival rate for each geographical atom. For the fire brigades model the arrival rates are based on the estimated risk for fire-related emergencies and non-medical emergencies at the peak hour of the day. For the ambulances the rates are based on the medical emergencies (see Section 3.2).
3. *Travel times*: were estimated with speed parameters that depend on the type of vehicle (ambulance or fire truck).
4. *Server locations*: the server locations are determined by the location problem.
5. *Servers*: at each location we require at least one server of each category (in the case of a medical emergency it is one ambulance, in the case of a non-medical emergency one server consists in three vehicles two different fire trucks and a command vehicle). If the average waiting time is too high for some BSUs then an additional server is added to one of the closest locations according to the local search heuristic.
6. *Server assignment*: one unit (ambulance or fire brigade) is sent for each call, if no server is available in the entire region of study, the call is put on a waiting list. In reality in the exceptional circumstance where too many servers would be busy in an area, some brigades would move in preventively to the fire station where no brigade is available anymore. This is neglected as such moves should remain exceptional.
7. *Fixed preference dispatching*: when an emergency arises in one BSU the servers will be called by order of time to arrive to the center of the BSU. This preference order is fixed and is not changed based on the conditions at the time of the call (some stations might already have almost no resources left). This corresponds to reality, although when the last unit of a station leaves, the station will call on stations that are not busy to send a brigade to stand-by in the empty station. As explained above this is neglected in the model.
8. *Service times*: the total service time (including travel time, on-site time and potential follow-up activities) is exponentially distributed. This assumption might seem very restrictive but it has widely been observed that for distributions with reasonable deviations the accuracy of the model stays very good.
9. *Service time dependence on travel time*: the variation of the service time due to travel is assumed to be of second order compared to the variation of the on-site time. The expected service time only depends on the server that handles the emergency. This assumption would not be satisfied at all if the model were used for a very large region. It is one of the reasons why the model is used region by region.

Given these assumptions the model computes the mean travel time and average workload for each fire station, the fraction of calls that are answered from a station that is not the closest for each BSU and the fraction of calls that have to wait before a suitable unit is available.

For N servers, this model requires the resolution of a system of 2^N linear equations. For one province the number of servers can quickly reach 100 (remember that one station can contain several servers), this makes the exact resolution impractical. We used the approximation procedure presented by [15] that only requires solving a system of N non-linear equations.

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