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Optimizing Fire Station Locations for the Istanbul Metropolitan Municipality

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The Istanbul Metropolitan Municipality (IMM) seeks to determine locations for additional fire stations to build in Istanbul; its objective is to make residences and historic sites reachable by emergency vehicles within five minutes of a fire station's receipt of a service request. In this paper, we discuss our development of a mathematical model to aid IMM in determining these locations by using data retrieved from its fire incident records. We use a geographic information system to implement the model on Istanbul's road network, and solve two location models—set-covering and maximal-covering—as what-if scenarios. We discuss 10 scenarios, including the situation that existed when we initiated the project and the scenario that IMM implemented. The scenario implemented increases the city's fire station coverage from 58.6 percent to 85.9 percent, based on a five-minute response time, with an implementation plan that spans three years.

Key words: fire station location; set-covering problem; maximal-covering problem; geographic information system.
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Determining fire station locations in any city has been, and will continue to be, of significant interest to practitioners and researchers. Suitable locations are critically important for megacities such as Istanbul, Turkey. With a population of 13.5 million (TURKSTAT 2011), Istanbul is among the world's largest cities and is the cultural and financial center of Turkey. The city extends across the European and Asian sides of the Bosporus Strait and is the world's only metropolis that is situated on two continents. Since 2003, Istanbul has welcomed 2.5 million immigrants and has continuously grown and expanded, resulting in problems such as traffic congestion and infrastructure deficiencies; consequently, fire station locations no longer meet the city's needs. Determining the number and location of fire stations to enable fire-fighting vehicles to respond to fire incidents (i.e., any instance of an open flame or other burning in a place not intended to contain the burning or in an uncontrolled manner) as quickly as possible is of utmost importance. The Istanbul Metropolitan Municipality (IMM) serves 790 mutually exclusive and collectively exhaustive subdistricts in Istanbul and aims to respond to each fire incident within five minutes.

Facility location problems involve the location of facilities to economically serve clients. The objective of the optimization problem is to choose a subset of locations at which to place facilities to minimize the cost of serving clients. The objective of the set-covering problem is to minimize the cost of a facility location to obtain a specified coverage level (i.e., reachability from a location to a client), as Owen and Daskin (1998) discuss. Although the set-covering problem determines the number of facilities needed to guarantee 100 percent coverage, a decision maker's allocated resources may be insufficient to build all the facilities that the model determines. Location goals must then be shifted to maximize the coverage the available resources can provide. This is the maximal-covering problem (Church and ReVelle 1974). As a variant of the set-covering problem, the maximal-covering problem seeks to maximize the amount of demand covered within the acceptable service time S by locating a fixed number of facilities. The main difference between the two problems is that all demand must be met (covered) in the set-covering problem, whereas some demand may be left unmet (uncovered) in the maximal-covering problem (Hale and Moberg 2003).

Many practical problems (e.g., this fire station location application) can be formulated as set-covering problems. Such problems include a set of potential sites (e.g., subdistricts of Istanbul), $N = \{1, \ldots, n\}$, for locating fire stations. Placing a station at site j costs c_j. They also include a set of communities, $N = \{1, \ldots, n\}$, that must be protected against fire events. Then, the subset of communities that can be protected from a station located at j is N_i, such that $j \in N_i$. For example, N_i is the set of communities that can be reached from j in five minutes (i.e., the acceptable service time S is five minutes). Then, the problem of choosing a minimum-cost set of locations for the fire stations, such that each community can be reached from some fire station in five minutes, is a set-covering problem (Nemhauser and Wolsey 1999).

We refer to the location of a potential fire incident as covered if it is reachable by a fire emergency vehicle within this time, and the coverage area of a fire station is the set of all subdistricts of the city that are reachable from the station in the determined time (i.e., five minutes for Istanbul). The location of a fire station is also a long-term capital investment decision because once a station has been built, it cannot be moved easily. Therefore, each station location must provide the best possible coverage for residents.

Two other factors contribute to the need for developing effective fire station coverage in Istanbul. First, the city is located on a seismic belt and has suffered many major earthquakes. The most recent significant earthquake occurred in 1999 within 100 kilometers (62 miles) of Istanbul's city center and claimed more than 17,000 lives (Madrigal 2009). Another major earthquake of magnitude seven or higher is expected in the region within the next 20 years. Clearly, such catastrophic events create a logistical nightmare for humanitarian aid and for fire response operations; therefore, appropriate preparations are necessary if emergency personnel are to save as many lives as possible. Second, with more than 2,500 years of history, Istanbul is a proud home to hundreds of palaces, castles, mansions, pavilions, fountains, monuments, and archaeological sites dating back to Ottoman and Roman times. In recognition of this cultural heritage, the European Union selected Istanbul as one of the three European capitals of culture in 2010, and the UNESCO world heritage list included historic areas of Istanbul in 1985 (UNESCO 2010). Sadly, some of this heritage is lost each year to fires that occur for a variety of reasons, including sabotage. Protecting these treasures from such damage with effective fire response operations is of crucial importance.

The main objective of our research is to guide IMM in its fire station location decisions. We include additional measures in this study to account for some of the factors discussed above, such as protecting cultural heritage sites. The remainder of this paper is organized as follows. *Istanbul's Fire Station Location Problem* describes the problem. The *Literature Review* section provides a literature survey for fire station location problems and the *Proposed Model* section gives highlights of the models we proposed for IMM. The *Solution Methodology* section discusses data acquisition and model development. This section also describes our scenario analysis, which we use to analyze the problem from various perspectives and to consider the historical value of the city. The *Approval and Implementation* section gives information about the project phases, IMM's response to the results, and the implementation. The *Impact* section elaborates on the significance and impact of our research comparing the existing situation at the beginning and at the end of the research. Finally the *Summary* section provides highlights of our research.

Istanbul's Fire Station Location Problem

In 2008, IMM decided to review the current status and service performance of Istanbul's fire stations. As part of an ongoing improvement initiative, *Istanbul, My Project*, IMM issued an open call to universities for research projects that would improve the quality of various public services that Istanbul offers. We submitted a proposal to develop a plan for facility expansion using a mathematical model, and IMM awarded us the project. Our project's objective is to aid IMM in determining the optimal locations of additional fire stations. To achieve this, we developed set-covering and maximal-covering models that serve to optimize the locations of fire stations under operational constraints.

Timeliness is one of the most important aspects of the quality of emergency services, such as medical or fire response, and mathematical programming is a frequently used approach to solve the emergency service location problem (Araz et al. 2007). The literature includes two main classes of models that address locating emergency response facilities: (1) set-covering or maximal-covering models, which aim to locate sufficient facilities to cover demand within a specified response time, and (2) center-type or p-center models, which aim to locate a fixed number of facilities to achieve a minimal systemwide maximum response time. With the latter approach, at most p new facilities can be located, potentially resulting in unacceptably long response times. Therefore, set-covering and maximal-covering models are more useful as emergency service location models. In the next sections, we provide an overview of the mainstream facility location literature on these two types of models, and discuss the models we use to solve IMM's fire station location problem.

Literature Review

A set-covering formulation seeks to select a minimum subset of candidate locations that collectively covers all demand points within the maximum allowable response time (Toregas et al. 1971). Hogan and ReVelle (1986) suggest a backup coverage scheme for decision making on emergency service locations. Church and ReVelle (1974) use the maximal-covering model for situations in which the number of vehicles available is less than the number necessary to cover all service requests, for example, in public services such as IMM's fire station location problem. Daskin et al. (1988), ReVelle et al. (1996), and Alsalloum and Rand (2006) study the integration of different coverage models such as multiple coverage, expected coverage, and coverage with surplus and surrogates. ReVelle and Hogan (1988) extend the notion of maximum expected coverage by introducing probabilistic location set-covering models. Karasakal and Karasakal (2004) examine the notion of partial coverage, which they define as a function of the distance of the service request points from the facility. Sorensen and Church (2010) combine the local reliability parameter of maximum availability with maximum expected coverage formulation in the context of emergency medical services, and use simulation to test the applicability of theoretical assumptions used in these models to real-world problem domains. Catay et al. (2008) propose a backup double-coverage model that is based on the well-known set-covering and maximal-covering location problems, and describe three heuristics to solve them.

The location problem of spatially distributed urban emergency service systems (e.g., police, fire, and ambulance services) is characterized by the maximum time or distance that separates a citizen from the closest service station (Toregas et al. 1971, Larson 1974). Such location problems are discrete optimization problems and have attracted the interest of many researchers, including Valinski (1955), Toregas and ReVelle (1973), Doeksen and Oehrtman (1976), Plane and Hendrick (1977), Schilling (1982), Badri et al. (1998), and Tzeng and Chen (1999). The problem is difficult to solve (Garey and Johnson 1979), and real-life applications with a large number of locations may require unacceptably long computation times and amounts of resources using standard exact solution approaches. Hence, many researchers, including Tzeng and Chen (1999), Cheung et al. (2001), and Salhi and Gamal (2003), propose metaheuristics (e.g., genetic algorithms) for solving large-scale problems. Previous researchers, including Cheung et al. (2001), Diwekar (2003), Badri et al. (1998), and Araz et al. (2007), also suggest multiobjective fire station location problems for incorporating strategic and operational objectives, such as considering politically favored sites or water availability of the site. Brandeau and Chiu (1989), Drezner (1995), and Drezner and Hamacher (2002) provide an extensive analysis of general location strategies for single-level location problems, and Sahin and Sural (2007) conduct the same analysis for hierarchical facility location problems. Goldberg (2004) provides a taxonomy of emergency system location problems. Finally, Swersey (1994) and Marianov and ReVelle (1995) provide a review of real-life applications of emergency service models, and Gormez et al. (2011) investigate the problem of locating disaster-response and relief facilities in Istanbul. They use mathematical models to determine the locations of new facilities; their objective is to minimize the weighted-average distance between casualty locations and their closest response and relief facilities, while opening the smallest possible number of new facilities, subject to distance limits and backup requirements under regional vulnerability considerations.

A geographic information system (GIS) is used frequently to give input to emergency location models (Dobson 1979, Liu et al. 2006). Church (2002) provides a detailed account of how such systems are used in location problems. We use them to characterize the fire incident data in terms of location and frequency.

Proposed Model

Based on the characteristics of the problem described previously, we use set-covering and maximal-covering models in our study. Our main objective is to minimize the number of new fire stations to serve all subdistricts within at most five minutes (i.e., fixed travel time). Binary decision variables are potential locations for fire stations in the subdistricts. The constraints ensure that each subdistrict is served by at least one fire station. The approach we present includes the use of a GIS to provide the necessary input data for the location problem. In building a discrete optimization model, a risk always exists that we will find that it cannot be solved within a reasonable time (Williams 1999). Fortunately, because of its relatively small problem size, we can solve our integer programming model using mathematical programming and optimization software.

The first step is to develop a set-covering model (see Appendix A). IMM's service level requires that each subdistrict must be reached in at most five minutes. This is in line with the classical set-covering model (Toregas and ReVelle 1973), which we apply to our fire station location problem. Similar response time criteria are also found in the United States (National Fire Protection Association 2011)—four minutes of travel time, excluding call taking and preparation time, to respond to at least 90 percent of incidents. The demand locations in our case are centroid subdistricts of the city; hence, covering a subdistrict means reaching the centroid within five minutes, which is equivalent to covering the entire subdistrict. Because fire incident data are recorded at the subdistrict level, we use subdistrict (i.e., service request) data points in the constraints.

In response to IMM's budget restrictions, we also formulate the problem using the maximal covering model (see Appendix B), where the objective is to cover the maximum number of possible locations by opening as many locations as possible, given budget constraints. This is particularly relevant because local governments operate on annual budgets and want to extend the services they offer in the best possible way using available financial resources.

Istanbul's history and culture necessitate special consideration. To incorporate additional rules imposed by IMM, we formulate and solve a hierarchical version of the maximal-covering problem (Moore and ReVelle 1982) to understand and address the fire risks associated with city's cultural heritage sites. Weighted set-covering models assign weight or cost values to location decisions; in this version of the proposed model, we assign weights to subdistricts in parallel with the presence of heritage sites. This effectively prioritizes different classes of service requests; that is, a service request might be viewed either in the traditional sense (i.e., subdistricts of the city that need fire coverage) or as historical or cultural assets. Appendix B provides further details of the maximal covering model.

A similar prioritization effect can be achieved by using a multicoverage facility location model from the literature. This type of model tries to cover places of higher importance more than once within the maximum response time, and the mathematical programming models accordingly determine optimal locations. Such a model requires more and larger facilities because multicoverage constraints result in more service requests; therefore, we do not to take this approach. Coincidentally, IMM's priority is to maximize coverage with respect to the five-minute response time under its fixed budget rather than maximizing multicoverage. However, we analyze the results in this respect to observe the level of ineluctable multicoverage, and find that the scenario selected by IMM, Scenario 6 (Budget) (see Table 3), produces double coverage for 35.6 percent of the subdistricts. To a degree, this eliminates the need to consider the possibility of simultaneous fire incidents that require the services of a single closest fire station.

Solution Methodology

Data Acquisition

At the beginning of this study, Istanbul had 60 active fire stations in four size categories: *A*, *B*, *C*, and *D* (see Table 1). Categories *A* and *B* are referred to as groups and act as centers; categories *C* and *D* are called squads and are designed as smaller outposts. For example, IMM's firefighters addressed 45,050 fire incidents in 2009, and their average working time on fire incidents was 40 minutes. We incorporate these differences in capacity and cost in the set-covering and maximal-covering models.

To implement our model, we obtain historical fire incident data for 1994–2006 from IMM. These include the number of fire incidents by subdistrict for Istanbul's 60 fire stations. Of these stations, 37 are located on the European side of the city and the remaining 23 are on the Asian side. We use fire incidents recorded by IMM as service requests issued from each subdistrict, and we use ArcGIS, a GIS for working with maps and geographic information, to facilitate data collection and processing for the set-covering and maximal-covering models. A GIS enables users to store, retrieve, manipulate, analyze, and visualize geographical content in various types of spatial data sets. Its central element is the use of a location-referencing system to enable users to analyze the data about a specific location relative to another location (Church 2002). It also enables users to display, edit, and analyze spatial data by linking digital map layers to spatially enabled databases. The layers of the GIS map relative to the fire station location problem include data sets, such as roads, parcels, hydrants, community networks, topography, lakes and rivers, business and community buildings, and fire station locations.

Station type	Size (square meters)	Cost ($)	Annual capacity per station	Stations in operation in 2009
A	3,650	1,018,413	13,140	14
B	2,900	809,150	10,950	16
C	2,525	704,519	8,760	20
D	2,150	599,887	4,380	10

Table 1: For each station category, the table shows size, cost, capacity information, and number of fire stations in operation when we initiated the project.

We use ArcGIS on a digital data set of Istanbul to determine the coverage areas of existing fire stations by considering the types of roads and travel speeds on these roads. We use network analysis tools in ArcGIS to calculate travel times between subdistricts of the city in both urban and rural areas. Istanbul's roads can be categorized as highways, major streets, or local streets—classifications based solely on the average speeds of firefighting vehicles. Highways have the highest average speed because they are less congested and have special emergency lanes that firefighting vehicles can use. Local streets have the lowest average speed because they have the narrowest lanes, the highest congestion level, and the slowest traffic flow because of constant interruptions by traffic lights and other obstacles. ArcGIS represents each road segment as a separate record associated with distance and average speed attributes. Using these attributes for each road segment, we calculate the time it takes a firefighting vehicle to traverse the respective road segment. We then build a topological network structure for Istanbul using all the calculated travel times.

Using ArcGIS, we first develop a map of Istanbul with its 40 districts and 790 subdistricts. Each subdistrict that does not have a fire station is a candidate location for opening a new fire station. We represent each subdistrict as a single point for distance calculations; to do this, we take the polygonal footprint of each building in the subdistrict, convert each footprint to a single point at the polygon's center of gravity, and merge all such points in the given subdistrict into a single point by averaging the $x-y$ coordinates of these points. This helps us to avoid locating fire stations in uninhabited areas, such as fields and forests. After determining all such candidate locations, we create a proximity matrix in which

	156	158	159	161	178	190	211	212	213	215	216	218	219	220
156	1		1	1			1		1			1	1	
158		1		1	1				1	1		1		1
159	1		1					1				1	1	
161	1	1		1			1		1	1				1
178		1			1	1	1			1	1	1		1
190					1	1		1	1			1	1	
211	1			1	1		1			1	1		1	
212			1			1		1	1	1				
213	1	1		1		1		1	1			1		
215		1		1	1		1	1		1		1	1	
216					1		1				1	1		1
218	1	1	1		1	1			1	1	1	1		1
219	1		1			1	1			1			1	
220		1		1	1						1	1		1

Table 2: In this proximity matrix example, the value in a cell is 1 if the representative point of a destination subdistrict can be reached from that of an origin subdistrict within five minutes; otherwise, it is blank.

each row and column represents an origin and destination subdistrict, respectively. Istanbul has 790 subdistricts; Table 2 shows a small subset of the 790 × 790 proximity matrix. Each subdistrict is covered if it is reachable from a subdistrict with a fire station within five minutes. We use the ArcGIS network analyst extension to calculate this matrix, which indicates the subdistricts that are within five minutes of travel time of each other, using the actual street network. We do not include villages, military areas, forests, or other special areas (e.g., airports) in the matrix because their fire station directives differ from those of IMM. The proximity matrix is not necessarily symmetric; the fastest route originating in one subdistrict and reaching another may differ from the fastest route in the reverse direction (e.g., because of road networks or one-way streets).

Using this data, we code the integer programming models (see Appendix A and Appendix B).

Scenario (number and title)	Description
1: Initial	Represents Istanbul's existing situation when we initiated the research, including the locations of existing fire stations and their respective coverage areas.
2: Full	Uses the set-covering model, which minimizes the number of fire stations to be opened, and the existing stations reported in Scenario 1 to fully cover Istanbul (100 percent coverage) within a five-minute response time.
3: Full forecast	Reports the coverage of fire stations opened in Scenario 2 with forecasted fire incidents for 2015.
4: Scratch	Assumes no existing fire stations and uses the set-covering model, which minimizes the number of fire stations to be opened to cover Istanbul fully (100 percent coverage, no existing stations assumed). The purpose of this scenario is to determine the percentage of IMM's fire station locations that would be included in the solution set if we built the fire station network from scratch.
5: Scratch forecast	Reports the coverage of fire stations opened in Scenario 4 with forecasted fire incidents for 2015.
6: Budget	Considers IMM's budget restrictions and uses the maximal-covering model, which maximizes the number of locations to be covered under IMM's given budget.
7: Budget forecast	Reports the coverage of fire stations opened in Scenario 6 with forecasted fire incidents for 2015.
8: Heritage	Considers the IMM's budget restriction and uses the maximal-covering model, which maximizes the number of locations, weighted by the presence of heritage sites to be covered under IMM's given budget.
9: Heritage forecast	Reports the coverage of fire stations opened in Scenario 8 with forecasted fire incidents for 2015.
10: Past	Looks at the coverage status in 2005. We use this scenario for comparison purposes.

Table 3: The table shows the scenarios we use and their corresponding explanations.

Scenario Analysis

We use set-covering (see Appendix A) and maximal-covering (see Appendix B) models to analyze Istanbul's fire station location problem using 10 scenarios (see Table 3).

We use Scenario 1, Istanbul's existing situation when we initiated the project, as the baseline for our analyses. Scenarios 2–5 consider the cost (c_j) of opening a station at j, which covers a set of subdistricts ($N_i \mid j \in N_i$); in these scenarios, we seek minimum-cost coverage (i.e., to minimize the number of fire stations). In Scenarios 6–9, we consider the weight (w_i) of covering sets of subdistricts (N_i), and we seek maximum-weight coverage (i.e., to maximize the number of locations covered). The number of fire incidents is especially important in Scenarios 6–9 because the objective function is to maximize coverage relative to service requests (see Appendix B for the mathematical model). In Scenario 8, we adjust the service requests, as described in Appendix B, using weights that represent the density of heritage in each subdistrict (i.e., number of heritage objects in each subdistrict).

In the odd-numbered scenarios (Scenarios 3, 5, 7, and 9), we use the solutions of the even-numbered scenarios (Scenarios 2, 4, 6, and 8) and calculate the coverage with forecasted fire incidents for 2015 to test the robustness of our solutions. We use a logistic function to forecast the number of fire incidents as a function of population increases in the districts, because the logistic model is consistent with Malthusian and other theories of constrained population growth (George et al. 2004), and we can estimate domestic fire incidents using population size (Tayman et al. 1994). Appendix C shows the details of our forecasting model. In Scenario 10, we report the coverage status in 2005 to give an overall picture of the past, present, and potential future with all our scenarios. Finally, we conduct sensitivity analysis for a range of budget limitations and compare the results to the existing budget.

Results

We use GAMS to code the integer programming model and solve it using the CPLEX 11.0 solver. The largest model has 3,208 binary variables and 6,416 constraints and required 0.781 seconds to solve using a personal computer with an Intel® Core™ 2 Duo CPU T7500 @ 2.20 GHz processor and 2 GB RAM on a 32-bit operating system. Table 4 shows the results that each scenario generated.

For each scenario, we evaluate three aspects of coverage. The first is the percentage of subdistricts covered (C_{SD}). In this aspect, we also report the percentage of subdistricts covered twice (C_{double}) and three times (C_{triple}) to determine the percentage of subdistricts within a five-minute travel time of at least two and three fire stations, respectively. The second aspect is the percentage of service requests (i.e., the percentage of fire incidents) in the subdistricts covered (C_{SR}). The third aspect is similar to the second; however, we change the weight of the subdistricts in the objective function according to the distribution of heritage service requests (C_{HSR}). For all three aspects of coverage, we assume that a subdistrict (or all fire incidents in that subdistrict) is covered if the subdistrict's center of gravity is reachable from a fire station

	Number of fire stations			Coverage (%)					
Scenario	E	N	T	C_{SD}	C_{double}	C_{triple}	C_{SR}	C_{HSR}	Total cost ($)
1	60	—	60	58.6	15.1	0.4	56.6	18.2	47,293,423
2	60	149	209	100	37.2	4.3	100	100	136,676,586
3				100	37.2	4.3	100	100	
4	—	193	193	100	28.4	0.8	100	100	115,778,191
5				100	28.4	0.8	100	100	
6	60	64	124	85.9	35.6	2.8	93.9	71.1	85,686,191
7				85.9	35.6	2.8	93.1	70.7	
8	60	64	124	82.0	31.0	3.1	86.6	98.4	85,686,191
9				82.0	31.0	3.1	85.1	96.9	
10	50	—	50	46	3	0	43	9.2	40,771,394

Table 4: The table shows the results of our analysis of each scenario.
***Notes*: E = existing, N = new, T = total, C_{SD} = subdistrict, C_{double} = doubly covered, C_{triple} = triply covered, C_{SR} = service requests, C_{HSR} = heritage service requests.**

within five minutes. Generally, either the entire area or the mainly inhabited area in the subdistrict satisfies this criterion. Appendix D shows the details of our coverage calculations. Finally, we calculate the costs of opening the required new stations in US dollars. We convert the cost in Turkish currency (TRY) using the exchange rate as of March 3, 2009, the day on which we did the calculations for the project; on that day, 1 USD = 1.7257 TRY.

In Scenario 1 in Table 4, the coverage of service requests in Istanbul at the time we initiated the project is 56.6 percent; for heritage service requests, it is 18.2 percent. Considering the value of Istanbul's historical treasures, this coverage percentage is dramatically low. In Scenario 2, the total number of stations required to achieve 100 percent coverage is 209, where 149 new stations should be opened at a cost of $136,676,586. This number of stations is about 8.3 percent more than the ideal situation in Scenario 4 (i.e., 193 stations for 100 percent coverage). The substantial cost difference between the two scenarios is because of the size of the stations that the models propose opening. In Scenario 4, all stations that the model suggests opening are type D; this result follows from the historical fire incident data, which indicates that the larger station types (A, B, and C) are typically underutilized and that the capacity of type D is sufficient to respond to most fire events, suggesting that the existing stations have excessive capacity.

Moreover, subdistricts are doubly covered (C_{double}) in Scenario 2 (37.2 percent), Scenario 4 (28.4 percent), Scenario 6 (35.6 percent), and Scenario 8 (31.0 percent); however, no model specifically includes this multicoverage feature. We can explain the difference between Scenarios 2 and 4 as follows: Scenario 4 minimizes the number of fire stations in the city, disregarding existing stations; hence, it distributes station locations on the city map more randomly. Furthermore, 59.6 percent of these doubly covered subdistricts are of historical importance (i.e., they have an above-average number of heritage objects). Such subdistricts have at least two fire stations within a radius of five minutes of travel time. This finding significantly eliminates the need to locate additional fire stations and the associated additional cost to achieve multicoverage.

When we analyze the results of the forecast scenarios (Scenarios 3, 5, 7, and 9) in Table 4, we observe that these scenarios, which incorporate future fire service requests with the fire station locations suggested by their counterparts (Scenarios 2, 4, 6, and 8, respectively), perform at approximately the same level as their counterparts; this indicates the robustness of the solutions produced under Scenarios 2, 4, 6, and 8. Our solutions produce similar coverage levels under service requests forecasted for 2015.

Figure 1 presents the existing fire station locations (Scenario 1) with their coverage areas. We show the locations of fire stations as white circles and the areas within the coverage radii of these locations in darker shades. The light-shaded areas are the subdistricts that cannot be served because of lack of coverage.

When we conducted this study in 2009, 58.6 percent of Istanbul (463 of 790 subdistricts) was covered by 60 fire stations. Many densely populated subdistricts cannot be served within the five-minute service threshold and need immediate action. This lack of coverage could be a result of the megacity's expansion or of changes in the road network structure. Moreover, based on historical fire incident data, fire stations in operation in Scenario 1 could respond to only 56.6 percent of service requests in under five minutes. This gap between subdistrict coverage and service request coverage results from misallocation of fire stations; they were built without considering changes in the city and potential demand for service over the years. Moreover, many areas in Istanbul were previously forests or uninhabited areas, which have been converted to residential and commercial zones and now need new fire station coverage.

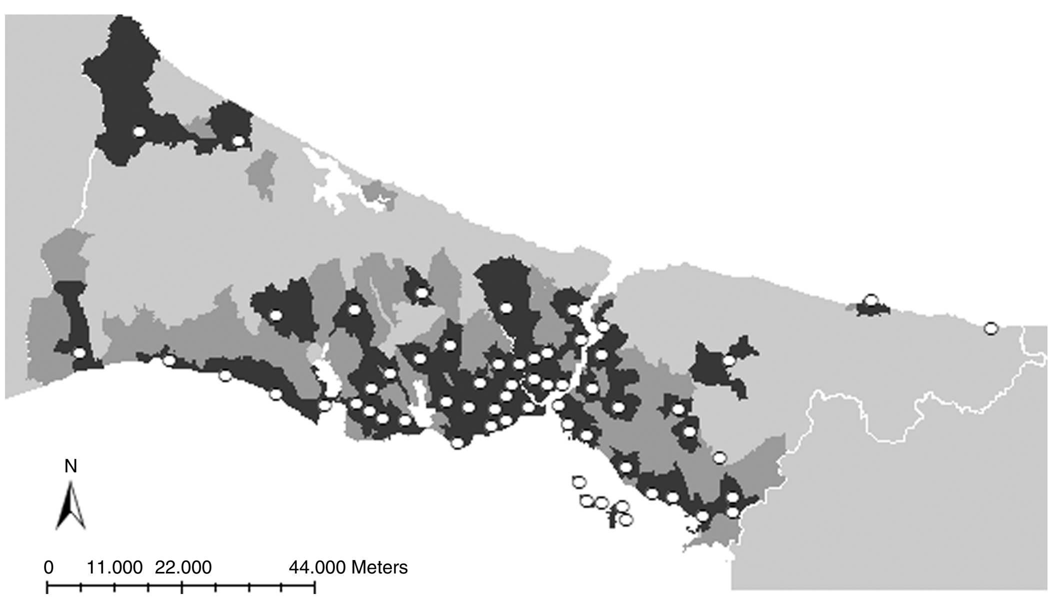

Figure 1: The map shows fire station locations and their respective coverage areas in Scenario 1.

In Scenario 4, 30 fire station locations overlap with the existing stations in Scenario 1, and 119 fire station locations overlap with the locations of stations suggested in Scenario 2. The overlap between these existing fire stations (Scenario 1) and fire stations built from scratch (Scenario 4) is favorable because discarding all of Istanbul's existing fire stations and building a new set from scratch is not a logistical or financially possible option.

Scenarios 2–5 have no budget limitation, and hence suggest that fire stations offer 100 percent coverage for all subdistricts, service requests, and adjusted service requests. Other than providing benchmark results, these solutions are not implementable in practice because IMM operates under a fixed budget for this type of infrastructure investment. Scenarios 6–9 consider the budget restriction of $38,392,768 for additional stations. This amount is sufficient to build 64 new fire stations of type *D*. The resulting set of proposed fire station locations can cover 85.9 percent of the subdistricts and 93.9 percent of the service requests under this budget constraint (Scenario 6). In Scenario 7, we see that coverage has dropped only slightly in terms of service requests (C_{SR}: 0.85 percent decrease) and heritage service requests (C_{HSR}: 0.56 percent decrease). Scenario 8 considers the heritage service requests and produces a solution that covers 82.0 percent of all subdistricts and 86.6 percent of all service requests with an additional 64 fire stations. Although coverage of service requests decreases by 7.3 percent, these scenarios achieve an additional 27.3 percent coverage of the city's historical assets.

We also conduct a sensitivity analysis for Scenarios 6 and 8 to understand the coverage response to an increase in the allowable number of fire stations (e.g., because of an increased budget). Figure 2 shows an increase in all three coverage measures as the number of fire stations increases. However, 38 additional fire stations (162 including the existing 60 and suggested 64) are needed before a significant impact on all coverage types is apparent. An addition of 38 fire stations makes all coverage aspects exceed 90 percent; therefore, it can serve as a saturation point for coverage increases. An additional fire station will improve coverage by less than 1 percent beyond 38 fire stations.

Figure 3 shows a dramatic increase in heritage service request coverage with a small number of additional fire stations, whereas the increases in

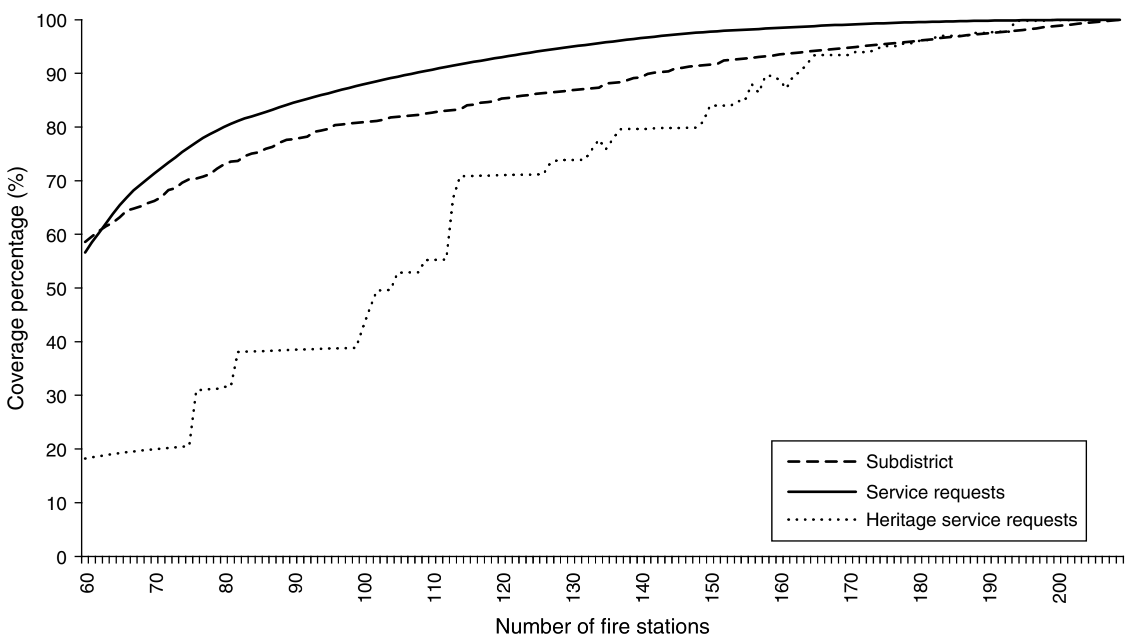

Figure 2: The graph illustrates changes in coverage of subdistricts, service requests, and heritage service requests with the addition of new stations in Scenario 6.

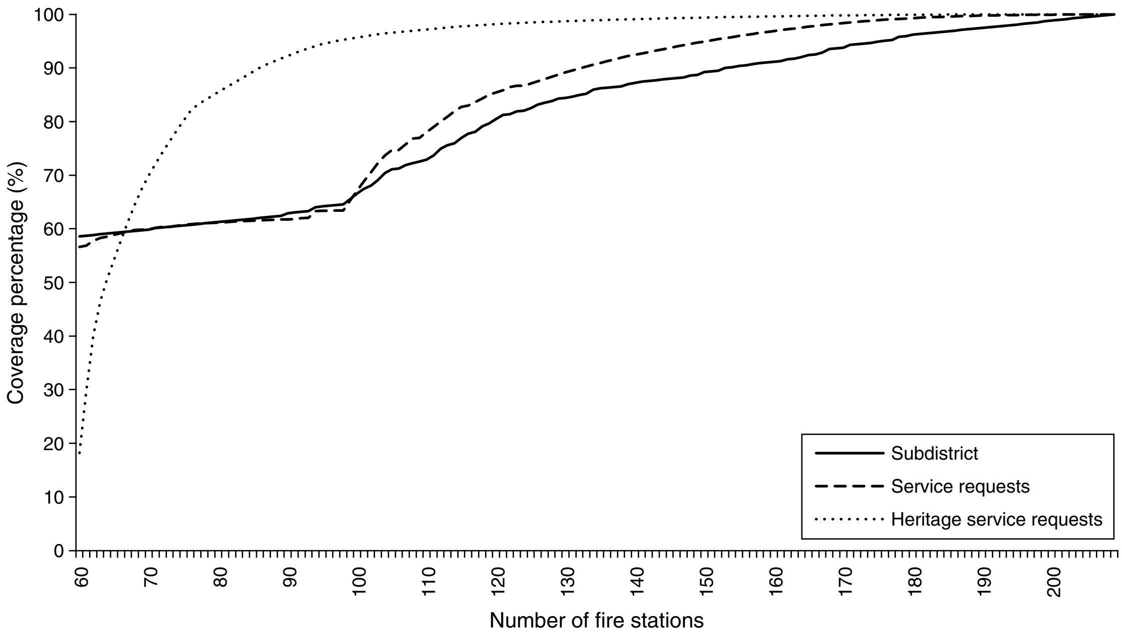

Figure 3: The graph illustrates changes in coverage of subdistricts, service requests, and heritage service requests with the addition of new stations in Scenario 8.

service request and subdistrict coverage remain stable when 35 new fire stations are added. Unlike the results of the previous sensitivity analysis (see Figure 3), 29 additional fire stations would be needed to reach 90 percent coverage in all three aspects (i.e., 153 including the existing 60 and suggested 64).

Figures 2 and 3 also indicate the cost-versus-service level (i.e., coverage percentage) trade-off because the cost of opening fire stations is linear relative to the number of new stations; in addition to the cost of land, each time a new station incurs the same fixed cost for IMM because the station size and equipment size are fixed. Hence, these figures provide IMM with additional information about the relationship between costs and service levels.

Approval and Implementation

We initially presented the results of this study to IMM in April 2009. IMM members were also project stakeholders because they were the acting directors and technicians of the fire department. They approved the results in August 2009. Prior to our final presentation and the subsequent approval, we presented the ongoing study to the IMM members for feedback. At the beginning of the project, IMM stated that it did not have budget restrictions and would like to reach 100 percent coverage for Istanbul; however, in the first project meeting, it imposed a budget restriction, allowing for opening only 64 stations of type D. This limit resulted from the limited investment budget available. Moreover, IMM expressed concerns about narrow and sloping streets and streets closed (by markets) to vehicle access on specific days of the week, exceptions that made achieving the five-minute service time goal difficult. However, we could not incorporate these exceptions into our models because of the lack of systematic data; we could use only data that were recorded in the road network. Unfortunately, the road network did not include the narrowness or sloping nature of streets or the street closures, and no plans were in place to update IMM's database to address these issues. If the relevant data are available through IMM or a third-party road network data provider in the future, we could easily incorporate these features into the preprocessing of data, where we use GIS tools to determine the proximity of subdistricts.

We incorporate other important rules (e.g., the European and Asian sides of Istanbul must be serviced separately) into our models by not allowing coverage from a station located on one side of the Bosporus to a subdistrict located on the other side. This concurs with practice because fire teams find that attempting to cross one of the two bridges connecting the two sides is risky because of possible traffic delays. This accommodation increases the acceptability of the proposed solutions because the model successfully incorporates a real-life requirement of not mixing jurisdictions on each side of the Bosporus. Therefore, we divide the problem into two smaller subproblems, thereby reducing the problem size.

At the beginning of the project, IMM anticipated a three-year implementation period for opening new stations. However, this was optimistic because its history in opening new stations suggests that it can, on average, open six stations per year under normal circumstances. Hence, achieving the target of 124 fire stations will take approximately 10 years. To give momentum to the project, the model recommends immediately opening 10 fire stations in areas it suggests, quickly increasing the coverage rate, especially in densely populated parts of Istanbul. Table 5 shows that all these stations are of type *D*; 6 are located on the Asian side of the Bosporus and 4 are located on the European side. Table 4 shows that the initial coverage in 2009 is 58.6 percent with 60 stations, and IMM will achieve 85.9 percent coverage by opening 64 new fire stations.

On average, we expect a contribution of 0.43 percent ($[85.9\% - 58.6\%]/64 = 0.43\%$) from opening of each station. Opening 10 stations (see Table 5) increases the total coverage from 58.6 percent to 65.8 percent, resulting in a 7.2 percent increase in coverage. This increase constitutes 26.37 percent of the overall increase in coverage ($85.0\% - 58.6\% = 27.3\%$; $7.2\%/27.3\% = 26.37\%$) to be achieved by the end of implementation. The average contribution of these 10 stations to overall coverage is greater than the average increase in coverage per station (i.e., 0.72 percent versus 0.43 percent, respectively). Currently, the number of stations is 85; IMM has opened 25 stations (instead of 32) since 2009. In 2010, IMM estimated that a comparable budget would be available for each year (i.e., it would complete the construction in approximately six years; however, general economic conditions hampered the construction work.

Station name	Station type	Location	Continent	Impact on coverage (%)
Beylikduzu squad	*D*	Beylikduzu	Europe	+0.71
Pendik 2nd squad	*D*	Pendik	Asia	+1.23
Tuzla Vernikçiler squad	*D*	Tuzla	Asia	+0.39
Zeytinburnu squad	*D*	Zeytinburnu	Europe	+0.80
Seyrantepe squad	*D*	Maslak	Europe	+0.66
West Ataşehir squad	*D*	Ataşehir	Asia	+0.73
Başıbüyük squad	*D*	Başıbüyük	Asia	+1.51
Abdurrahmangazi squad	*D*	Samandıra	Asia	+0.37
Hamidiye squad	*D*	Çamlıca	Asia	+0.42
Pınartepe squad	*D*	Pınartepe	Europe	+0.38
Total				+7.2

Table 5: The table shows newly opened stations, and each station's type, location, and respective impact on coverage.

Impact

At the beginning of this study, we conducted an initial analysis (Scenario 1) to investigate the coverage of 60 existing fire stations. This analysis revealed that it was possible to cover only 56.6 percent of service requests within the critical five-minute threshold, an unacceptably low level of coverage. Using the proposed models, IMM now has a clear view of the number and locations of additional fire stations required to achieve 100 percent coverage. The remaining scenarios presented above will further help IMM to assess different aspects of the location problem, such as budget constraints or the introduction of the heritage aspect. Scenario 2, which does not impose any budget restrictions, proposes opening an additional 149 fire stations to reach 100 percent coverage; however, implementing this is difficult economically and practically, because even if the necessary funds were available to construct 149 fire stations, Istanbul's jurisdiction will have been extended and its population will have grown by the time IMM completes opening these stations—in approximately 25 years if IMM opens an average of six stations per year. We obtain a more realistic solution when we add IMM's budget restriction of 64 type-*D* stations to the model. This scenario is economically feasible and provides 93.9 percent coverage for service requests and 85.9 percent coverage for subdistricts.

The 93.9 percent coverage is reasonably close to the ideal 100 percent coverage and represents a significant improvement over the initial situation.

Although IMM imposed no such requirement in the project contract, we introduced the concept of the city's historical treasures into the model analysis after these discussions were raised in our project meetings. In Scenario 8, we change the weights of subdistricts in the maximal-covering model to put more emphasis on subdistricts with heritage objects, and we obtain a new solution. In this scenario, the proposed fire station locations cover 86.6 percent of service requests and 82 percent of subdistricts, and the coverage rate of historical treasures increases to 98.4 percent. IMM continues to build new stations based on Scenario 6; however, it now has the additional opportunity to do a trade-off analysis that considers different budget and coverage levels in terms of subdistricts and heritage. In that respect, our sensitivity analyses provide additional feedback to IMM.

Summary

We present an implementation of set-covering and maximal-covering models for solving IMM's fire station location problem. Istanbul is a densely populated and historically important metropolis in which the entire city requires effective coverage by strategically located fire stations. We solve set-covering and maximal-covering models to optimality using GAMS software and a CPLEX solver. The solution that IMM selected increases subdistrict coverage from 58.6 percent to 85.9 percent. We solve variants of this model to consider what-if scenarios, such as unlimited budget, building all fire stations from scratch, or placing additional weight on covering cultural and historical treasures. We use a GIS to store and retrieve all geographical input data for the model, to calculate network distances between candidate locations and subdistricts, to calculate coverage percentages, and to visualize various model solutions. We also use a logistic function to forecast fire incidents into 2015 to check the robustness of our proposed optimal locations. Results suggest minor changes in the coverage percentages of the scenarios. Overall, the mathematical model and the visual GIS interface serve as a decision support system for IMM to use in future analyses.

Appendix A

The set-covering problem seeks to locate the minimum number of facilities, such that each demand node (i.e., each subdistrict in the context of our paper) has at least one facility sited at a location within a specified maximum distance or time (ReVelle et al. 2002). We use the following minimization problem:

$$\min \sum_{j\in J}\sum_{k\in K} c_k x_{jk} \tag{A1}$$

$$\text{s.t.} \sum_{j\in N_i}\sum_{k\in K} r_k x_{jk} \geq f_i \quad \forall\, i \in I \tag{A2}$$

$$\sum_{k\in K} x_{jk} \leq 1 \quad \forall\, j \in J \tag{A3}$$

$$x_{jk} \in \{0, 1\} \quad \forall\, j \in J,\ \forall\, k \in K, \tag{A4}$$

where

$I =$ set of subdistricts; $i \in \{1, \ldots, 790\}$;
$J =$ set of candidate fire station locations (i.e., subdistricts); $j \in \{1, \ldots, 790\}$;
$K =$ set of candidate fire station types; $k \in \{A, B, C, D\}$;
$c_k =$ fixed cost of opening a fire station of type k;
$r_k =$ capacity of a fire station of type k per year;
$f_i =$ historical fire incident records of subdistrict i per year;
$d_{ij} =$ time to travel between subdistricts i and j;
$S =$ time standard for a fire station sited at a subdistrict j to be eligible to serve subdistrict i. $S = 5$ minutes of travel time in our research;
$N_i =$ set of subdistricts j within the time standard S of subdistrict i, that is, $N_i = \{j \mid d_{ij} \leq S\}$;
$x_{jk} =$ binary decision variable (1 if a fire station is opened in subdistrict j, 0 otherwise).

Equation (A1) is the objective function that minimizes the cost of opening fire stations. Equation (A2) ensures that the right type of station is opened to respond to service requests from each subdistrict. Equation (A3) ensures that only one type of fire station is opened in a subdistrict. Equation (A4) represents the binary decision variable of locating a fire station in a subdistrict.

Appendix B

The maximal coverage problem maximizes the coverage of subdistricts, given that the number of fire stations to be opened is limited, to achieve 100 percent coverage (ReVelle et al. 2002). We use the following maximization problem:

$$\max \sum_{i\in I} w_i y_i \tag{B1}$$

$$\text{s.t.} \sum_{j\in N_i}\sum_{k\in K} r_k x_{jk} \geq w_i y_i \quad \forall\, i \in I \tag{B2}$$

$$\sum_{j\in J}\sum_{k\in K} x_{jk} \leq P \tag{B3}$$

$$\sum_{k\in K} x_{jk} \leq 1 \quad \forall\, j \in J \tag{B4}$$

$$x_{jk} \in \{0, 1\} \quad \forall j \in J, \forall k \in K \tag{B5}$$

$$y_i \in \{0, 1\} \quad \forall i \in I, \tag{B6}$$

where

I = set of subdistricts; $i \in \{1, \ldots, 790\}$;
J = set of candidate fire station locations (i.e., subdistricts); $j \in \{1, \ldots, 790\}$;
K = set of candidate fire station types; $k \in \{A, B, C, D\}$;
w_i = weight of subdistrict i;
r_k = capacity of a fire station of type k per year;
f_i = historical fire incident records of subdistrict i per year;
h_i = historical fire incident records of subdistrict i per year adjusted based on the existence of heritage objects in subdistrict i;
o_i = number of heritage objects in subdistrict i;
d_{ij} = time between subdistricts i and j;
S = time standard for a fire station sited at a subdistrict j to be eligible to serve subdistrict i ($S = 5$ minutes of travel time in our research);
N_i = set of subdistricts j within the time standard S of subdistrict i; that is, $N_i = \{j \mid d_{ij} \le S\}$;
P = number of fire stations to be opened (64 in our research);
x_{jk} = binary decision variable (1 if a fire station is opened in subdistrict j, 0 otherwise);
y_i = binary decision variable (1 if a fire station is opened in subdistrict j and is eligible to serve subdistrict i, 0 otherwise).

Equation (B1) is the objective function that maximizes the coverage of service requests in each subdistrict. Equation (B2) ensures that the right type of station is opened to respond to service requests from each subdistrict. Equation (B3) ensures that the number of fire stations opened is within the set limit. Equation (B4) ensures that only one type of fire station is opened in a subdistrict. Equation (B5) represents the binary decision variable of opening fire stations. Equation (B6) represents the binary decision variable of covering the service requests in subdistricts.

The Difference in w_i for Scenario 6 (Budget) and Scenario 8 (Heritage)

In Scenario 6, $w_i = f_i$ when we maximize the coverage of service requests (i.e., c_{SR}); in Scenario 8, $w_i = h_i$ when we maximize the coverage of heritage service requests (i.e., c_{HSR}). The relationship between f_i, h_i, and o_i is:

$$h_i = f_i \times \left(9 \times \left[\frac{o_i - \min_{i\in I} o_i}{\max_{i\in I} o_i - \min_{i\in I} o_i}\right] + 1\right). \tag{B7}$$

We adjust service requests in Scenario 8 by a factor of 1 to 10, depending on the relative density of heritage objects in each subdistrict.

Appendix C

Logistic functions are often used to describe certain kinds of growth. These functions, like exponential functions, grow quickly at first; however, because of restrictions that place limits on the size of the underlying population, they eventually grow more slowly and then level off. We transform our forecast model into a fixed-effect panel data model to observe the behavior of fire incidents across time, and we represent each district with a dummy variable. We assume that the number of fire incidents in one district has no influence on the number of fire incidents in another district. This assumption is valid because the residual cross correlation corresponding to each district is close to 0. We also assume that the developing districts will show a growth pattern similar to past patterns; this is also evident from actual growth figures of the districts (TURKSTAT 2011). From Connally et al. (1998), we calculate the number of fire incidents as follows:

$$F_{it} = \frac{\beta_{0i}}{1 + \exp(\beta_1 POP_{it})}, \quad \forall i, t \tag{C1}$$

where F_{it} is number of fire incidents and POP_{it} is the population at district i, in year t, β_{0i} is the stabilized annual number of fire incidents, and β_1 is the change speed parameter of the number of fire incidents with respect to the population of districts. We solve the model using E-views 7.0 software. One might think that it is appropriate to include the commercial and industrial activities or income generated as explanatory variables in a forecasting model because they are related to economic activities. However, those types of variables generally show a high level of correlation with the population figures, resulting in a multicollinearity problem. Additionally, the acquisition of this type of data for each district is problematic. Therefore, we do not include such variables in the model. The model is predicted using the maximum-likelihood estimation, the β_1 coefficient is 0.052 (z-statistics = 3.16 and $p < 0.000$), and the R^2 value is 0.72. Positive β_1 indicates that the logistic function is increasing. We also observe this from the fire incident data; however, the increase is very low (approximately 5 percent per year); therefore, the coverage percentages are lower in Scenarios 7 and 9 than in their counterparts, Scenarios 6 and 8.

Appendix D

We use the following equations to calculate the coverage of subdistricts (C_{SD}), the coverage of service requests (C_{SR}), and the coverage of heritage service requests (C_{HSR}):

$$c_{SD} = \frac{\sum_{i\in I} y_i}{|I|} \tag{D1}$$

$$c_{SR} = \frac{\sum_{i\in I} f_i y_i}{\sum_{i\in I} f_i} \tag{D2}$$

$$c_{HSR} = \frac{\sum_{i\in I} h_i y_i}{\sum_{i\in I} h_i}. \tag{D3}$$

$I =$ set of subdistricts; $i \in \{1, \ldots, 790\}$.
$y_i =$ binary decision variable (1 if a fire station is opened in subdistrict j and is eligible to serve subdistrict i, 0 otherwise).
$f_i =$ historical fire incident records of subdistrict i per year.
$h_i =$ historical fire incident records of subdistrict i per year, adjusted based on the existence f heritage objects in subdistrict i.

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Verification Letter

Abdurrahman Ince, chemical engineer, director of Istanbul Fire Brigade, Research Planning Coordination Department, writes:

"I would like to write about an operations research implementation that took place in Istanbul, Turkey to select locations for new fire stations. I am writing this letter to support the publication of this work, that was part of the coordination project named "My Project Istanbul (Sustainable cooperation project which provides support to academic researchers and which is executed between municipality and universities)" which aims to direct the academic research potential of our universities to the solutions of urban problems and to contribute to making Istanbul a world city with high life standards; the study "Optimizing Fire Station Locations" was selected from numerous applications.

"After a successful collaboration with esteemed members of Dogus University and Istanbul Technical University, the final report was accepted in August 2009. Knowing the complexity of the problem on hand, this study was very beneficial for us to implement a new location selection decision policy, and the sub-districts proposed in this study will be the priority for opening new fire stations. The suggested locations, as the output of this study, were put in an advisory report and submitted to municipality commitees for approval.

"The new stations will be opened in 6 phases, each phase consisting of 10 stations, and are prioritized by the administrative council. Right now, the first phase is completed and received good feedback from the community. The remaining 5 phases are planned to be concluded within a 3-year period.

"I believe that with this study, we have benefited from existing research potential of universities in our city to improve a crucial municipality service, "Fire Brigade," and developed an applicable solution for an imminent problem, also contributing to improvement in life quality of the citizens of Istanbul. I hope that this information is useful in pursuing the publication of the project."

Emel Aktaş is a lecturer of sustainability and operations management at Brunel Business School. She earned her B.S., M.Sc., and Ph.D. degrees in industrial engineering from Istanbul Technical University, Turkey. Her B.S. degree was in logistics management, her M.Sc. degree was in healthcare management, and her Ph.D. degree was in supply chain contracting. She took part as a researcher in both public and private funded projects on diverse areas such as location selection, shift scheduling or transportation master plan strategy. Her refereed articles have appeared in a variety of journals including *European Journal of Operational Research*, *Socio-Economic Planning Sciences*, and *Transportation Research Part A: Policy and Practice*.

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