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Istanbul Metropolitan Municipality

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Emel Akta¸s

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Brunel Business School, Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom,

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emel.aktas@brunel.ac.uk

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Özay Özaydın

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Department of Industrial Engineering, Dogus University, Istanbul 34722, Turkey, oozaydin@dogus.edu.tr

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Burçin Bozkaya

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Sabancı School of Management, Sabancı University, Istanbul 34956, Turkey, bbozkaya@sabanciuniv.edu

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Füsun Ülengin, ¸Sule Önsel

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Department of Industrial Engineering, Dogus University, Istanbul 34722, Turkey

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{fulengin@dogus.edu.tr, sonsel@dogus.edu.tr}

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The Istanbul Metropolitan Municipality (IMM) seeks to determine locations for additional fire stations to build

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in Istanbul; its objective is to make residences and historic sites reachable by emergency vehicles within five

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minutes of a fire station’s receipt of a service request. In this paper, we discuss our development of a mathe q

matical model to aid IMM in determining these locations by using data retrieved from its fire incident records.

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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

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the situation that existed when we initiated the project and the scenario that IMM implemented. The scenario

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implemented increases the city’s fire station coverage from 58.6 percent to 85.9 percent, based on a five-minute e

response time, with an implementation plan that spans three years.

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*Key words*: fire station location; set-covering problem; maximal-covering problem; geographic information P

system.

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*History*: This paper was refereed. Published online in *Articles in Advance*.

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Determining fire station locations in any city has

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instance of an open flame or other burning in a

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been, and will continue to be, of significant inter

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est to practitioners and researchers. Suitable loca g

tions are critically important for megacities such as

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Istanbul, Turkey. With a population of 13.5 million

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(TURKSTAT 2011), Istanbul is among the world’s

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largest cities and is the cultural and financial center

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of Turkey. The city extends across the European and

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Asian sides of the Bosporus Strait and is the world’s

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only metropolis that is situated on two continents.

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Since 2003, Istanbul has welcomed 2.5 million immi

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grants and has continuously grown and expanded, y

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resulting in problems such as traffic congestion and a

infrastructure deficiencies; consequently, fire station

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locations no longer meet the city’s needs. Determining

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t

the number and location of fire stations to enable fire s

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fighting vehicles to respond to fire incidents (i.e., any p

place not intended to contain the burning or in an uncontrolled manner) as quickly as possible is of utmost importance. The Istanbul Metropolitan Munic ipality (IMM) serves 790 mutually exclusive and col lectively 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 facil ity 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

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to guarantee 100 percent coverage, a decision maker’s

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allocated resources may be insufficient to build all the

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facilities that the model determines. Location goals

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must then be shifted to maximize the coverage the

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available resources can provide. This is the maximal

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covering problem (Church and ReVelle 1974). As a

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variant of the set-covering problem, the maximal

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covering problem seeks to maximize the amount of

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demand covered within the acceptable service time *S*

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by locating a fixed number of facilities. The main dif

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ference between the two problems is that all demand

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must be met (covered) in the set-covering problem,

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whereas some demand may be left unmet (uncov

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ered) in the maximal-covering problem (Hale and

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Moberg 2003).

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Many practical problems (e.g., this fire station loca

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tion application) can be formulated as set-covering s

problems. Such problems include a set of potential

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sites (e.g., subdistricts of Istanbul), *N* = *8*1*1000 1 n9*,

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for locating fire stations. Placing a station at site *j*

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costs *cj*. They also include a set of communities, *N* =

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*8*1*1000 1 n9*, that must be protected against fire events. a

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Then, the subset of communities that can be protected n

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from a station located at *j* is *Ni*, such that *j* ∈ *Ni*.

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For example, *Ni*is the set of communities that can

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be reached from *j* in five minutes (i.e., the accept

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able service time *S* is five minutes). Then, the prob .

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lem of choosing a minimum-cost set of locations for

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the fire stations, such that each community can be

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reached from some fire station in five minutes, is a

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set-covering problem (Nemhauser and Wolsey 1999).

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We refer to the location of a potential fire incident as e

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covered if it is reachable by a fire emergency vehicle t

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within this time, and the coverage area of a fire station

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is the set of all subdistricts of the city that are reach

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able from the station in the determined time (i.e., five

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minutes for Istanbul). The location of a fire station is

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also a long-term capital investment decision because

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once a station has been built, it cannot be moved eas

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ily. Therefore, each station location must provide the

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best possible coverage for residents.

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Two other factors contribute to the need for devel y

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oping effective fire station coverage in Istanbul. First, a

the city is located on a seismic belt and has suffered

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many major earthquakes. The most recent significant

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earthquake occurred in 1999 within 100 kilometers s

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(62 miles) of Istanbul’s city center and claimed more p

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 his tory, 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 addi tional 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 Loca tion Problem* describes the problem. The *Literature Review* section provides a literature survey for fire sta tion location problems and the *Proposed Model* sec tion 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 ana lyze 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 com paring 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

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of an ongoing improvement initiative, *Istanbul, My*

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*Project*, IMM issued an open call to universities for

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research projects that would improve the quality of

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various public services that Istanbul offers. We sub @

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mitted a proposal to develop a plan for facility expan

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sion using a mathematical model, and IMM awarded

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us the project. Our project’s objective is to aid IMM

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in determining the optimal locations of additional fire

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stations. To achieve this, we developed set-covering

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and maximal-covering models that serve to opti

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mize the locations of fire stations under operational

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constraints.

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Timeliness is one of the most important aspects

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of the quality of emergency services, such as medi

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cal or fire response, and mathematical programming

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is a frequently used approach to solve the emer g

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gency service location problem (Araz et al. 2007). r

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The literature includes two main classes of models

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that address locating emergency response facilities:

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(1) set-covering or maximal-covering models, which

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aim to locate sufficient facilities to cover demand y

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within a specified response time, and (2) center-type a

or *p*-center models, which aim to locate a fixed num

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ber of facilities to achieve a minimal systemwide max

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imum response time. With the latter approach, at most

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*p* new facilities can be located, potentially resulting

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in unacceptably long response times. Therefore, set

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covering and maximal-covering models are more use

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ful as emergency service location models. In the next

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sections, we provide an overview of the mainstream

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facility location literature on these two types of mod

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els, and discuss the models we use to solve IMM’s e

fire station location problem.

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Literature Review

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A set-covering formulation seeks to select a mini

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mum subset of candidate locations that collectively

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covers all demand points within the maximum allow

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able response time (Toregas et al. 1971). Hogan and

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ReVelle (1986) suggest a backup coverage scheme

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for decision making on emergency service locations.

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Church and ReVelle (1974) use the maximal-covering y

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model for situations in which the number of vehi a

cles available is less than the number necessary to

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cover all service requests, for example, in public

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services such as IMM’s fire station location prob s

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lem. Daskin et al. (1988), ReVelle et al. (1996), and p

Alsalloum and Rand (2006) study the integration of different coverage models such as multiple cover age, 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 par tial 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 sim ulation to test the applicability of theoretical assump tions 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 maxi mum time or distance that separates a citizen from the closest service station (Toregas et al. 1971, Larson 1974). Such location problems are discrete optimiza tion 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 solu tion approaches. Hence, many researchers, includ ing Tzeng and Chen (1999), Cheung et al. (2001), and Salhi and Gamal (2003), propose metaheuris tics (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 strate gic 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 exten sive analysis of general location strategies for single level location problems, and Sahin and Sural (2007)

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conduct the same analysis for hierarchical facility

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location problems. Goldberg (2004) provides a taxon

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omy of emergency system location problems. Finally,

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Swersey (1994) and Marianov and ReVelle (1995) pro @

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vide a review of real-life applications of emergency

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service models, and Gormez et al. (2011) investigate

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the problem of locating disaster-response and relief

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facilities in Istanbul. They use mathematical models to

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determine the locations of new facilities; their objec

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tive is to minimize the weighted-average distance

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between casualty locations and their closest response

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and relief facilities, while opening the smallest possi s

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ble number of new facilities, subject to distance limits

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and backup requirements under regional vulnerabil

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ity considerations.

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A geographic information system (GIS) is used fre g

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quently to give input to emergency location models r

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(Dobson 1979, Liu et al. 2006). Church (2002) provides

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a detailed account of how such systems are used in

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location problems. We use them to characterize the

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fire incident data in terms of location and frequency. y

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Proposed Model

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Based on the characteristics of the problem described e

previously, we use set-covering and maximal

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covering models in our study. Our main objective

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is to minimize the number of new fire stations to

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serve all subdistricts within at most five minutes (i.e.,

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fixed travel time). Binary decision variables are poten

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tial locations for fire stations in the subdistricts. The

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constraints ensure that each subdistrict is served by

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at least one fire station. The approach we present e

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includes the use of a GIS to provide the necessary g

input data for the location problem. In building a dis

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crete optimization model, a risk always exists that

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we will find that it cannot be solved within a rea

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sonable time (Williams 1999). Fortunately, because of

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its relatively small problem size, we can solve our

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integer programming model using mathematical pro

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gramming and optimization software.

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The first step is to develop a set-covering model

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(see Appendix A). IMM’s service level requires y

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that each subdistrict must be reached in at most a

five minutes. This is in line with the classical set

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covering model (Toregas and ReVelle 1973), which

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we apply to our fire station location problem. Simi s

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lar response time criteria are also found in the United p

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 cen troid subdistricts of the city; hence, covering a subdis trict means reaching the centroid within five minutes, which is equivalent to covering the entire subdistrict. Because fire incident data are recorded at the sub district 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 spe cial consideration. To incorporate additional rules imposed by IMM, we formulate and solve a hierarchi cal 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 effec tively 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

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maximizing multicoverage. However, we analyze

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the results in this respect to observe the level of

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ineluctable multicoverage, and find that the scenario

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selected by IMM, Scenario 6 (Budget) (see Table 3),

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produces double coverage for 35.6 percent of the sub

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districts. To a degree, this eliminates the need to con

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sider the possibility of simultaneous fire incidents that

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require the services of a single closest fire station.

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Solution Methodology

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Data Acquisition

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At the beginning of this study, Istanbul had 60 active

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fire stations in four size categories: *A*, *B*, *C*, and *D*

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(see Table 1). Categories *A* and *B* are referred to as

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groups and act as centers; categories *C* and *D* are

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called squads and are designed as smaller outposts. s

For example, IMM’s firefighters addressed 45,050 fire

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incidents in 2009, and their average working time on

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fire incidents was 40 minutes. We incorporate these

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differences in capacity and cost in the set-covering

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and maximal-covering models.

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To implement our model, we obtain historical

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fire incident data for 1994–2006 from IMM. These s

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include the number of fire incidents by subdistrict for

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Istanbul’s 60 fire stations. Of these stations, 37 are

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located on the European side of the city and the

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remaining 23 are on the Asian side. We use fire inci

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dents recorded by IMM as service requests issued

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from each subdistrict, and we use ArcGIS, a GIS

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for working with maps and geographic information,

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to facilitate data collection and processing for the e

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set-covering and maximal-covering models. A GIS g

enables users to store, retrieve, manipulate, analyze,

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and visualize geographical content in various types

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of spatial data sets. Its central element is the use

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Station Size Annual capacity Stations in e

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type (square meters) Cost ($) per station operation in 2009 r

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D 2,150 5991887 41380 10

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Table 1: For each station category, the table shows size, cost, capacity

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information, and number of fire stations in operation when we initiated

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the project.

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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 link ing digital map layers to spatially enabled databases. The layers of the GIS map relative to the fire sta tion location problem include data sets, such as roads, parcels, hydrants, community networks, topography, lakes and rivers, business and community buildings, and fire station locations.

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 narrow est lanes, the highest congestion level, and the slow est 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 candi date location for opening a new fire station. We rep resent each subdistrict as a single point for distance calculations; to do this, we take the polygonal foot print 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 sub district 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 candi date locations, we create a proximity matrix in which

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Table 2: In this proximity matrix example, the value in a cell is 1 if the

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representative point of a destination subdistrict can be reached from that

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of an origin subdistrict within five minutes; otherwise, it is blank.

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each row and column represents an origin and desti

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nation subdistrict, respectively. Istanbul has 790 sub

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districts; Table 2 shows a small subset of the 790 × q

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790 proximity matrix. Each subdistrict is covered if

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it is reachable from a subdistrict with a fire station d

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within five minutes. We use the ArcGIS network ana

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lyst extension to calculate this matrix, which indicates e

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the subdistricts that are within five minutes of travel a

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time of each other, using the actual street network. We P

do not include villages, military areas, forests, or other

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special areas (e.g., airports) in the matrix because their s

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fire station directives differ from those of IMM. The

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proximity matrix is not necessarily symmetric; the

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fastest route originating in one subdistrict and reach a

ing another may differ from the fastest route in the

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reverse direction (e.g., because of road networks or g

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one-way streets).

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Using this data, we code the integer programming

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models (see Appendix A and Appendix B).

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Scenario Analysis

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We use set-covering (see Appendix A) and maximal

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covering (see Appendix B) models to analyze

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Istanbul’s fire station location problem using 10 sce

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narios (see Table 3).

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We use Scenario 1, Istanbul’s existing situation a

when we initiated the project, as the baseline for our

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analyses. Scenarios 2–5 consider the cost *4cj5* of open

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ing a station at *j*, which covers a set of subdistricts s

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*4Ni* *j* ∈ *Ni5*; in these scenarios, we seek minimum-cost p

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.

coverage (i.e., to minimize the number of fire sta tions). In Scenarios 6–9, we consider the weight *4wi5* of covering sets of subdistricts *4Ni5*, and we seek maximum-weight coverage (i.e., to maximize the number of locations covered). The number of fire inci dents is especially important in Scenarios 6–9 because the objective function is to maximize coverage relative to service requests (see Appendix B for the mathe matical model). In Scenario 8, we adjust the service

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requests, as described in Appendix B, using weights

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Number of

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fire stations Coverage (%)

that represent the density of heritage in each sub

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district (i.e., number of heritage objects in each

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subdistrict).

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In the odd-numbered scenarios (Scenarios 3, 5, 7,

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and 9), we use the solutions of the even-numbered

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scenarios (Scenarios 2, 4, 6, and 8) and calculate

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the coverage with forecasted fire incidents for 2015

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to test the robustness of our solutions. We use a

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logistic function to forecast the number of fire inci

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dents as a function of population increases in the dis

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tricts, because the logistic model is consistent with s

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Malthusian and other theories of constrained popula

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tion growth (George et al. 2004), and we can estimate

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domestic fire incidents using population size (Tayman

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et al. 1994). Appendix C shows the details of our fore

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casting model. In Scenario 10, we report the coverage r

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status in 2005 to give an overall picture of the past, n

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present, and potential future with all our scenarios.

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Finally, we conduct sensitivity analysis for a range

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of budget limitations and compare the results to the y

existing budget.

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Results

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We use GAMS to code the integer programming e

model and solve it using the CPLEX 11.0 solver.

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The largest model has 3,208 binary variables and

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6,416 constraints and required 0.781 seconds to solve

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using a personal computer with an Intel® Core™ 2 s

Duo CPU T7500 @ 2.20 GHz processor and 2 GB RAM

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on a 32-bit operating system. Table 4 shows the results

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that each scenario generated.

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For each scenario, we evaluate three aspects of

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coverage. The first is the percentage of subdistricts g

covered (*CSD5*. In this aspect, we also report the per

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centage of subdistricts covered twice (*Cdouble5* and three

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times (*Ctriple5* to determine the percentage of subdis

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tricts within a five-minute travel time of at least two

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and three fire stations, respectively. The second aspect

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is the percentage of service requests (i.e., the percent w

age of fire incidents) in the subdistricts covered (*CSR5*.

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The third aspect is similar to the second; however,

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we change the weight of the subdistricts in the objec y

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tive function according to the distribution of her a

itage service requests (*CHSR5*. For all three aspects of

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coverage, we assume that a subdistrict (or all fire

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incidents in that subdistrict) is covered if the subdis s

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trict’s center of gravity is reachable from a fire station p

Scenario E N T CSD Cdouble Ctriple CSR CHSR Total cost ($)

1 60 — 60 5806 1501 004 5606 1802 4712931423

2 60 149 209 100 3702 403 100 100 13616761586 3 100 3702 403 100 100

4 — 193 193 100 2804 008 100 100 11517781191 5 100 2804 008 100 100

6 60 64 124 8509 3506 208 9309 7101 8516861191 7 8509 3506 208 9301 7007

8 60 64 124 8200 3100 301 8606 9804 8516861191 9 8200 3100 301 8501 9609

10 50 — 50 46 3 0 43 902 4017711394

Table 4: The table shows the results of our analysis of each scenario. Notes: E = existing, N = new, T = total, CSD = subdistrict, Cdouble = doubly covered, Ctriple = triply covered, CSR = service requests, CHSR = 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*0*7257 TRY.

In Scenario 1 in Table 4, the coverage of ser vice requests in Istanbul at the time we initi ated 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 per centage 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 sta tions is about 8.3 percent more than the ideal situ ation 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

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fire events, suggesting that the existing stations have

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excessive capacity.

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Moreover, subdistricts are doubly covered (*Cdouble5*

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in Scenario 2 (37.2 percent), Scenario 4 (28.4 percent),

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Scenario 6 (35.6 percent), and Scenario 8 (31.0 percent);

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however, no model specifically includes this multicov

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erage feature. We can explain the difference between

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Scenarios 2 and 4 as follows: Scenario 4 minimizes the

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number of fire stations in the city, disregarding exist

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ing stations; hence, it distributes station locations on

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the city map more randomly. Furthermore, 59.6 per

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cent of these doubly covered subdistricts are of his

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torical importance (i.e., they have an above-average

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number of heritage objects). Such subdistricts have at

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least two fire stations within a radius of five minutes

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of travel time. This finding significantly eliminates the

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need to locate additional fire stations and the associ s

ated additional cost to achieve multicoverage.

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When we analyze the results of the forecast scenar s

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ios (Scenarios 3, 5, 7, and 9) in Table 4, we observe

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that these scenarios, which incorporate future fire ser y

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vice requests with the fire station locations suggested a

by their counterparts (Scenarios 2, 4, 6, and 8, respec

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tively), perform at approximately the same level as s

their counterparts; this indicates the robustness of the

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solutions produced under Scenarios 2, 4, 6, and 8.

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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 per cent of Istanbul (463 of 790 subdistricts) was covered by 60 fire stations. Many densely populated subdis tricts 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. More over, based on historical fire incident data, fire sta tions 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 sta tions; they were built without considering changes in the city and potential demand for service over the years. Moreover, many areas in Istanbul were previ ously forests or uninhabited areas, which have been converted to residential and commercial zones and now need new fire station coverage.

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

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In Scenario 4, 30 fire station locations overlap with

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the existing stations in Scenario 1, and 119 fire sta

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tion locations overlap with the locations of stations

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suggested in Scenario 2. The overlap between these

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existing fire stations (Scenario 1) and fire stations built

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from scratch (Scenario 4) is favorable because discard

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ing all of Istanbul’s existing fire stations and building

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a new set from scratch is not a logistical or financially

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possible option.

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Scenarios 2–5 have no budget limitation, and hence

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suggest that fire stations offer 100 percent cover o

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age for all subdistricts, service requests, and adjusted

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service requests. Other than providing benchmark

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results, these solutions are not implementable in prac

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tice because IMM operates under a fixed budget for

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this type of infrastructure investment. Scenarios 6–9 g

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consider the budget restriction of $38,392,768 for addi s

tional stations. This amount is sufficient to build 64

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new fire stations of type *D*. The resulting set of pro

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posed fire station locations can cover 85.9 percent

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of the subdistricts and 93.9 percent of the service y

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requests under this budget constraint (Scenario 6). a

In Scenario 7, we see that coverage has dropped only

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slightly in terms of service requests (*CSR*: 0.85 percent s

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decrease) and heritage service requests (*CHSR*: 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 Scenar ios 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 num ber of fire stations increases. However, 38 additional fire stations (162 including the existing 60 and sug gested 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 cover age 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

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Subdistrict

Service requests

Heritage service requests

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Figure 2: The graph illustrates changes in coverage of subdistricts, service requests, and heritage service

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requests with the addition of new stations in Scenario 6.

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Subdistrict

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Number of fire stations

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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.

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service request and subdistrict coverage remain sta

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ble when 35 new fire stations are added. Unlike the e

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results of the previous sensitivity analysis (see Fig

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ure 3), 29 additional fire stations would be needed P

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to reach 90 percent coverage in all three aspects (i.e.,

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153 including the existing 60 and suggested 64). s

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Figures 2 and 3 also indicate the cost-versus-service

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level (i.e., coverage percentage) trade-off because the

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cost of opening fire stations is linear relative to the a

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number of new stations; in addition to the cost of

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land, each time a new station incurs the same fixed g

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cost for IMM because the station size and equip

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ment size are fixed. Hence, these figures provide IMM

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with additional information about the relationship ,

between costs and service levels.

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Approval and Implementation

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We initially presented the results of this study to IMM

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in April 2009. IMM members were also project stake y

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holders because they were the acting directors and a

technicians of the fire department. They approved the

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results in August 2009. Prior to our final presenta

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tion and the subsequent approval, we presented the s

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ongoing study to the IMM members for feedback. p

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 restric tion, allowing for opening only 64 stations of type *D*. This limit resulted from the limited investment bud get 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 net work data provider in the future, we could easily incorporate these features into the preprocessing of data, where we use GIS tools to determine the prox imity of subdistricts.

We incorporate other important rules (e.g., the European and Asian sides of Istanbul must be

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serviced separately) into our models by not allowing

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coverage from a station located on one side of the

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Bosporus to a subdistrict located on the other side.

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This concurs with practice because fire teams find that

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attempting to cross one of the two bridges connect

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ing the two sides is risky because of possible traffic

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delays. This accommodation increases the acceptabil

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ity of the proposed solutions because the model suc

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cessfully incorporates a real-life requirement of not

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mixing jurisdictions on each side of the Bosporus.

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Therefore, we divide the problem into two smaller

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subproblems, thereby reducing the problem size.

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At the beginning of the project, IMM anticipated

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a three-year implementation period for opening new

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stations. However, this was optimistic because its his

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tory in opening new stations suggests that it can,

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on average, open six stations per year under nor s

mal circumstances. Hence, achieving the target of 124

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fire stations will take approximately 10 years. To give

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momentum to the project, the model recommends

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immediately opening 10 fire stations in areas it sug

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gests, quickly increasing the coverage rate, especially a

d

in densely populated parts of Istanbul. Table 5 shows n

e

that all these stations are of type *D*; 6 are located on s

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the Asian side of the Bosporus and 4 are located on s

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the European side. Table 4 shows that the initial cov

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erage in 2009 is 58.6 percent with 60 stations, and .

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IMM will achieve 85.9 percent coverage by opening

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64 new fire stations.

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On average, we expect a contribution of 0.43 per

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cent *46*85*0*9% − 58*0*6%*7/*64 = 0*0*43%*5* from opening

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Station Impact on

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i

Station name type Location Continent coverage (%)

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Beylikduzu squad D Beylikduzu Europe +0071 ,

e

Pendik 2nd squad D Pendik Asia +1023

t

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s

Tuzla Vernikçiler squad D Tuzla Asia +0039 b

Zeytinburnu squad D Zeytinburnu Europe +0080

e

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Seyrantepe squad D Maslak Europe +0066 r

West Ata¸sehir squad D Ata¸sehir Asia +0073

e

h

t

Ba¸sıbüyük squad D Ba¸sıbüyük Asia +1051 o

Abdurrahmangazi squad D Samandıra Asia +0037 y

Hamidiye squad D Çamlıca Asia +0042

n

a

Pınartepe squad D Pınartepe Europe +0038 n

o

Total +702 d

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Table 5: The table shows newly opened stations, and each station’s type,

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location, and respective impact on coverage.

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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 *4*85*0*0% − 58*0*6% = 27*0*3%*3* 7*0*2%*/*27*0*3% = 26*0*37%*5* 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 construc tion work.

Impact

At the beginning of this study, we conducted an ini tial 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 ser vice requests within the critical five-minute thresh old, 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 remain ing 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 addi tional 149 fire stations to reach 100 percent coverage; however, implementing this is difficult economi cally 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* sta tions to the model. This scenario is economically fea sible and provides 93.9 percent coverage for service requests and 85.9 percent coverage for subdistricts.

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The 93.9 percent coverage is reasonably close to the

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ideal 100 percent coverage and represents a significant

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improvement over the initial situation.

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Although IMM imposed no such requirement in @

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the project contract, we introduced the concept of the

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city’s historical treasures into the model analysis after

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s

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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 facil ity sited at a location within a specified maximum distance or time (ReVelle et al. 2002). We use the following minimiza tion problem:

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sr

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bi

these discussions were raised in our project meetings.

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In Scenario 8, we change the weights of subdistricts

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min X *j*∈*J*

X *k*∈*K*

*ckxjk* (A1)

r

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in the maximal-covering model to put more emphasis

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on subdistricts with heritage objects, and we obtain a

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new solution. In this scenario, the proposed fire sta

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s.t. X

*j*∈*Ni*

X

X *k*∈*K*

*rkxjk* ≥ *fi* ∀*i* ∈ *I* (A2)

o t

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tion locations cover 86.6 percent of service requests

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*k*∈*K*

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and 82 percent of subdistricts, and the coverage rate

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*xjk* ≤ 1 ∀*j* ∈ *J* (A3)

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of historical treasures increases to 98.4 percent. IMM

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continues to build new stations based on Scenario 6;

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however, it now has the additional opportunity to g

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do a trade-off analysis that considers different budget r

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and coverage levels in terms of subdistricts and her

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itage. In that respect, our sensitivity analyses provide

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additional feedback to IMM.

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Summary

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We present an implementation of set-covering and

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maximal-covering models for solving IMM’s fire sta e

tion location problem. Istanbul is a densely popu

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lated and historically important metropolis in which

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the entire city requires effective coverage by strategi

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cally located fire stations. We solve set-covering and

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maximal-covering models to optimality using GAMS

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software and a CPLEX solver. The solution that IMM

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selected increases subdistrict coverage from 58.6 per

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cent to 85.9 percent. We solve variants of this model e

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to consider what-if scenarios, such as unlimited bud g

get, building all fire stations from scratch, or placing

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additional weight on covering cultural and histori

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cal treasures. We use a GIS to store and retrieve all

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geographical input data for the model, to calculate

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network distances between candidate locations and

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subdistricts, to calculate coverage percentages, and

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to visualize various model solutions. We also use a

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logistic function to forecast fire incidents into 2015 to

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t

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*xjk* ∈ *8*0*1* 1*9* ∀*j* ∈ *J 1* ∀*k* ∈ *K1* (A4)

where

*I* = set of subdistricts; *i* ∈ *8*1*1000 1* 790*9*;

*J* = set of candidate fire station locations (i.e., subdistricts); *j* ∈ *8*1*1000 1* 790*9*;

*K* = set of candidate fire station types; *k* ∈ *8A1 B1 C1 D9*; *ck* = fixed cost of opening a fire station of type *k*; *rk* = capacity of a fire station of type *k* per year; *fi* = historical fire incident records of subdistrict *i* per year; *dij* = 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;

*Ni* = set of subdistricts *j* within the time standard *S* of sub district *i*, that is, *Ni* = *8j*  *dij* ≤ *S9*; *xjk* = 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 sta tion 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 X

*wiyi*(B1)

*i*∈*I*

F

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th

check the robustness of our proposed optimal loca y

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tions. Results suggest minor changes in the coverage a

percentages of the scenarios. Overall, the mathemat

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s.t. X

*j*∈*Ni*

X

X

*k*∈*K* X

*rkxjk* ≥ *wiyi* ∀*i* ∈ *I* (B2)

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ical model and the visual GIS interface serve as a

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*j*∈*J*

*k*∈*K*

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decision support system for IMM to use in future

X

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*xjk* ≤ *P* (B3)

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analyses.

*xjk* ≤ 1 ∀*j* ∈ *J* (B4) *k*∈*K*

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Appendix C

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*xjk* ∈ *8*0*1* 1*9* ∀*j* ∈ *J 1* ∀*k* ∈ *K* (B5)

s

Logistic functions are often used to describe certain kinds

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*yi* ∈ *8*0*1* 1*9* ∀*i* ∈ *I1* (B6)

of growth. These functions, like exponential functions, grow

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quickly at first; however, because of restrictions that place

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limits on the size of the underlying population, they even

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*I* = set of subdistricts; *i* ∈ *8*1*1000 1* 790*9*;

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*J* = set of candidate fire station locations (i.e., subdistricts);

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i

*j* ∈ *8*1*1000 1* 790*9*;

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*K* = set of candidate fire station types; *k* ∈ *8A1 B1 C1 D9*; p

*wi* = weight of subdistrict *i*;

o

t

*rk* = capacity of a fire station of type *k* per year;

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i

*fi* = historical fire incident records of subdistrict *i* per year;

l

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*hi* = historical fire incident records of subdistrict *i* per year

p

adjusted based on the existence of heritage objects in

s

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subdistrict *i*;

g

*oi* = number of heritage objects in subdistrict *i*;

n

i

*dij* = time between subdistricts *i* and *j*;

d

r

a

*S* = time standard for a fire station sited at a subdistrict *j* g

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to be eligible to serve subdistrict *i* (*S* = 5 minutes of r

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travel time in our research);

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*Ni* = set of subdistricts *j* within the time standard *S* of sub

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district *i*; that is, *Ni* = *8j*  *dij* ≤ *S9*;

e

u

*P* = number of fire stations to be opened (64 in our q

research);

y

n

*xjk* = binary decision variable (1 if a fire station is opened

a

in subdistrict *j*, 0 otherwise);

d

n

*yi* = binary decision variable (1 if a fire station is opened

e

s

in subdistrict *j* and is eligible to serve subdistrict *i*, 0 e

s

otherwise).

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Equation (B1) is the objective function that maximizes .

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the coverage of service requests in each subdistrict. Equa

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tion (B2) ensures that the right type of station is opened s

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to respond to service requests from each subdistrict. Equa

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tion (B3) ensures that the number of fire stations opened

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is within the set limit. Equation (B4) ensures that only one a

type of fire station is opened in a subdistrict. Equation (B5)

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represents the binary decision variable of opening fire sta

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tions. Equation (B6) represents the binary decision variable

n

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of covering the service requests in subdistricts.

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The Difference in *wi*for Scenario 6 (Budget) and

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e

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Scenario 8 (Heritage)

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In Scenario 6, *wi* = *fi* when we maximize the coverage of e

w

service requests (i.e., *cSR5*; in Scenario 8, *wi* = *hi* when we r

maximize the coverage of heritage service requests (i.e.,

e

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*cHSR5*. The relationship between *fi*, *hi*, and *oi*is:

t

o

tually 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 influ ence 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 Con nally et al. (1998), we calculate the number of fire incidents as follows:

*Fit* =0*i*

1 + exp*4*1*POPit51* ∀*i1 t* (C1)

where *Fit* is number of fire incidents and *POPit* is the popu lation at district *i*, in year *t*, 0*i*is the stabilized annual num ber of fire incidents, and 1is the change speed parameter of the number of fire incidents with respect to the popula tion of districts. We solve the model using E-views 7.0 soft ware. 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 1coefficient is 0.052 (*z*-statistics = 3*0*16 and *p <* 0*0*000), and the *R*2 value is 0.72. Positive 1indicates 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 (*CSD5*, the coverage of service requests (*CSR5*, and the coverage of heritage service requests (*CHSR5*: P

*i*∈*I yi*

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*hi* = *fi* ×

9 ×

*oi* − min*i*∈*I oi*

+ 1

*0* (B7)

*cSD* =

P

*I*(D1)

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max*i*∈*I oi* − min*i*∈*I oi*

n

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We adjust service requests in Scenario 8 by a factor of 1 to

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10, depending on the relative density of heritage objects in

s

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each subdistrict.

p

*cSR* = *cHSR* =

*i*∈*Ifiyi* ~~P~~

*i*∈*Ifi*(D2) P

*i*∈*I hiyi* ~~P~~

*0* (D3)

*i*∈*I hi*

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*I* = set of subdistricts; *i* ∈ *8*1*1000 1* 790*9*.

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*yi* = binary decision variable (1 if a fire station is opened

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in subdistrict *j* and is eligible to serve subdistrict *i*, 0

o

f

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i

otherwise).

@

*fi* = historical fire incident records of subdistrict *i* per year.

s

n

*hi* = historical fire incident records of subdistrict *i* per year,

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i

s

adjusted based on the existence *f* heritage objects in

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subdistrict *i*.

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Acknowledgments

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y

c

i

l

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p

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Ince (chief of research, planning and coordination, fire sta g

tion) for his support during the model’s development, data

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acquisition, and implementation. We also express our spe

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cial thanks to the associate editor and two anonymous

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reviewers for their constructive criticisms and support in

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Verification Letter

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Abdurrahman Ince, chemical engineer, director of Istan

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bul Fire Brigade, Research Planning Coordination Depart

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ment, writes:

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“I would like to write about an operations research e

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implementation that took place in Istanbul, Turkey to select

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locations for new fire stations. I am writing this letter y

to support the publication of this work, that was part

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of the coordination project named “My Project Istanbul n

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academic research potential of our universities to the p

solutions of urban problems and to contribute to mak ing 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 mem bers 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 deci sion 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 advi sory 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 adminis trative council. Right now, the first phase is completed and received good feedback from the community. The remain ing 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 cit izens of Istanbul. I hope that this information is useful in pursuing the publication of the project.”

Emel Akta¸s 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 loca tion 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*.

Özay Özaydın is a lecturer at Dogus University, Engi neering Faculty, Industrial Engineering Department. He received his B.Sc. degree in aeronautical engineering, M.Sc. degree in engineering management, and Ph.D. degree in industrial engineering, all three from Istanbul Technical University. He participated in various projects for Istan bul Metropolitan Municipality, Worldbank, and Competi tiveness Forum. His research areas are decision making, emergency management, and product and process design.

Burçin Bozkaya earned his B.S. and M.S. degrees in industrial engineering at Bilkent University, and his Ph.D. in management science at the University of Alberta, Canada. Between 1999–2004, he worked as a senior operations research analyst at ESRI (Environmental Systems Research Institute, Inc.) in Redlands, California, specializing in

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applications of GIS (Geographic Information Systems) in the s

transportation and logistics arena. Since 2004, Dr. Bozkaya

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is a faculty member at Sabancı School of Management, and

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is the author of various scholarly publications in the areas @

of location analysis, vehicle routing, heuristic optimization, s

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and applications of GIS as a decision support system.

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Füsun Ülengin is professor of operations research, Indus

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trial Engineering Department, Dogus University, Istanbul,

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Turkey. She acts as the dean of the Engineering Faculty as

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well as the head of the Industrial Engineering Department. o

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She earned a B.S. in managerial engineering from Istanbul y

Technical University, and an M.Sc. in industrial engineer

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ing from Bosphorus University, Istanbul. She pursued her

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Ph.D. education at Waterloo University, Ontario, Canada

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Management Faculty, Turkey. She did post-doctoral research on logistics at Birmingham University, Department of Pro duction Engineering, as an honorary research fellow. She is currently the vice-chair of the WCTR Society and the advi sor of the Transportation and Logistics sector in the Turkish Union of Chambers and Commodity Exchanges (TOBB).

¸Sule Önsel is an associate professor in Industrial Engi neering Department, Dogus University, Istanbul, Turkey. She acts as the vice-dean of the Engineering Faculty. Her research topics are decision making, neural networks, sce nario analysis, cognitive mapping, and Bayesian causal maps. Her refereed articles have appeared in a variety of journals including *Expert Systems with Applications, Trans portation Research Part C, Socio-Economic Planning Sciences, European Journal of Operational Research*, and *International Journal of Production Research*.