ARTICLE IN PRESS

Fire Safety Journal ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Optimising the spatial location of urban fire stations

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ARTICLE INFO

Keywords:
Optimization
Fire station siting
GIS

ABSTRACT

One of the most essential public services in urban areas is fire protection and response. It also happens to be one of the most costly. As urban areas grow, develop and change, it is important to plan services accordingly, both in terms of safety as well as being fiscally responsible. This paper discusses strategic planning goals and objectives in fire protection and response, and details modeling approaches to support fire station siting. A case study examining a fire service system for a city in California is used to illustrate the importance of strategic planning and system re-evaluation when expanding services.

1. Introduction

The protection of people, property and the environment from fire has long been a major concern in urban (and rural) areas. This is not surprising as fires take or threaten lives, damage property and alter the natural environment in many ways. Because of this, substantial resources are devoted to fire protection and response services. All communities have fire protection services of some sort. Fire departments can be found throughout urban areas, staffed with a complement of first responders, which typically include ladder and truck companies to pump and deliver water and perform basic firefighting. They may also have additional training and/or staff for general emergency response, perform advanced and basic life support as well as undertake search and rescue.

Providing fire protection and response services is not trivial. There are fixed costs to build and sufficiently equip stations as well as annual costs for maintenance. Current estimates for a new fire station are about $2 million. Of course there are also annual, reoccurring costs for personnel. In fact, the annual costs to staff and maintain a fire station are significant [6], roughly equivalent to the fixed costs of a station [18,2,15].

Fire protection and response are widely held as a necessity, and deemed worthy of public funding and support. However, it is a costly endeavor. Responsible fiscal oversight of public expenditures, especially in times of economic hardship, demands that the provision of services like fire protection and response undergo systematic (re-)evaluation and review as changes occur. Such changes include but are not limited to, aging of facilities and equipment, technological innovations, population growth and decline, and urban development, among others. More important is that a fire protection system, like many other service provision systems, is the outgrowth of incremental evolution, where new facilities are opened and closed as demand for service changes [28,18,23]. The unfortunate reality is that existing systems typically do not reflect the most efficient configuration possible due to such incremental change through station addition/subtraction. For fire protection and response, where spatial coverage is fundamentally important, this is particularly true. It is likely then that service efficiencies may be achieved through strategic system enhancements, especially when new fire stations are anticipated.

This paper discusses the need for systematic evaluation and review of a fire protection system, focusing primarily on the spatial configuration of stations that house fire response personnel and equipment. The next section provides background associated with fire station siting. This is followed by a review of optimization models that have been used to assist fire station location decision making in order to maintain industry performance standards. To highlight touched upon issues, a study is included of a fire service system in California, illustrating the potential for system improvements in the context of responsible fiscal management. The paper ends with discussion and concluding comments.

2. Background

The services offered by fire stations have long been a prerequisite of urban amenities. In particular, fire endangers people and property. The Insurance Services Office (ISO), a company specializing in providing information on property and liability risk, is used by insurers and government regulators in the United States for ensuring adequate fire protection services. Most countries have an equivalent organization. At the heart of this information is relative risk and associated fire response. As a result, there are typically well-established response time standards that seek to mitigate risk for people and property loss. An example is the guidelines

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0379-7112/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.firesaf.2013.03.002

established by National Fire Protection Association (NFPA) [17] advising that fire services be located in order to achieve a 9 min response time for 90 % of calls in urban areas. While the exact criteria utilized by a city/municipality may vary (e.g., 8 min for 85% of calls, etc.), this general intent is universally mandated. Urban fire protection is committed to speedy response to the majority of calls for service.

The significance of this is that the standards and guidelines established for most, if not all, urban areas are inherently spatial. The response time standard effectively corresponds to a geographic footprint for each fire station, reflecting those locations in the urban area where it is possible to respond to a call for service within the stipulated time standard.

The spatial nature of response from a fire station is reflected in the ever growing number of studies associated with locational site selection. The classic work of Plane and Hendrick [18] reported fire station siting in Denver, Colorado, detailing the use of a coverage response standard. Reilly and Mirchandani [19] looked at fire station location in Albany, New York, highlighting the need for maximizing accessibility to potential demand as well as a maximum response standard. Other studies have followed, including Schreuder [24] for Rotterdam, Badri et al. [2] for Dubai, Yang et al. [29] for Derbyshire England, and in recent years Kanoun et al. [11] for Sfax, Liu et al. [30] for Singapore, Catay [3] for Istanbul, Chevalier et al. [4] for Belgium and Murray et al. [15] or Elk Grove, California. Again, there are many others as well. Characteristic features of these studies is the use of spatial optimization models to support locational decision making regarding where fire stations should be sited in order to ensure the best system performance possible.

Approaches to aid fire station siting are widely recognized, with much practical and theoretical work being carried out over the past 40+ years. Extensive reviews of the various models can be found in ReVelle [20], Marianov and ReVelle [12], Badri et al. [2] and Sorensen and Church [25]; this material will not be repeated here. Instead, a more selective and brief overview is given, with a primary focus on the literature related to the fire protection response time standards touched upon above. Hogg [10] is noteworthy as it is one of first articulations of the need for systems analysis in fire protection: select the optimal number of fire stations as well as where to locate them in order to minimize total loss due to fire. Building on this is the study of Plane and Hendrick [18] who applied the location set covering problem (LSCP), detailed originally in Toregas et al. [31], using response time as a coverage standard. A different approach was put forth in Reilly and Mirchandani [19] based on so called median models, namely the *p*-median problem of ReVelle and Swain [22], in order to get at the issue of maximizing accessibility to potential calls for service. Schilling et al. [23] detailed the use of a maximal coverage location problem (MCLP) type approach (the MCLP was originally proposed by Church and ReVelle [5]). Finally, Murray and Tong [14] as well as Chevalier etal. [32] applied variants of the MCLP. The MCLP and extensions are important because they enable one to explicitly address issues of response time coverage in addition to regional goals for system response as set forth in standards and guidelines, such as those issued by the NFPA.

3. Model support

There are a variety of different considerations involved in fire protection, and the siting of stations. As noted above, there are many alternative and complementary modeling approaches that may be relied upon in support of fire station siting decisions. As a result, it would be difficult to formally present even a representative sampling of these approaches. Rather than pursue a broad ranging review with little substantive detail, this paper instead focuses on the widely adhered to situation where fire services are to be located in order to best achieve a S minute response time for Ψ percent of calls in urban areas. As noted previously, NFPA recommends standards of S equal to 9 min and Ψ equal to 90% of all calls. Discrete optimization models are therefore presented to support planning and decision making where these concerns are expressly addressed.

Responsible fiscal oversight of a publically funded fire protection system suggests that it is also important to minimize total operational costs. It is assumed that the fixed (capital) costs of a fire station are essentially the same across a region and that each station provides the same basic services. These are reasonable, and generally observed in practice. If the costs and services are effectively the same for any potential station location, a strategic goal is therefore to minimize the number of fire stations in operation that enable the desired/required level of service performance to be achieved.

Service systems are generally complicated by both technical and political considerations. Further, most operational systems are the byproduct of evolution over time. This places most fire station siting efforts as one where the intent is to site one or more additional stations in order to complement and enhance current service provision. That is, there are existing fire stations, but they are unable to sufficiently serve current or projected demand. The path forward then is often to focus on where the new stations should go, taking existing stations as fixed. This was in fact the case in the studies of Kanoun et al. [11] and Murray et al. [15]. While this makes sense in some ways, over time this may in fact prove to be far more costly. Many have suggested and shown that the perspective to simply expand an existing system is problematic (see [18,2]). System efficiency may well dictate that it is most prudent to close and/or relocate stations. The reason is that annual costs are significant, so re-configuration to gain increased efficiency can likely offset additional fixed costs, even over a short period of time. Thus, there is merit in complete system evaluation and assessment. As a result, the modeling discussion below begins with a focus on siting as if there are no existing stations. This is done to simplify the technical presentation, but also to highlight that system-wide evaluation is extremely important. Following this, existing system considerations are addressed.

It is assumed that when an emergency call is received, personnel at a station are available to respond. Consider the following notation:

i=index of neighborhoods to be served;
j=index of potential fire stations;
a_i=expected service demand in neighborhood i;
S=suitable response time/distance standard;
Ω_i=set of potential fire stations capable of suitably responding to neighborhood i;
p=number of fire stations to be sited.

Worth further explanation are the sets Ω_i. If the travel time from neighborhood i to potential station j is denoted t_{ij}, then a fire station located at j can respond to a call for service in neighborhood i within S when $t_{ij} \le S$. Thus, $\Omega_i = \left\{ j \middle| t_{ij} \le S \right\}$. What remains then are decision variables corresponding to siting and suitable coverage of neighborhoods, respectively:

$$X_j = \begin{cases} 1, & \text{if fire station } j \text{ selected} \\ 0, & \text{otherwise} \end{cases}$$

$$Y_i = \begin{cases} 1, & \text{if neighborhood } i \text{ is suitably served by one or more sited fire stations} \\ 0, & \text{otherwise} \end{cases}$$

This notation enables us to structure one of the most widely applied, utilized and extended models to support fire station

Please cite this article as: A.T. Murray, Optimising the spatial location of urban fire stations (2013), http://dx.doi.org/10.1016/j.firesaf.2013.03.002