Consistency-Based Multi-Criteria Group Decision-Making for Fire Station Staffing

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Determining staffing requirements for a fire station is quite difficult as one must balance the cost of additional human resources and the risk of not having an effective force to respond to a given incident. This paper presents an application of a new AHP-based method, incorporating multiple decision-makers and multiple decisions, to fire station staffing in a large residential and industrial complex. Anew practical and comprehensive model is formulated for fire station staffing. Moreover, an effective method is developed to integrate multiple decisions and decision-makers in multi-criteria group decision-making (MCGDM). The paper presents a two-stage decision-making approach. The first stage is applying AHP to each decision and each decision-maker. The second stage is integrating the inputs to reach a group decision using consistency-based weights of individual decision-makers. The method integrates the different decisions into a set of ranked final decisions using the weighted scores for the combination of decision alternatives.

Keywords: Analytic Hierarchy Process (AHP), Multi-Criteria Decision Making, Group Decision, Fire Station Staffing, Consistency-Based Weights

1. Introduction

Determining staffing requirements for a fire station is quite challenging as one must balance between the cost of additional resources (firefighters and fire trucks) and the risk of not having an effective response force to respond to a given incident. Fire station staffing decisions involve difficult trade-offs among many important factors such as human life, public safety, and economic impact. The cost of additional protection must be weighed against possible human, property, and economic losses resulting from potential fire incidents. Additional staffing naturally provides higher protection levels, but the relationship between the crew size and fire safety is not well defined. In the U.S.A., the NFPA (National Fire Protection Association) issues general recommendations for fire station staffing levels. However, there are no universally accepted procedures to determine the best staffing level for each fire station.

The appropriate staffing level for a given fire station, commonly referred to as the effective response force, is determined by considering two main factors. The first factor is the required number of firefighters per fire truck (i.e., crew size), and the second factor is the required number of fire trucks. This paper presents a new multi-criteria group decision-making (MCGDM) approach based on the analytic hierarchy process (AHP) for fire station staffing. This approach is applied to determine the effective response force for a fire station in a large residential and industrial complex. Inputs for this decision problem are obtained from four expert fire chiefs on the two fundamental fire station staffing decisions: the crew size per truck and the number of fire trucks.

The problem addressed in this paper has multiple decisions, multiple criteria/ sub-criteria, and multiple decision-makers (DMs). Specifically, the problem is to determine both the number of fire trucks and the number of firefighters per truck for an industrial fire station, based on multi-criteria decision making by a group of expert fire chiefs. Traditionally, the analytic hierarchy process (AHP) is used to handle multi-decision making (MCDM) problems with hierarchical criteria and sub-criteria structures. In this paper, a new AHP-based method is proposed to combine the two decisions, i.e. the number of trucks and the number of firefighters per truck. The proposed method combines the different DMs' inputs into a weighted average of their inputs, where the relative weights of fire chiefs are dependent on their consistency levels.

This paper presents a new multi-criteria group decision-making (MCGDM) approach to fire station staffing with three main original contributions. First, a new model of the fire station staffing problem is formulated, including multiple decisions, multiple criteria, multiple decision-makers, and multiple levels of criteria and sub-criteria. Second, a simple process is developed to combine the two decisions (crew size and number of trucks) and rank the pairs of alternatives based on the combined score. Third, a new consistency-based weighting method is proposed to combine individual decision makers' inputs into a group decision.

Subsequent sections are organized as follows. In Section 2, a review of relevant literature is presented. In Section 3, the overall approach is explained. In Section 4, AHP is applied to individual fire chiefs. In Section 5, a method is described to integrate the individual inputs and to reach consensus among the group. In Section 6, conclusions and suggestions for future research are provided.

2. Literature Review

This paper presents a multi-criteria group decision-making (MCGDM) problem where the goal is to determine fire station staffing. The paper also provides an AHP-based aggregation technique to reach consensus in MCGDM problems involving multiple decisions. Therefore, this section covers recent publications in three categories: (1) optimum fire station staffing, (2) MCGDM in fire and risk management, and (3) aggregation of individual decisions makers’ inputs in MCGDM.

2.1 Optimum Fire Station Staffing

In the fire protection community, two standards are commonly referred to when discussing the fire station's staffing level (Averill et al. 2011; National Fire Protection Association 2020). The fire ground field experiments conducted by the National Institute of Standards and Technology (NIST) are among the most notable works on fire station staffing (Averill et al. 2011). NIST conducted 60 field experiments to measure the impact of varying the crew size per fire truck on the overall scene time while keeping the number of fire trucks fixed at two. The NIST study does not provide any specific conclusion regarding the choice of crew size. However, it provides various performance measures that the decision-maker could use to select the crew size required. Another notable reference on fire station staffing is NFPA1710 (2016), a standard developed by the National Fire Protection Association (NFPA). In NFPA 1710, however, the number of personnel for a single station is not specified. The NFPA1710 recommends that each fire department should plan to respond to different types of fires with a minimum of 15 personnel, including firefighters and emergency medical services (EMS) personnel. However, the total number of firefighters may need to be increased depending on the fire incident type or location. The NFPA study is not very relevant to our region since firefighters and EMS personnel are not governed by the same entity.

Several operations research approaches have been developed to optimize fire station staffing. Simpson and Hancock (2009) reviewed the literature in the past fifty years on operations research approaches to emergency response facilities in general, including fire stations, police stations, and ambulance services. Lawrence (2001) presented an analytical approach in which the community demands and expectations are used to determine the fire station's staffing level. Four simulated fire and rescue experiments were used to test the crew size/time relationship and compare different possible staffing levels. Utilizing a similar approach, Geason (2002) used seven practical experiments that simulate common fire station tasks to compare four different crew sizes at several fire stations. The study showed a significant difference in efficiency and safety between the alternative staffing levels and recommended an immediate increase in the number of firefighters at those fire stations. Fry et al. (2006) modelled the annual staffing level for a fire department to minimize the total expected costs, subject to satisfying minimum staffing requirements. The model, which is derived from the newsvendor inventory problem, accounts for absenteeism and hiring limitations within the firefighters' work schedule.

Green and Kolesar (2004) examined the literature of management science and operation research applications in emergency and fire operations. Dalby (2007) used decision analysis to calculate the expected risk of specific staffing decisions. The model generated scenarios for different staffing levels to provide the decision-maker with quantifiable measures of the cost, benefit, and expected risk. Wei et al. (2014) developed a two-stage probabilistic model to minimize the total daily cost of fire suppression resources. The model considers several assumptions to estimate the adequate daily cost and determine the allocation of fire suppression resources. Lolli et al. (2015) presented a bi-objective model to minimize the traveling distance and time of a fire station’s response to simultaneous requests of micro calamities. Their work stresses modelling with humanitarian and risk-based objectives rather than cost-based objectives, and this is in line with the concepts in this paper. Stevanović et al. (2016) used a linear programming model to determine the required staffing level of firefighters for special events. The objective is to minimize the total cost of the daily allowances for multiple shifts, subject to meeting special event requirements for firefighters in each shift. Although several optimization approaches have been used to optimize fire station staffing, none of them simultaneously determines the number of fire trucks and the crew size per truck.

2.2 MCGDM in Fire and Risk Management

Multi-criteria group decision-making (MCGDM) techniques have been frequently used in fire and emergency management. Millet and Wedley (2002) applied AHP to determine risk criteria, risk probabilities, and risk performance measures for several typical case studies. Meacham (2004) reviewed decision-making approaches for fire risk problems, outlining the relevant processes, challenges, and tools. Levy and Taji (2007) developed a Group Analytic Network Process (GANP) approach for multi-criteria hazards planning and emergency operations. Individual criteria weights are expressed by interval preferences, while group scores for the decision options are obtained by quadratic programming. Yu and Lai (2011) proposed an MCGDM approach for emergency decisions and applied it to a chemical spill case. The objective is to maximize the decision makers' agreement by minimizing the sum of squared distances between their decisions. Wilson et al. (2011) analyzed the decision-making biases of wildfire management officers in the United States Department of Agriculture's Forest Service. Chaudhary et al. (2016) combined AHP, Group Decision Making, and Geographic Information Systems (GIS) for locating fire stations. Akaa et al. (2016) used group AHP to compare fire protection options for steel structures, utilizing the Geometric Mean Method to combine the individual stakeholders' inputs. Many of the previous MCGDM fire and emergency management studies use AHP variants and combinations, but none specifically addresses fire station staffing.

2.3 Aggregation and Consistency of Individual inputs in MCGDM

Several aggregation techniques have been proposed to combine individual decision makers' inputs into a single group decision. Ossadnik et al. (2016) reviewed the literature on aggregation techniques in group decision-making problems and provided the assumptions under which a specific technique might be used for a given context. Alfares and Duffuaa (2008) proposed empirical methods to combine individual criteria ranks into aggregate weights for multi-criteria group decision making. Grošelj et al. (2015) compared nine aggregation methods for group AHP based on five performance measures, concluding that method selection should be based on the given application. Akaa et al. (2017) used the geometric mean in group Analytic Network Process (ANP) to balance multidisciplinary stakeholders' views on fire protection options for steel structure. Koksalmis et al. (2018) surveyed methods for deriving DMs weights for group decisions and classified them into five main types: similarity-based, indexed-based, clustering-based, integrated, and other approaches.

AHP consistency ratios have been considered in several aggregation approaches in MCGDM. Aull-Hyde et al. (2006) analyzed the group judgment's consistency based on the aggregated geometric mean (AGM) of individual judgments. Simulation experiments showed that the AGM-based group judgment is always consistent if the group size is large, even if the individual judgments are not consistent. Grošelj and Stirn (2012) provided analytical proof of the simulation-based results of Aull-Hyde et al. (2006) and determined the sufficient conditions for the group's AGM to be consistent. Moreno-Jiménez et al. (2008) combined the AHP consistency ratio with two other measures to develop the Consistency Consensus Matrix, which is used to minimize divergence among DMs in group decision making. Cho and Cho (2008) combined AHP consistency ratios and Taguchi's loss function to aggregate individual judgments into group weights for the different criteria.

Previously proposed aggregation methods are designed for other decision problems under different assumptions not applicable to our problem. Therefore, a new aggregation method is proposed for fire station staffing with consistency-based weights of individual fire chiefs.

This section has shown the problem uniqueness and the need for the new solution method presented in this paper. Evidently, the fire station staffing problem under consideration is unique as it has several distinguishing features. The proposed solution method is also new and has not been used previously in the literature. This proposed method, which is used to integrate two independent decisions and aggregate inputs from several decision-makers, is presented in the following sections.

3. Overall Approach

In this section, a new AHP-based multi-criteria, sequential group decision-making approach is proposed to determine the appropriate fire station staffing level. The choice of AHP as the base technique to develop the proposed method is due to several factors. First, AHP is the most popular and effective MCDM technique. Second, AHP has a distinct hierarchical structure that facilitates the comparison of multiple decision alternatives and multiple criteria/sub-criteria. Third, AHP requires only simple pair wise comparisons instead of explicit criteria weights and explicit score for alternative decision options.

The total staffing (workforce size) for the station depends on two independent decisions: (1) the crew size, i.e., the number of firefighters per truck, and (2) the number of fire trucks. The input data used in making the two decisions are obtained from four expert fire chiefs in the company. The four decision-makers (fire chiefs) have practically the same level of experience, knowledge, and education. Their inputs reflect their personal judgments and preferences, based on their long experiences in different fire stations. To avoid influencing their inputs, the fire chiefs were not told that their weights would be determined based on their consistency levels. In fact, they were not even told that their individual inputs might be given different weights. The choice among different decision options is based on several factors (criteria) relevant to fire station staffing, such as coverage area type and distance to the nearest fire station. The full list of criteria and sub-criteria will be specified and explained in Section 4.

The calculation process is divided into two stages. In the first stage, AHP is applied individually for each fire chief to determine their personal priorities for each alternative under the two decisions. This process involves pair wise comparisons between the different criteria, as well as between the different options under each criterion. Due to the nature of subjective judgments, the pair wise comparison matrices used to compare both the criteria and the decision alternatives involve certain degrees of inconsistency that vary from one fire chief to another.

In the second stage, the consistency ratios of the fire chief are calculated and used to give are lative weight for each fire chief's judgement. These weights are then used to combine the individual inputs of the four fire chiefs and to reach the best overall group decision. According to Cho and Cho (2008), higher consistency means better evaluation quality. In fact, DMs with high inconsistency (consistency ratios above 0.1) are usually excluded from the aggregated decision, indicating their relative weights are considered to be zero. Therefore, it is logical to assume that higher consistency reflects better DM judgment. Based on this assumption, we propose an aggregation method that gives greater weights to DMs with higher consistency levels. As far as we know, this is a new way of determining the weights of different DMs in group decision making. Cho and Cho (2008) used consistency to determine group weights of individual criteria, but we use consistency to determine individual DMs' weights. The new consistency-based DM-weighting method is especially useful if the DMs are essentially equal in all other aspects, such as the four fire chiefs in this study.

The index i is used for indicating the four fire chiefs (i = 1, …, 4). The index j is used to indicate the two decision problems (j = 1 for the crew size, and j = 2 for the number of trucks). The index k is used to indicate the different decision alternatives. The index m is used to indicate the different pair wise matrices (m = 1, …, M), where M is the number of matrices for each decision problem. Using these symbols, the steps of the process are described in greater detail below.

Step 1 From each fire chief, obtain their relevant pair wise comparison matrices. Using these matrices, apply AHP method to obtain the fire chief's individual preferences for the different options under the two decision problems: (1) crew size per truck and (2) number of fire trucks. The output of this step is given by
S_{ijk} = Score of alternative *k* under decision *j* for fire chief *i*

Step 2 For each fire chief (*i*), each decision problem (*j*) and each pair wise comparisons matrix (*m*), calculate the consistency ratio CR_{ijm} using the AHP method. If CR ijm is less than or equal to 0.1, then the matrix is deemed consistent. For CRijm values greater than 0.1, a re-examination of the fire chief's inputs is warranted for the given pair wise comparison matrix. The process is repeated until a CR ijm value not exceeding 0.1 is reached.

Step 3 For each fire chief (*i*) and each decision problem (*j*), determine the total consistency ratio (TCR_{ij}), which is the sum of the fire chief's CR_{ijm} values for all pair wise-comparison matrices (*m*) under the given decision problem. As shown in equation (1), this sum should include all matrices where the criteria are evaluated against each other and matrices where the alternatives are evaluated with respect to a given criterion. For a perfectly consistent decision-maker, the TCR_{ij} value should be zero, but this rarely happens in subjective judgments.

$$\boldsymbol{TCR_{ij}} = \sum_{\boldsymbol{m=1}}^{\boldsymbol{M}} \boldsymbol{CR_{ijm}} \quad i = 1, \ldots, 4, j = 1, 2 \tag{1}$$

Step 4 Determine the Fire Chief's Perfect Judgement Index (P_{ij}) for each decision problem. According to their consistency levels, the Index (Pij) is used to assign weights to different fire chiefs. Since TCR_{ij} is a negative criterion (i.e., less is better), higher weights should be given to fire chiefs with lower TCR_{ij} values. In this paper, we propose a new linear novel weighting scheme specified by equation (2).As far as we know, this weighting method has not been used before in previous literature. This method assigns a weight to each fire chief which is the sum of the TCR_{ij} scores of the other fire chiefs. The rationale is that each fire chief gets credit for all the errors they did not make. For cases where all decision-makers are consistent or all decisions have two criteria, the formula will have a division by zero. For such cases, weights for the DMs should be either assumed or assigned based on other applicable factors. The proposed formula is proposed for cases where at least two decision-makers exhibit some inconsistency.

$$\boldsymbol{P_{ij}} = \frac{(\sum_{i=1}^{4} \boldsymbol{TCR_{ij}}) - \boldsymbol{TCR_{ij}}}{3(\sum_{i=1}^{4} \boldsymbol{TCR_{ij}})} \quad i = 1, \ldots, 4,\ j = 1, 2 \tag{2}$$

Dividing by $(3 \sum_{i=1}^{4} TCR_{ij})$ ensures the weights add up to one. The number 3 is simply 4–1, which is the total number of fire chiefs minus one. The proposed weighting method expressed in (2) can be generalized for any negative criterion, such as cost or inconsistency, where lower values are better. Assuming the scores for n alternatives/DMs are given by $x_1, \ldots, x_n$, then the relative weight w_i of each alternative/DM $i$is found by equation (3). The purpose of dividing by $(n - 1)(\sum_{i=1}^{n} x_i)$ is to normalize the weights to make their sum equal to 1; since the denominator is the sum of the values in the numerator for $i = 1, \ldots, n$, at least one x_i element must be non-zero to avoid dividing by zero. Moreover, the only way that (3) can give a zero weight to any item i is if $(\sum_{i=1}^{n} x_i) = x_i$, which can be true only if the sum$\sum_{i=1}^{n} x_i$ contains only one non-zero item, x_i. Therefore, at least two values in the set $\{x_1, \ldots, x_n\}$ must be non-zero to avoid assigning a zero weight to any alternative/DM. Under these conditions, the generalized form of equation (2) is given by:

$$\boldsymbol{w_i} = \frac{(\sum_{i=1}^{n} \boldsymbol{x_i}) - \boldsymbol{x_i}}{(\boldsymbol{n}-\mathbf{1})(\sum_{i=1}^{n} \boldsymbol{x_i})} \quad i = 1, \ldots, n \tag{3}$$

Step 5 For each decision problem j, determine the group weighted score WS_{jk} for each alternative $k$by multiplying the normalized weights P_{ij} for each fire chief by their corresponding AHP scores.

$$\boldsymbol{WS_{jk}} = \sum_{i=1}^{4} \boldsymbol{P_{ij}} * \boldsymbol{S_{ijk}} \quad j = 1, 2,\ k = 1, \ldots, 3 \tag{4}$$

Step 6 For all available pairs of (crew size/number of trucks) decisions, add the group weights for both decision alternatives, and then rank these pairs according to the total weighted score values. For decision number k on the crew size and decision number l on the number of trucks, the overall score of the (k, l) decision pair is given by either the arithmetic mean AM_{kl} or the geometric mean GM_{kl}, as shown below. The rationale behind using the arithmetic or geometric average scores is to maximize the overall preference or priority of a given combination of decisions.

$$AM_{kl} = (WS_{1k} + WS_{2l})/2,\ k = 1, \ldots, 3,\ l = 1, \ldots, 3 \tag{5}$$

$$GM_{kl} = (WS_{1k} \times WS_{2l})^{½},\ k = 1, \ldots, 3,\ l = 1, \ldots, 3 \tag{6}$$

4. Applying AHP Steps

4.1 Identify the Decision Process Elements

To identify the relevant criteria and the feasible alternatives for fire station staffing decisions, the 6-3-5 Brain writing technique developed by Rhorbach (1969) was used. This methodology was chosen because it is easy to learn, it leads to full and fair participation by all DMs, and it generates many ideas in a short time. Several structured brainstorming sessions were conducted with the four fire chiefs to reach a final list of criteria and alternatives. As a validation step, another group of experienced fire chief were interviewed to validate and approve the final list. For the two fire station staffing decisions (crew size and the number of fire trucks), the applicable criteria and alternatives are summarized in Figure 1. The cost is not included as a criterion because economic aspects have very low priority in making fire station decisions. The company has a strong focus on safety and a high value for the fire station's essential role in protecting lives, property, and the environment. An explanation of the rationale for choosing the alternatives and the criteria of each decision is provided below.

4.1.1 Crew Size

In the fire protection community, the most notable work on crew size variation is the fire ground field experiments conducted by the National Institute of Standards and Technology (NIST). NIST conducted 60 experiments to measure the impact of varying the crew size per fire apparatus on the overall scene time. For this case study, inputs were obtained from four local experienced fire chiefs. After multiple rounds of workshops with these fire chiefs, the crew sizes (i.e., the alternatives) of relevance to our region were found to be 3, 4, or 5. Also, the four fire chiefs involved in our study proposed to use the following main criteria to select the crew size:

1. Coverage area, which has three categories (sub-criteria):
- Industrial,
- Community and
- Aviation.
2. Nearest fire station to support
3. Fire station risk classification

The coverage area is an important criterion since the strategy to approach each fire incident is dependent on the primary coverage area. For example, the strategy for community fires is to attack and be aggressive to avoid the possibility of a loss of life. In contrast, the strategy for industrial fires is to contain the fire and limit its exposure. There are three primary coverage area categories for fire stations in Saudi Arabia: Community, Industrial, and Aviation. These coverage area categories are defined at the corporate level, and each fire station is given one or more coverage category. After multiple rounds of interviews with each fire chief, it was agreed that these categories are to be used as sub-criteria under the coverage area criterion. The Nearest fire station to support is an important criterion in deciding the required crew size as proposed by the fire chiefs. Fire stations in remote locations that do not have supporting fire stations nearby require more resources (i.e., firemen) to respond to incidents on their own effectively. On the other hand, stations close to other fire stations generally have agreements on mutual support for dealing with incidents. Fire risk classification is based on the company's engineering standards, and it significantly affects the number of firefighters required. Fire risk classification is used in the company's fire department business planning as an important factor in all ocating labor bud gets to different fire stations. This classification is also a key factor in deciding the importance of a fire station based on two main components: the population size and the criticality of the response area.

4.1.2 Number of Fire Trucks

There is quite a debate on the appropriate number of fire trucks to base the fire station staffing. After multiple workshops with the four fire chiefs, the number of fire trucks (i.e., the alternatives) of relevance to our region was found to be either one, two, or three trucks. The fire chiefs also proposed to use the following main criteria to determine the number of fire apparatus required:

1. Cover on their own
2. Supplemental support

Cover on their own is a measure of how often a given fire station can respond to a given incident alone. Supplemental support is a measure of how many fire trucks are required for support from nearby fire stations. Evidently, a fire station must make sure it can cover the majority of its area's incidents on its own with minimal support from other stations. This is reflected in the fire chiefs' judgements, as we will see in their pair wise comparison inputs. Supplemental support is important for fire stations, especially when the fire station's criticality is not of the greatest concern. Nonetheless, it is always a factor to be considered when deciding on the number of fire trucks.

The above-described criteria for the crew size and the number of fire trucks form the basis for developing the mobilization plan. The mobilization plan is developed for each type of incident, taking into account all the above criteria to ensure an effective response force (the combination of crew size per truck and number of trucks). Figure 1 shows the decision problem structure, indicating the two decisions on crew size and the number of trucks, and their corresponding criteria, sub-criteria, and alternatives.

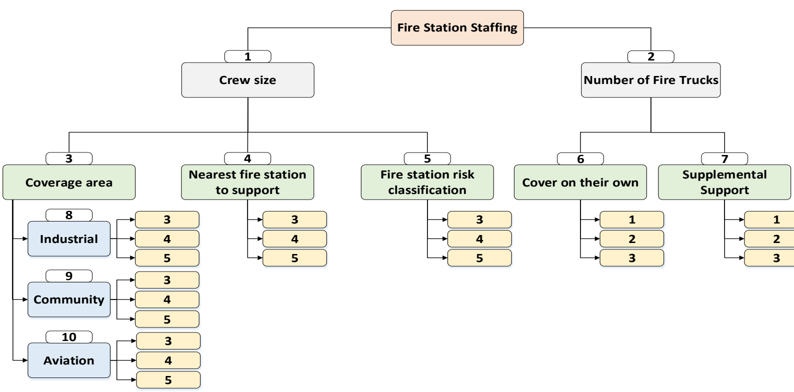

Figure 1 *The Fire Station Decision Problem and its Elements*

4.2 Criteria and Alternative Ranking

Each fire chief evaluated the alternatives and criteria to determine the ranking of decision alternatives. After multiple workshops with each fire chief, the criteria and alternatives were ranked using pairwise comparisons. Subjective judgments by each Fire chief were re-examined until the acceptable consistency ratio ($CR < 0.1$) was reached for all pairwise comparison matrices.

From Figure 1, there are ten pairwise comparison matrices in total: seven for the crew size and three for the number of fire trucks. For the crew size decision, there are two pairwise matrices (1 and 3) to compare the main and sub-criteria criteria and five matrices (4, 5, 8, 9, and 10) to compare the three alternatives with respect to the criteria and sub-criteria. For the number of trucks decision, there is one pairwise matrix (2) to compare the criteria and two matrices (6 and 7) to compare the three alternatives with respect to both criteria. Now, we can proceed to the next step in performing the AHP process, which is determining the overall priority for each alternative based on each fire chief's judgement.

4.3 Alternatives Overall Priority (Score)

Pairwise comparison matrices given by each fire chief were processed using the standard AHP calculations[1]. The resulting criteria weights and the scores for each alternative are given for each fire chief in Table 1 for the crew size decision and in Table 2 for the number of trucks decision.

To determine each alternative's overall priority (score), the normalized scores of each alternative under each criterion and the global criterion weights are needed. The global weight is determined by multiplying the sub-criteria weights by the weight of their parent criterion. For example, for fire chief 1, the global weight of the Industrial coverage area (0.1471) is obtained by multiplying the weight of the Industrial area(0.3088)by the weight of the Coverage area (0.4762), which is the parent criterion. The global weights are multiplied by each alternative's normalized weights across all criteria to determine the overall priority (score) for each alternative. For illustration, the equation below shows the process to calculate the overall priority (score)given by fire chief 1 for a crew size of 3.

$$S_{111} = 0.333\times0.1258 + 0.1471\times0.2128 + 0.2521\times0.2128 + 0.0770\times0.0591 + 0.1905\times0.5351$$
$$= 0.2334$$

Using the same AHP process, the overall scores for each alternative and each fire chief were calculated. These scores are shown in Tables 1 and 2 for the two decisions (crew size and the number of trucks). For each fire chief, the highest value (i.e., the best alternative) based on the AHP method is highlighted in bold. Clearly, the results indicate no agreement on a single decision by all fire chiefs, on either the crew size or on the number of trucks. Therefore, the second stage of the proposed method is applied next to combine the different scores of the fire chiefs in order to determine the best alternative (i.e., fire station staffing) for the whole group of four fire chiefs.

Table 1 *AHP Results for the Crew Size Decision*

Fire Chief 1	Industrial	Community	Aviation	Nearest Fire	Risk classification	Overall Priorities
Global Weights	0.1471	0.2521	0.0770	0.3333	0.1905	
3	0.2128	0.2128	0.0591	0.1258	0.5351	0.2334
4	0.1915	0.5957	0.3393	0.3974	0.3679	**0.4070**
5	0.5957	0.1915	0.6015	0.4768	0.0970	0.3596
Fire Chief 2						
Global Weights	0.2470	0.1698	0.0448	0.3692	0.1692	
3	0.2632	0.1692	0.2652	0.1338	0.4768	0.2357
4	0.3158	0.3692	0.6061	0.2548	0.3974	0.3291
5	0.4211	0.4615	0.1288	0.6115	0.1258	**0.4352**
Fire Chief 3						
Global Weights	0.1458	0.3749	0.1562	0.2398	0.0833	
3	0.2308	0.0591	0.1133	0.4211	0.1905	0.1903
4	0.5538	0.3393	0.3695	0.2632	0.4762	0.3684
5	0.2154	0.6015	0.5172	0.3158	0.3333	**0.4412**
Fire Chief 4						
Global Weights	0.2006	0.2553	0.0547	0.1489	0.3404	
3	0.1969	0.2308	0.1618	0.5749	0.5538	0.3814
4	0.6299	0.5538	0.3088	0.3114	0.2154	**0.4044**
5	0.1732	0.2154	0.5294	0.1138	0.2308	0.2142

Table 2 *AHP Results for the Number of Fire Trucks Decision*

Fire Chief 1	Cover on their Own	Supplemental Support	Overall Priorities
Global Weights	0.8333	0.1667	
1	0.1692	0.5538	0.2333
2	0.3692	0.2308	0.3462
3	0.4615	0.2154	**0.4205**

Fire Chief 2			
Global Weights	0.6667	0.3333	
1	0.4211	0.3692	**0.4038**
2	0.3158	0.4615	0.3644
3	0.2632	0.1692	0.2318
Fire Chief 3			
Global Weights	0.8000	0.2000	
1	0.2308	0.4615	0.2769
2	0.5538	0.1692	**0.4769**
3	0.2154	0.3692	0.2462
Fire Chief 4			
Global Weights	0.8000	0.2000	
1	0.3158	0.5106	0.3548
2	0.4211	0.3404	**0.4049**
3	0.2632	0.1489	0.2403

5. Determining the Group Decision

Following the AHP steps, each pairwise matrix's consistency ratio is calculated and shown in Table 3 for the crew size decision and in Table 4 for the number of fire trucks decision. Next, the sum of all consistency ratios of each fire chief for each decision (TCRij) is calculated using equation (1). Subsequently, the Perfect Judgment Index Pijis calculated using equation (2). Logically, the higher the value of Pij, the more consistent a decision-maker is for a given decision. For illustration, using equations (1) and (2), the calculations used to obtain the perfect judgement index of fire chief 1 for the crew size decision are shown below

$$\sum_{i=1}^{4} TCR_{i1} = 0.3010 + 0.1570 + 0.3014 + 0.3598 = 1.1193$$

$$P_{11} = \frac{1.1193-0.3010}{3(1.1193)} = 0.2437$$

Table 3 *Consistency Ratios* CR_{i1m} *for the Crew Size Decision*

Matrix (m)	Pairwise matrix description	Fire Chief 1	Fire Chief 2	Fire Chief 3	Fire Chief 4
1	Main Criteria for Crew Size	0.0523	0.0192	0.0421	0.0599
3	Sub-criteria under Coverage area	0.0096	0.033	0.0178	0.0687
4	Alternatives versus Nearest Fire Station	0.0112	0.0202	0.0479	0.0873
5	Alternatives versus Fire station risk classification	0.0330	0.0112	0.0523	0.0178
8	Alternatives versus Industrial Sub-criterion	0.0543	0.0479	0.0178	0.0987
9	Alternatives versus Community Sub-criterion	0.0543	0.0192	0.0863	0.0178
10	Alternatives versus Aviation Sub-criterion	0.0863	0.0064	0.0372	0.0096

TCR_{i1}	Total of all consistency ratios	0.301	0.1571	0.3014	0.3598
P_{i1}	Perfect Judgment Index	0.2437	0.2865	0.2436	0.2262

Table 4 *Consistency Ratios CR_{i2m} for the Number of Trucks Decision*

Matrix (*m*)	Pairwise matrix description	Fire Chief 1	Fire Chief 2	Fire Chief 3	Fire Chief 4
2	Main Criteria for Number of Trucks*	0	0	0	0
6	Alternatives versus Cover on their own	0.0192	0.0479	0.0178	0.0479
7	Alternatives versus Supplemental support	0.0178	0.0192	0.0192	0.0599
TCR_{i2}	Total of all consistency ratios	0.037	0.0671	0.037	0.1078
P_{i2}	Perfect Judgment Index	0.2838	0.2435	0.2838	0.1890

- CR is always zero for any 2×2 matrix.

An important advantage of the proposed consistency-based weighting scheme described in equation (3) is that it smooths possibly large differences among the decision-makers (fire chiefs in this case) in the TCR_{ij} values. In Table 4, for example, the total consistency ratio of fire chief 4 (TCR_{42} = 0.1078) is about three times as much as that of fire chief 1 (TCR_{12} = 0.037). However, the weight given to fire chief 1 (P_{12} = 0.2838) is approximately 1.5 times the weight of fire chief 4 (P_{42} = 0.1890), not three times as much. This smoothing property prevents the assignment of disproportionately large variations in weights to decision-makers, which may lead to one or few decision-makers dominating the decision while the others are marginalized.

Using equation (4), the Pij values in Tables 3 and4 are now used as weights for the AHP scores Sijk in Tables1 and 2 to determine the group weighted scores WSjk. As an example, the equation used to calculateWS11 is shown below. Similarly, all other weighted scores are calculated using equation (4), and the results are shown in Table 5. Effectively, a higher weighted score means a better decision in terms of both higher consistency and higher preference for the whole group.

WS11 = 0.2437×0.2334 +0.2866×0.2357+ 0.2436×0.1903 + 0.2262×0.3814
= 0.2571

Table 5 *Weighted Score of each Alternative k under each Decision*

Crew Size	WS_{1k}	Number of Fire Trucks	WS_{2k}
3	0.2570	1	0.3101
4	0.3747	2	0.3988
5	0.3683	3	0.2911

Finally, using equation (5), the weighted scores in Table 5are combined for each pair of alternatives, considering the two staffing decisions. Since we have two decisions, each one with three alternatives, then the total number of combinations (pairs) is nine. For example, the pair (4, 2) indicate the crew size is equal to 4firefighters per truck, and the number of trucks is equal to 2, and hence the total staffing is equal to 8 firefighters. The results for all possible decision pairs are shown in Table 6.

Table 6 *Ranking of Fire Station Staffing Alternatives*

Crew size k	No. of trucks l	Total station staff	AM_{kl}	GM_{kl}
4	2	8	0.3868	0.3866
5	2	10	0.3836	0.3832
4	1	4	0.3424	0.3409
5	1	5	0.3392	0.3379
4	3	12	0.3329	0.3303
5	3	15	0.3297	0.3274
3	2	6	0.3279	0.3201
3	1	3	0.2836	0.2823
3	3	9	0.2741	0.2735

The results in Table 6 are arranged in decreasing order of the average scores for both decisions, namely the crew size and the number of trucks. For the fire station staffing problem, both the arithmetic mean AM_{kl} and the geometric mean GM_{kl} give the same order of decision pairs. Based on this order of preference, the final decision is given as follows

Crew size per truck =4
Number of fire trucks = 2
Total fire station staff = 8

The above results show the validity of the model and the value of using the consistency-based weights. Different decisions by the four decision-makers can be combined by considering several factors, such as (1) simple voting, i.e. the number of DMs choosing each alternative, (2) the simple sum of priority scores for each alternative, and (3) the consistency-based weighted priority score average for each alternative. It will be shown that the proposed use of consistency-based weights provides results that are logical, i.e. consistent with simple voting and simple sum of scores, and useful in breaking possible ties.

Table 1 shows that two DMs (fire chiefs 1 and 4) preferred 4 fire fighters per truck for the crew size decision, while the two other DMs (fire chiefs 2 and 3) preferred five firefighters. With simple voting, there is a tie resulting in the inability to make a decision. Now, calculating the sums of priority scores given by all fire chiefs in Table 3, the total scores for crew sizes 3, 4, and 5 are 1.0408, 1.5089, and 1.4502, respectively. This indicates a higher preference for a crew size of four firefighters per truck. In this particular example, the difference between the sums for crew sizes 4 and 5 is slight. In general, two decision alternatives can be equal in terms of simple voting and equal or semi-equal in terms of sums of priority scores. In such cases, another factor is needed to break the ties, and this is when the consistency-based weights become necessary. As shown in Table 5, the consistency-based weighted priority score average is highest for the crew size of 4. This decision is consistent with the decision made based on simple sum of priority scores.

Table 2 shows that one DM preferred 1 fire truck for the number of trucks decision, two DMs preferred two trucks, and 1 DM preferred three trucks. From Table 4, the simple sums of priority scores for 1, 2, and 3 trucks are respectively 1.2688, 1.5924, and 1.1388. From Table 5, the consistency-based weighted averages of priority scores for 1, 2, and 3 trucks are respectively 0.3101, 0.3988, and 0.2911. Therefore, the same decision is obtained with simple voting, simple sums of scores, and consistency-based weighted averages, which is two fire trucks for the station.

6. Conclusions

This paper presented a new AHP-based multi-criteria group decision-making method for fire station staffing. The method was applied for staffing a typical fire station in a large residential and industrial complex. The problem considered involves multiple criteria, multiple decision-makers, and two main staffing decisions: the crew size per truck and the number of fire trucks. The method can be summarized as a two-stage approach. The first stage is applying AHP to each decision and each decision-maker. The second stage is integrating the individual decisions in order to reach a group consensus in both decisions. A new technique is proposed to assign weights to different decision-makers based on their varying consistency levels.

The proposed consistency-based method utilizes the fact that no decision-maker is perfectly consistent, and hence it gives higher weights to decision-makers with greater degrees of consistency. Starting from the results of usual AHP calculations, the proposed method is simple to apply. After using AHP to calculate the decision options' scores and the DMs' consistency indices, only simple calculations are required to determine the individual weight of each DM. The proposed method is effective in breaking possible ties among decision alternatives. It also provides an objective and quantitative procedure for differentiating between DMs, especially when the DMs are equal in all other aspects. The results obtained by the proposed method are logical, as they do not contradict with results obtained by other methods such as simple voting and total scores of alternatives. The method also allows for the objective assessment of the alternatives under different decisions. The method integrates the different decisions into a ranked order of final decision sets using the weighted scores of the decision option combinations.

There are several possibilities for extending this work. One way is to consider fuzzy AHP to see the impact on the ranked pairs of decision alternatives. Another possible extension is to consider using TOPSIS or other multi-criteria decision-making techniques instead of AHP to estimate the weighted scores of different decision alternatives. Other possibilities include developing alternative ways of developing consistency-based weights, other methods of aggregating individual DMs' inputs, and alternative methods of integrating multiple decisions into ranked decision combinations.

7. References

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