MULTI-ATTRIBUTE WAREHOUSE LOCATION SELECTION IN HUMANITARIAN LOGISTICS USING HESITANT FUZZY AHP

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ABSTRACT

Deploying warehouses at strategic locations becomes an important issue for humanitarian relief organizations in order to improve their relief aid capability and rescue plan. The delivery of sufficient technical equipment and provision of shelter and reinforcement to victims is a significant event during relief operations. Warehouse location selection in humanitarian logistics (HL) is a challenging process because choosing a non-optimal location may cause additional problems during rescue activities. The conventional decision making tools used for a warehouse location selection problem tend to be less effective in dealing with the imprecise or vague nature of the linguistic assessment. In many situations, the values of the qualitative attributes are often incompletely determined by the decision-makers. The fuzzy set theory can capture this type of uncertainty. In this paper, a recent extension of ordinary fuzzy sets, namely hesitant fuzzy sets, is used for considering the decision makers hesitancy in the evaluation. To solve the HL warehouse location selection problem, we propose a new hesitant fuzzy Analytic Hierarchy Process (AHP) method. We also present a HL warehouse location selection case study for a Turkish humanitarian relief organization by using hesitant fuzzy preference information.

Keywords: Warehouse location selection; Multi-attribute decision-making (MADM); fuzzy logic; humanitarian logistics; Hesitant Fuzzy Sets

1. Introduction

For the purpose of alleviating the suffering of vulnerable people, the activities of planning, implementing and controlling the efficient, cost-effective flow of and storage of goods and materials from production to consumption are called *humanitarian logistics* (Thomas & Kopczak, 2005). Another definition for humanitarian logistics is given in this way: the processes and systems involved in mobilizing people, resources, skills and knowledge to help vulnerable people affected by disaster (Van Wassenhove, 2006).

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Natural disasters, both rapid-onset events (such as earthquakes and floods) and slow-onset events (such as hunger, poverty and drought) or man-made crises (such as war and civil unrest), increase vulnerability of nations or regions and seriously affect local and national economies (Roh et al., 2015). In this paper, we focus on rapid-onset natural disasters which appear suddenly with no warning. Hence, disaster management, a vital issue to deal with natural and man-made disasters, needs a systematic approach (Ahmadi et al., 2015). Disaster management has four main phases which are mitigation, preparation, response and recovery (Ivgin, 2013). Long-term efforts should be made to keep the occurrence of disasters in the mitigation phase (Chou et al., 2015). The preparation phase is also another important part of disaster management. Government or social organizations should make a plan which includes the preparation phase before the occurrence of a disaster.

The warehouse location in humanitarian logistics has high importance since it determines the success of the disaster response after an event. There are few studies on the warehouse location problem regarding humanitarian relief logistics in the literature. Warehouse location selection in humanitarian logistics has also drawn a lot of attention from humanitarian relief organizations in recent years. The world's biggest humanitarian relief organizations, such as World Food Programme (WFP), International Federation of Red Cross and Red Crescent Societies (IFRC), and Action Against Hunger (AAH), have begun to deploy strategic pre-positioned warehouses around the world.

Different researchers have studied the importance of the preparedness phase and the need for pre-positioned warehouses in humanitarian relief operations, but only a small number of papers are related to the warehouse location selection problem in humanitarian logistics (Dekle et al., 2005; Balcik and Beamon, 2008; Huang et al., 2015; Rath & Gutjahr, 2014; Florez et al., 2015). The evaluation process for the warehouse location decision usually includes different and possibly conflicting tangible and intangible attributes, which requires an evaluation to be performed with vague and incomplete information (Onut & Soner, 2007; Demirel & Kahraman, 2010). This reality generally forces decision makers to model the problem by applying a fuzzy multi-attribute decision-making (MADM) approach.

The fuzzy set theory has a history starting with the introduction of ordinary fuzzy sets by L. A. Zadeh (1965) and continuing with the extensions of these sets as illustrated in Figure 1 (Kahraman et al., 2016).

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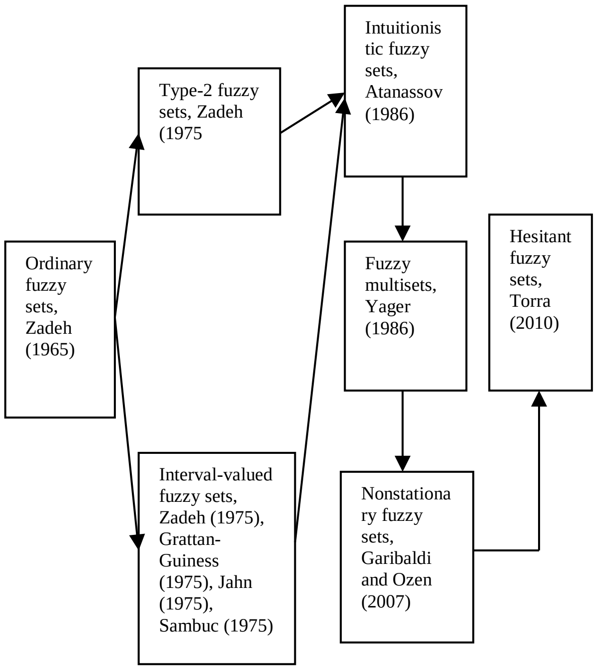

Figure 1. History of the fuzzy set theory

Ordinary fuzzy sets and their new extensions have been extensively used in the solution of industrial problems: outsourcing (Bottani & Rizzi, 2006; Kahraman et al., 2010), transportation (Chana & Kuchta, 1996; Kaya et al., 2012), energy (Heo et al., 2010; Cevik Onar et al., 2015), urban transformation (Olazabal & Pascual, 2016; Oztaysi et al., 2016), engineering economics (Shahriari, 2011; Kahraman et al., 2015).

In the literature, the most used MADM method is the Analytic Hierarchy Process (AHP) developed by Saaty (1980). It has been used in the solution of various MADM problems: outsourcing (Atkinson et al., 2015), capability development (Dangol et al, 2015) and personnel management (Kashi, 2016), etc.

In our proposed MADM method, we utilize hesitant fuzzy sets (HFSs), which are the latest extension of ordinary fuzzy sets. HFSs are a novel extension of fuzzy sets aiming at modeling the uncertainty caused by the hesitation arising in the assignment of membership degrees of the elements to a fuzzy set. A HFS is defined in terms of a function that returns a set of membership values for each element in the domain (Rodriguez et al., 2014). In this paper, we used hesitant fuzzy linguistic term sets (HFLTS) which was introduced by Rodríguez et al. (2012). Through the usage of HFLTS, different linguistic evaluations of different actors can be aggregated without loss of information. HFLTS enable expressing the hesitance existing in linguistic evaluation as clearly as possible. A multi-attribute warehouse location selection problem in humanitarian logistics employs linguistic evaluations which mostly include hesitance of multiple experts.

The proposed hesitant fuzzy MADM method evaluates warehouse location alternatives in humanitarian logistics using a number of tangible and intangible

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attributes. The proposed MADM method is based on a new hesitant fuzzy AHP method for the evaluation of alternative warehouse locations. The novelty of the developed fuzzy HFLTS based AHP method is its capability to overcome the hesitancy involved in multi criteria warehouse selection problem with linguistic assessments of multiple experts.

Our paper is structured as follows.: in Section 2, a literature review on Humanitarian Logistics (HL) and related definitions is presented. Warehouse location selection attributes in HL are given in Section 3. Section 4 focuses on the methodological background of the hesitant fuzzy sets and hesitant fuzzy AHP. A case study and a sensitivity analysis are given in Section 5. Finally, conclusions and future directions are presented in Section 6.

2. Humanitarian Logistics (HL)

The creation of an effective disaster supply chain to deliver necessary goods to disaster relief organizations is an essential function of disaster management. This function is also called humanitarian logistics. Humanitarian logistics is a broad term that covers the operations concerning supply chain strategies, processes, and technologies that will maintain the flow of goods and materials needed for the humanitarian effort. The management of the supply chain in disaster relief operations is considered an essential element in the resolution of a crisis since the tsunami in South East Asia (December, 26th 2004) and Hurricane Katrina (August, 2005). Security is a very important requirement in humanitarian logistics. In the aftermath of a disaster, many goods (e.g., medicine, foods), which are usually available in normal conditions, became extremely valuable and a potential target of thieves.

Supply chain management for business applications had a long evolution and many companies have well established supply chains around the world, but the strategic goal of commercial supply chains and disaster supply chains is different. Commercial supply chains are focused on quality and profitability whereas humanitarian supply chains must be focused on minimizing loss of life and suffering.

The works on HL can be classified into conceptual and strategic works and operation research (OR) based works. Some recent papers on conceptual and strategic HL are as follows. Vaillancourt (2016) developed a theoretical framework to better understand incentives and obstacles to consolidation of materials in humanitarian logistics. L'Hermitte et al. (2016) explored the underlying strategic mechanisms of agility in a humanitarian logistics context. Based on the research conducted in business disciplines, the paper empirically examines a set of four strategic dimensions (being purposeful, being action-focused, being collaborative, and being learning-oriented) and identifies an emergent relationship between these capabilities and agile humanitarian logistics operations. Vega and Roussat (2015) investigated the role of logistics service providers in humanitarian relief. Leiras et al. (2014) presented a literature review of HL that aims to identify trends and suggest some directions for future research.

Some recent papers on operation research (OR) based HL are as follows. Tofighi et al. (2016) addressed a two-echelon humanitarian logistics network design problem involving multiple central warehouses and local distribution centers and developed a novel two-stage scenario-based possibilistic-stochastic programming approach. Ransikarbum and Mason (2016) presented a multiple objective, integrated network optimization model for making strategic decisions in the supply distribution and

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network restoration phases of humanitarian logistics operations. Their model provides an equity-based solution for constrained capacity, budget and resource problems in post-disaster logistics management. Gralla et al. (2015) provided a basis for the design and improvement of simulated emergency training exercises, which are common in the humanitarian practice community. Özdamar and Ertem (2015) presented a survey that focused on the response and recovery planning phases of the disaster lifecycle. The related mathematical models developed in this research area were classified in terms of vehicle/network representation structures and their functionality. Díaz-Delgado and Gaytán Iniestra (2014) dealt with the relationship between a flood risk assessment and the humanitarian logistics process design related to emergency events caused by flooding. The magnitude and timing of the flooding is estimated using a forecasting model that requires a hydrologic component to convert rainfall into runoff as well as a hydraulic component to route the flow through the stream network predicting time and severity of the flood wave.

Figure 2 illustrates the frequencies of publications on HL with respect to publication years. This figure was obtained by entering “humanitarian logistics” as an “article title, abstract or keywords” to the Scopus database considering the publications up to August 2016. As seen in Figure 2, researchers have been focused on HL especially after the year 2005 since disasters such as the tsunami in South East Asia in 2004 and Hurricane Katrina in 2005 which caused the deaths of many people.

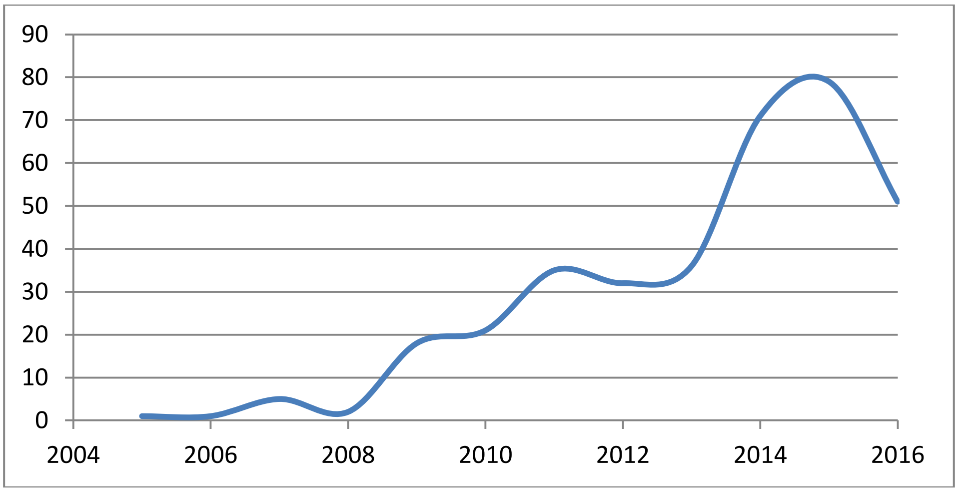

Figure 2. Frequencies of publications on HL with respect to publication years

Figure 3 presents the journals publishing HL papers. *The Journal of Humanitarian Logistics and Supply Chain Management* is the leading journal publishing HL papers. The journals that publish the second most HL papers are *Procedia Engineering* and *Socio Economic Planning Sciences*.

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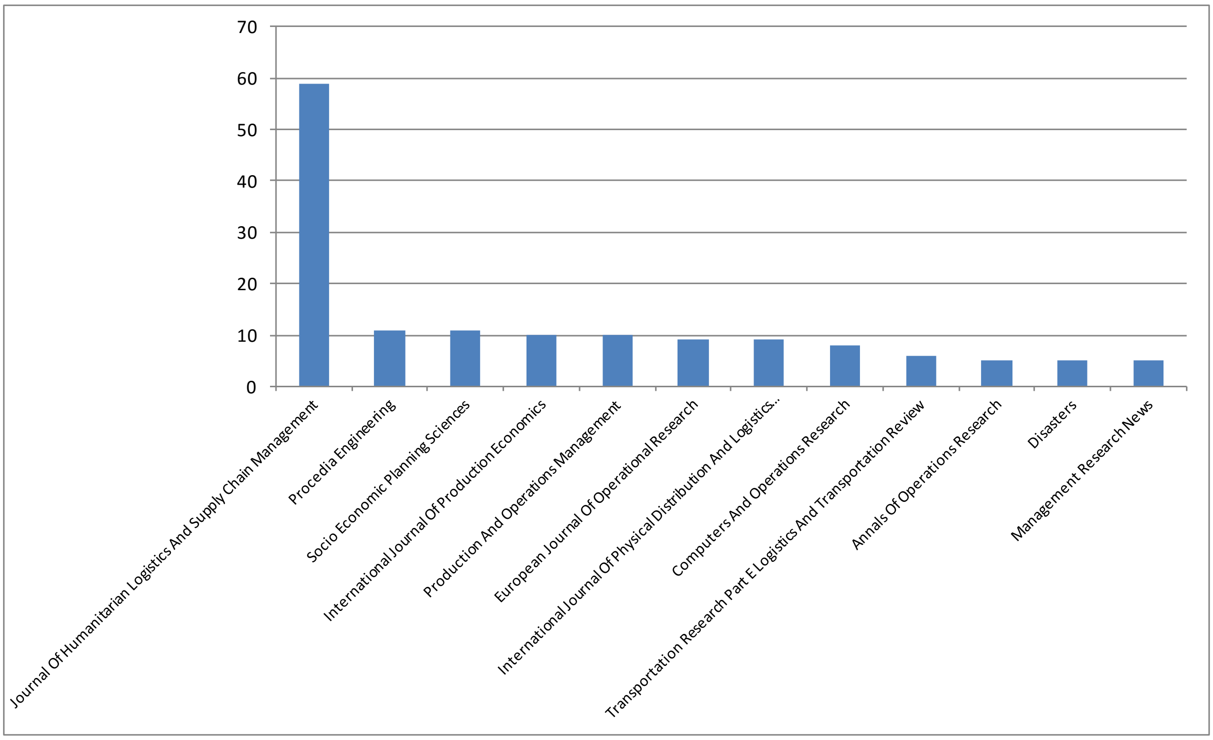

Figure 3. Journals publishing HL works

Figure 4 shows the document types of the publications on HL. Articles and conference papers are by far the first two most popular ways of publication media for HL works.

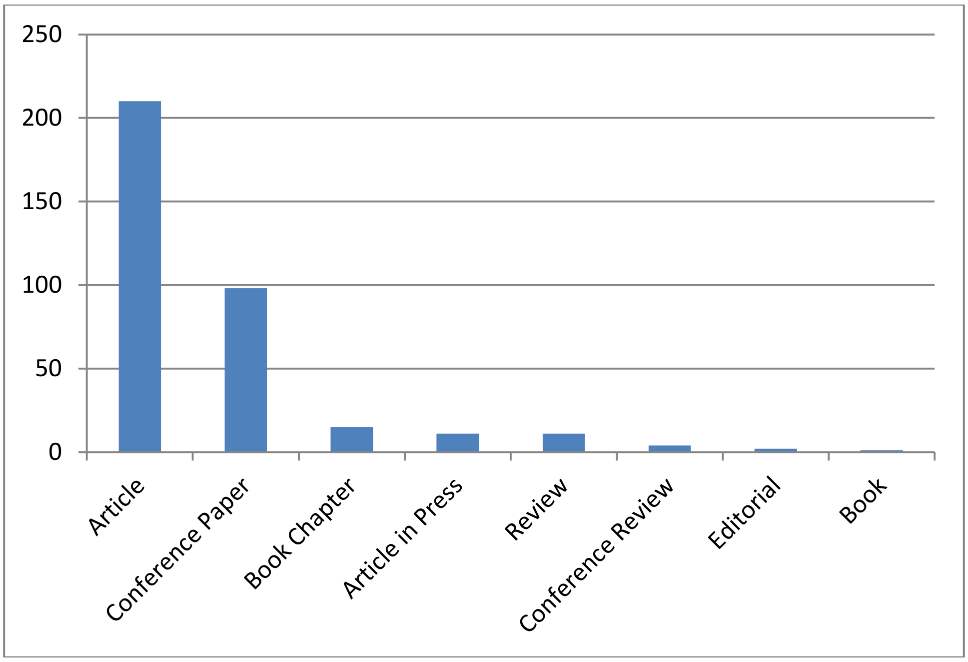

Figure 4. Document types of the publications on HL

Figure 5 illustrates the subject areas of the publications on HL. Business, management and accounting, decision sciences, engineering, computer science, and social sciences are the leading subject areas used in HL.

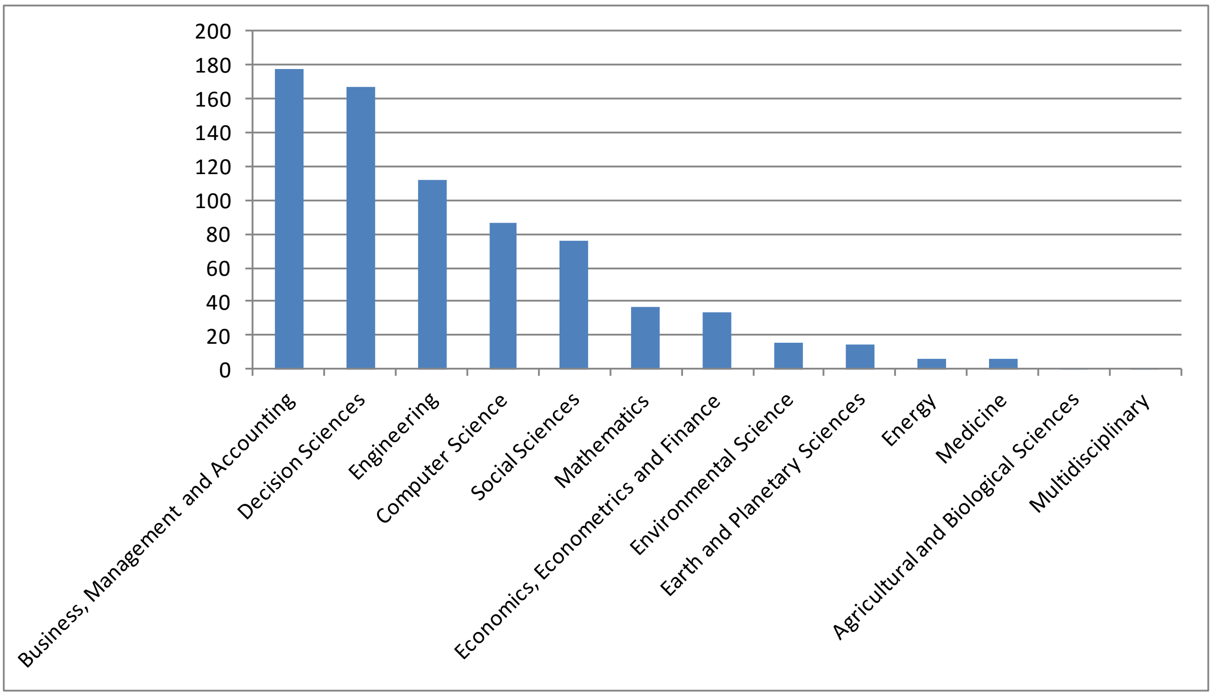

Figure 5. Subject areas of the publications on HL

3. Warehouse location selection in HL

Warehousing is essentially an act of storing goods between the time they are assembled and the time they are handed to the customer. Warehousing commonly depends on human resources and required facilities and equipment costs (Stock & Lambert, 2001). Besides, warehouse performance directly affects the whole supply chain performance of a firm or organization (Tuzkaya & Önüt, 2009). Ineffective warehouse location selection, design or management will threaten the achievement of a humanitarian relief organization and result in unnecessarily high costs (Pazour & Carlo, 2015). Logistic researchers commonly agree that warehouse location is a problem of strategic level network design (Powers, 1989; Özcan et al., 2011; Ashrafzadeh et al., 2012). This kind of decision is long-term and the influence of the warehouse location selection affects the profitability of the company. A warehouse system not only reduces cost and simplifies operations, but also allows companies to focus on their main targets (Choi et al., 2001). We know that items are transformed into final products by being processed sequentially at multiple locations in supply chain networks. Hence, a warehouse is a vital part of a typical supply chain management.

In recent years, the demand for strategic stock-holding for humanitarian purposes has become increasingly vital. Human relief organizations or governments notice that a large number of high-impact natural and man-made disasters influence the stability of states (Guha-Sapir et al., 2013**;** Roh et al., 2015). For instance, the 2004 earthquake and resulting tsunami in South Asia caused approximately 230,000 deaths and displaced 1.7 million people in many urban areas. More than 40 countries and 700 nongovernmental organizations (NGOs) provided humanitarian materials (Russell, 2005; Cozzolino, 2012).

Warehouse location selection is a multi-attribute decision making problem including both tangible and intangible attributes. Table 1 summarizes the attributes used in warehouse location selection problems in the literature.

Table l
Literature on warehouse location selection attributes

Researchers	**Research Areas**	**Main Evaluation attributes for Warehouse (or Logistics Center) Selection**
Korpela, J., Tuominen, M., (1996).	A decision aid in warehouse site selection.	Reliability Compliance; Flexibility Special, Strategic compatibility
Alberto, P., (2000).	The logistics of industrial location decisions.	Environmental aspects, Cost, Quality of living, Local incentives, Time reliability provided to customers, Response flexibility to customer's demand, Integration with customers
Sarkis, J., Sundarraj, R.P., (2002).	Hub location selection for Digital Equipment Corporation	Cost, Accessibility, Time, Regulatory, Risk, Labour, Strategy
Demirel, T., Demirel, N. Ç., & Kahraman, C. (2010).	Warehouse location selection using Choquet integral.	Costs, Labor characteristics, Infrastructure, Markets, Macro environment
Kayikci, Y., (2010)	Logistics center location using conceptual model.	Economical scale, National stability, Intermodal operation and management, International market location, and Environmental effect
Li, Y., Liu, X., Chen, Y. (2011).	Selection of logistics centre	Weather and landform condition, Water supply, Power supply, Solid cast-off disposal, Communication, Traffic, Candidate land area, Candidate land shape, Candidate land circumjacent main line, Candidate land land-value, Freight transport, and Fundamental construction investment.
Özcan, T., Çelebi, N., & Esnaf, Ş. (2011).	Warehouse location selection problem using multi-attributes decision making methodologies.	Unit price ($/m2), Stock holding capacity (unit), Average distance to shops (kilometer), Average distance to main suppliers (kilometer), Movement, Flexibility,
Roh, S. Y., Jang, H. M., & Han, C. H. (2013).	Warehouse location decision factors in humanitarian relief logistics.	Location, Logistics, National stability, Cost, Cooperation.
Roh, S., Pettit, S., Harris, I., & Beresford, A. (2015).	The pre-positioning of warehouses at regional and local levels.	Location, National Stability, Cost, Cooperation, Logistics

Based on the above literature review, warehouse location selection attributes have been determined as follows:

- Geographical location (Roh, 2015): Geographic location refers to a position on the Earth. Absolute geographic location of a point is defined by two coordinates, longitude and latitude. This attribute is crucial in order to provide a cost-effective flow and storage of goods. It has four sub-attributes determined as “proximity to disaster areas”, “logistics experts” availability”, “warehouse security”, “proximity to urban facilities”, and “closeness to other warehouses”.

- Transport connectivity (Vitoriano et al., 2011; Barbarosoglu and Arda, 2004): Transportation is a critical issue in humanitarian relief operations to deliver

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aid at the right time and to the right place. We know that the deliveries must be fast, fair and safe. Decision makers must consider the actual fuel availability, available vehicles, climate, road conditions and airports and port's capacity after the disaster during planning process of transportation operations (Wassenhove & Martinez, 2012). This attribute includes the sub-attributes "availability of seaport and airport", "near to (potential) beneficiaries", "adequate warehouse facilities", "adequate warehouse infrastructure", and "warehouse accessibility".

- Cost (Roh et al., 2013; Kahraman et al., 2007; Sari et al., 2013): Cost effective flow and storage of goods and materials is one of the main issues in humanitarian logistics together with the planning, implementing and controlling processes (Tomasini &Wassenhove, 2009). When developing a warehouse location selection plan for a new organization, decision makers must assign cost estimates in order to assess whether an organization's budget will cover costs. Costs are usually underestimated; it should be analyzed during the execution of humanitarian relief operations. Although there are different types of cost in management (Blocher et al., 2008), we have classified the sub-attributes as "storage cost", "cost relate to logistics", "land cost", "labor price", and "replenishment cost".

- Stable government (Roh et al., 2015; Seaman, 1999): A stable political situation is important for the operation of the pre-positioned warehouse. If the political, economic, and social state of a country is very fragile and unstable, it will be difficult for a humanitarian organization to operate their supply chain in a risky and dangerous environment. The stable government attribute has four sub-attributes "cooperation with logistics agents", "political and economic stability", "existence of other agents (NGOs)", and "IT/Communication".

- Labor availability (Roh et al., 2013; Demirel et al., 2010): Today's warehouses include large amounts of materials, machines, and people and have complex infrastructures. Thus, the availability of qualified labor is another issue for our proposed model. This is one of the main requirements of warehouse management in order to perform a better humanitarian relief operation. We assume that the qualified labor does not have the same standards at each location. The sub-attributes of availability of labor are "trained and qualified personnel", "flexible customs regulations", "population density", and "climate".

Based on the determined main-attributes and sub-attributes, the hierarchy of the proposed model is given in Figure 6. There are 5 main attributes and 4 sub-attributes under each main attribute, and 5 HL warehouse location alternatives (HLW).

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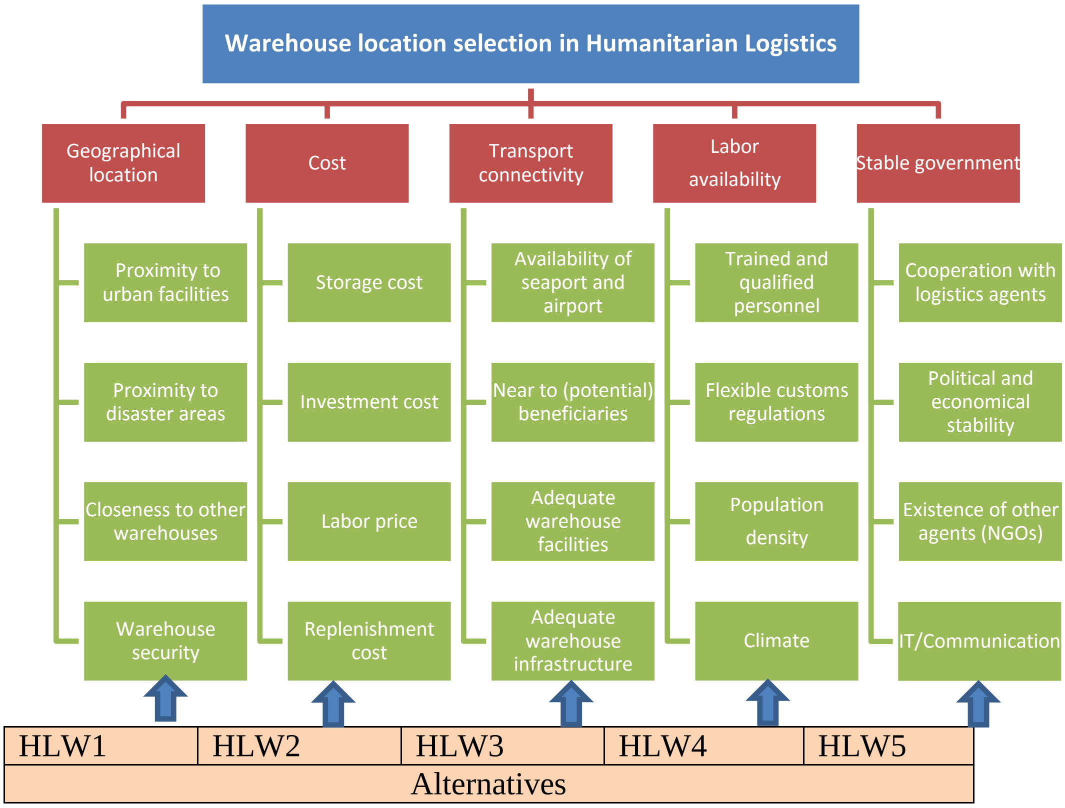

Figure 6. Hierarchy of the problem

4. Preliminaries: Hesitant Fuzzy Sets

Torra (2010) introduced Hesitant Fuzzy Sets (HFSs) since determining the membership degree of an element to a fuzzy set is not an easy work. The difficulty comes from possible values that cause hesitation about which one would be the right one.

Definition 1: Let X be a fixed set, a hesitant fuzzy set (HFS) on X is in terms of a function that when applied to X returns a subset of [0, 1] (Torra, 2010). Mathematical expression for HFS is as follows:

$$E = \{< x, h_E(x) > | \, x \epsilon \, X \}, \quad (1)$$

where $h_E(x)$ is a set of some values in [0, 1], denoting the possible membership degrees of the element $x \epsilon \, X$ to the set E. Xia and Xu (2011) give some basic definition about *h* as follows.

Definition 2: The upper and lower bound is defined as in Eq. 2 and Eq. 3.

$$h^-(x) = \min h(x)\,; \quad (2)$$
$$h^+(x) = \max h(x)\,; \quad (3)$$

Definition 3: The compliment of h is given in Eq. 4.

$$h^c = \cup_{\gamma \in h} \{1 - \gamma\}; \quad (4)$$

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Definition 4: The envelope of h, $A_{env(h)}$, is an intuitionistic fuzzy set which is defined as

$$A_{env(h)} = \{x, \mu(x), v(x)\} \quad (5)$$

where

$$\mu(x) = h^{-}(x) \quad (6)$$

$$v(x) = 1 - h^{+}(x) \quad (7)$$

The basic operations on HFSs can be found in Zhang and Wei (2013).

Rodríguez et al. (2012) have introduced hesitant fuzzy linguistic term sets (HFLTS) to improve the elicitation of linguistic information in decision making when experts hesitate among several linguistic terms to express their assessments. These sets provide greater flexibility to elicit comparative linguistic expressions by using context-free grammar that formalizes the generation of flexible linguistic expressions. Hence, we prefer the use HFLTS in this paper.

Definition 5. The envelope of an hesitant fuzzy linguistic term sets (HFLTS), env(HS), is a linguistic interval whose limits are obtained by means of its upper bound and lower bound:

$$env(H_S) = [H_{S^-}, H_{S^+}],\ H_{S^-} \leq H_{S^+}, \quad (8)$$

where the upper bound and lower bound are defined as

$$H_{S^+} = max\{S_i\} = S_j, S_i \leq S_j \text{ and } S_i \in H_S, \forall i, \quad (9)$$

$$H_{S^-} = min\{S_i\} = S_j, S_i \geq S_j \text{ and } S_i \in H_S, \forall i, \quad (10)$$

Definition 6. An OWA operator of dimension n is a mapping OWA: $R^n \to R$, so that

$$OWA(a_1, a_2, \dots, a_n) = \sum_{j=1}^{n} w_j b_j \quad (11)$$

where b_j is the jth largest of the aggregated arguments $a_1, a_2, \dots, a_n$, and $W = (w_1, w_2, \dots, w_n)^T$ is the associated weighting vector satisfying $\mathrm{w_i} \in [0,1], \mathrm{i} = 1,2, \dots, \mathrm{n}$ and $\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{w_i} = 1$.

Definition 7. A triangular fuzzy membership function $\tilde{A}$=(a, b, c) is used as the representation of the comparative linguistic expressions based on HFLTS, the definition domain of $\tilde{A}$ should be the same as the linguistic terms $\{\mathrm{s_i}, \dots, \mathrm{s_j}\} \in \mathrm{H_S}$. The min and the max operators are used to compute a and c.

$$a = min\{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\} = a_L^i \quad (12)$$

$$c = max\{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\} = a_R^i \quad (13)$$

The remaining elements $a_M^i, a_M^{i+1}, \dots, a_M^j \in T$ should contribute to the computation of the parameter b. The aggregation operator OWA will be used to aggregate them:

$$b = OWA_{W^S}(a_M^i, a_M^{i+1}, \dots, a_M^j) \quad (14)$$

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5. Hesitant Fuzzy AHP model

In the proposed hesitant fuzzy AHP method, we first determine the main and sub-attributes and the hierarchy for the warehouse location selection problem, then make a multi-attributes evaluation of the warehouse location alternatives to illustrate how the proposed model is used to solve it.

The steps of the Hesitant Fuzzy AHP extended based on Buckley (1985)'s AHP method are given:

Step 1. Pairwise comparison matrices for attributes, sub-attributes and alternatives are constructed and expert's evaluations using linguistic terms are collected.

Step 2. Using the scale given in Table 1, the linguistic terms are transformed into triangular fuzzy numbers (Tan et al., 2014) and trapezoidal fuzzy numbers.

Table 2
Linguistic scale for Hesitant Fuzzy AHP

Linguistic Term	**Abb.**	**Triangular Fuzzy Number**	**Trapezoidal Fuzzy Number**
Absolutely High Importance	(AHI)	(7,9,9)	(7,9,9,9)
Very High Importance	(VHI)	(5,7,9)	(5,7,7,9)
Essentially High Importance	(ESHI)	(3,5,7)	(3,5,5,7)
Weakly High Importance	(WHI)	(1,3,5)	(1,3,3,5)
Equally High Importance	(EHI)	(1,1,3)	(1,1,1,3)
Exactly Equal	(EE)	(1,1,1)	(1,1,1,1)
Equally Low Importance	(ELI)	(0.33,1,1)	(0.33,1,1,1)
Weakly Low Importance	(WLI)	(0.2,0.33,1)	(0.2,0.33,0.33,1)
Essentially Low Importance	(ESLI)	(0.14,0.2,0.33)	(0.14,0.2,0.2, 0.33)
Very Low Importance	(VLI)	(0.11,0.14,0.2)	(0.11,0.14,0.14,0.2)
Absolutely Low Importance	(ALI)	(0.11,0.11,0.14)	(0.11,0.11,0.11,0.14)

Each element ($\tilde{a}_{ij}^k$) of the pairwise comparison matrix $\tilde{A}^k$ is a fuzzy number corresponding to its linguistic term. The pairwise comparison matrix is given by;

$$\tilde{A}^k = \begin{vmatrix} 1 & \tilde{a}_{12}^k & \cdots & \tilde{a}_{1n}^k \\ \tilde{a}_{21}^k & 1 & \cdots & \tilde{a}_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1}^k & \tilde{a}_{n2}^k & \cdots & 1 \end{vmatrix} \tag{15}$$

where ($\tilde{a}_{ij}^k$) represents the kth expert's evaluation on comparison of ith element to jth element.

Step 3. The consistency of each fuzzy pairwise comparison matrix is examined. In order to check the consistency of the fuzzy pairwise comparison matrices, pairwise comparison values are defuzzified by the graded mean integration approach (Hsieh & Chen, 1999). Assume $\tilde{A} = [\tilde{a}_{ij}]$ is a fuzzy positive reciprocal matrix and $A = [a_{ij}]$ is its defuzzified positive reciprocal matrix. If the result of the comparisons of $A = [a_{ij}]$ is consistent, then it can imply that the result of the comparisons of $\tilde{A} = [\tilde{a}_{ij}]$ is also consistent (Buckley, 1985). According to the graded mean integration approach, a triangular fuzzy number $\tilde{A} = (l, m, u)$ can be transformed into a crisp number by employing the below equation:

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$$A = \frac{l+4m+u}{6} \tag{16}$$

If the pairwise comparisons are not consistent, experts must reevaluate the pairwise comparisons.

Step 4: Identification of conflicts and renewing the evaluations. The evaluations of the experts are checked for their closeness to each other. If the evaluations are not close then experts are informed of the need to discuss the situation and renew their evaluations.

Step 5: Fuzzy envelope approach, proposed by Liu and Rodriguez (2014), is used to combine expert evaluations.

The scale given in Table 1 is sorted from the lowest (s_0) to the highest (s_g). Assume the expert evaluations vary between two terms i.e. s_i and s_j. Then $s_0 \leq s_i < s_j \leq s_0$.

The parameters a and d of the trapezoidal fuzzy membership function $\tilde{A}$ = (a, b, c, d) are computed as

$$a = \min\{a_L^i, a_M^i, a_M^{i+1}, \dots\dots a_M^j, a_R^j\} = a_L^i \tag{17}$$

$$d = \min\{a_L^i, a_M^i, a_M^{i+1}, \dots\dots a_M^j, a_R^j\} = a_R^j \tag{18}$$

$$b = \begin{cases} a_m^i \ , \ if\ i+1=j \\ OWA_{w^2}\left(a_m^i, \dots\dots a_m^{\frac{i+j}{2}}\right), \ \ if\ i+j\ is\ even \\ OWA_{w^2}\left(a_m^i, \dots\dots a_m^{\frac{i+j-1}{2}}\right), \ \ if\ i+j\ is\ odd \end{cases} \tag{19}$$

$$c = \begin{cases} a_m^{i+1} \ , \ if\ i+1=j \\ OWA_{w^1}\left(a_m^j, a_m^{j-1} \dots\dots a_m^{\frac{i+j}{2}}\right), \ \ if\ i+j\ is\ even \\ c = OWA_{w^1}\left(a_m^j, a_m^{j-1}, \dots\dots a_m^{\frac{i+j+1}{2}}\right), \ \ if\ i+j\ is\ odd \end{cases} \tag{20}$$

OWA operation given in Definition 6 requires a weight vector. Filev and Yager (1998) define the first and second type of weights using α parameter which belong to the unit interval [0,1]. The first kind of weights $W^1 = (w_1^1, w_2^1 \dots w_n^1)$ is defined as:

$$w_1^1 = \alpha_2, w_2^1 = \alpha_2(1-\alpha_2), \dots\dots. w_n^1 = \alpha_2(1-\alpha_2)^{n-2}$$

The second kind of weights $W^2 = (w_1^2, w_2^2 \dots w_n^2)$ is defined as:

$$w_1^2 = {\alpha_1}^{n-1}, w_2^2 = (1-\alpha_1){\alpha_1}^{n-2}, \dots\dots. w_n^2 = 1-\alpha_1,$$

where $\alpha_1 = \frac{g-(j-i)}{g-1}$ and $\alpha_2 = \frac{(j-i)-1}{g-1}$

where g is the number of terms in the evaluation scale, j is the rank of highest evaluation and i is the rank of lowest evaluation value of the given interval.

Step 6: Collaborative pairwise comparison matrix ($\tilde{C}$) is formed.

ISSN 1936-6744
http://dx.doi.org/10.13033/ijahp.v8i2.387

$$\tilde{C} = \begin{vmatrix} 1 & \tilde{c}_{12} \cdots \tilde{c}_{1n} \\ \tilde{c}_{21} & 1 \ \cdots \tilde{c}_{2n} \\ \vdots & \vdots \ \vdots \ \vdots \\ \tilde{c}_{n1} & \tilde{c}_{n2} \cdots \ 1 \end{vmatrix} \quad (21)$$

where $\tilde{c}_{ij} = (c_{ij_l}, c_{ij_{m1}}, c_{ij_{m2}}, c_{ij_u})$

Since the fuzzy envelopes, obtained in the previous step are trapezoidal fuzzy numbers, reciprocal values are calculated as follows:

$$\tilde{c}_{ji} = (\frac{1}{c_{ij_u}}, \frac{1}{c_{ij_{m2}}}, \frac{1}{c_{ij_{m1}}}, \frac{1}{c_{ij_l}}) \quad (22)$$

Step 7: Fuzzy geometric mean for each row ($\tilde{r}_i$) of the collaborative pairwise matrix is computed using Eq. 23.

$$\tilde{r}_i = (\tilde{c}_{i1} \otimes \tilde{c}_{i2} \dots \otimes \tilde{c}_{in})^{1/n} \quad (23)$$

Step 8: The fuzzy weight ($\widetilde{w}_i$) of each attribute (or alternative) is calculated using ($\tilde{r}_i$) values as follows:

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \dots \oplus \tilde{r}_n)^{-1} \quad (24)$$

In this study, $\tilde{r}_1 \oplus \tilde{r}_2 \dots \oplus \tilde{r}_n$ value is accepted as the maximum parameter of the Absolutely High Importance in Table 1 in order to decrease the deviation in the weights.

Step 9: The next step is to calculate the fuzzy performance scores of each alternative. To this end, steps 1 – 7 are repeated for each pairwise comparison matrix formed according to the predetermined decision model. The final fuzzy score of each alternative is calculated by Eq 25.

$$\tilde{S}_i = \sum_{j=1}^{n} \widetilde{w}_j \tilde{s}_j, \forall i. \quad (25)$$

where $\tilde{S}_i$ is the fuzzy performance score of alternative i; $\widetilde{w}_j$ is the weight of the attribute j, and $\tilde{s}_j$ is the performance score of alternative i with respect to attribute j.

Step 10: Trapezoidal fuzzy numbers are defuzzified in order to determine the importance ranking of the alternatives. Defuzzification of the trapezoidal fuzzy numbers is made using Eq. 26 (Sahoo et al., 2016).

$$D = \frac{c_l + 2c_{m1} + 2c_{m2} + c_u}{6} \quad (26)$$

Step 11: The alternatives are ranked according to the defuzzified values and the alternative with the best score is selected.

6. A case study

The presented multi-attribute HL warehouse location selection model was applied for an earthquake prone area in the northwest of Turkey. This area contains eight districts and has 23 million inhabitants. Approximately 67,000 km² and 8.5% of Turkey's revenue comes from this region. It is Turkey's main industrial region and includes the city İstanbul, the center of Turkish economy. However, in this region there is a giant earthquake risk, and the expected damage of an earthquake here is very large anticipating a high number of deaths and physical destruction. The level of damage occurred by the Izmit earthquake in 1999 was so high that it killed around 17,000 people and left almost half a million people homeless.

The prioritization of five feasible HL warehouse location alternatives is required in Marmara region. The possible alternatives are Lüleburgaz, Çorlu, Kocaeli, Bursa, and Gönen. The main and sub-attributes given in Fig. 6 are used in the multi-attribute evaluation. The five alternative locations for a warehouse are shown in Fig. 7.

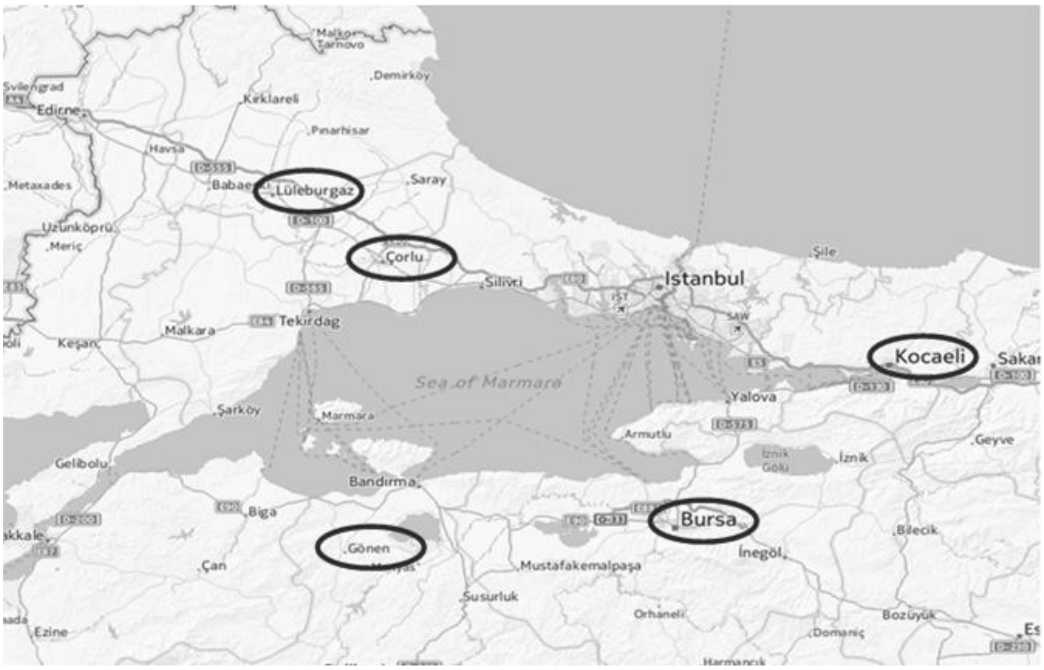

Figure 7. Alternative locations for warehouse selection

A team of three experts discussed the importance of the main attributes and came to a compromise. Table 3 presents the compromised pairwise comparisons of main attributes using HFLTS.

Table 3
Pairwise comparison of main attributes using HFLTS

Comparison of Main Attributes w.r.t. Goal	Geographical location	Cost	Transport connectivity	Labor availability	Stable government
Geographical location	EE	Between WLI and EE	Between ELI and EHI	Between EHI and ESHI	Between WLI and ELI
Cost		EE	Between EHI and ESHI	Between EHI and ESHI	Between ELI and EHI
Transport connectivity			EE	Between EHI and WHI	Between ESLI and ELI
Labor availability				EE	Between EHI and WHI
Stable government					EE

Using the OWA operations defined in Eqs. 17-20, HFLTSs are aggregated into trapezoidal fuzzy sets as in Table 4.

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Table 4
Aggregated HFLTS scores

Comparison of Main Attributes w.r.t. Goal	**Geographical location**	**Cost**	**Transport connectivity**	**Labor availability**	**Stable government**
Geographical location	(1,1,1,1)	(0.2,0.926,1,1)	(0.333,1,1,3)	(1,2.778,3.222,7)	(0.2,0.333,1,1)
Cost	(1,0.931,1.08,5)	(1,1,1,1)	(1,2.778,3.222,7)	(1,2.778,3.222,7)	(0.333,1,1,3)
Transport connectivity	(0.333,1,1,3)	(0.143,0.31,0.36,1)	(1,1,1,1)	(1,1,3,5)	(0.143,0.319,0.348,1)
Labor availability	(0.143,0.31,0.36,1)	(0.143,0.31,0.36,1)	(0.2,0.333,1,1)	(1,1,1,1)	(1,1,3,5)
Stable government	(1,1,3,5)	(0.333,1,1,3)	(1,2.872,3.14,7)	(0.2,0.333,1,1)	(1,1,1,1)

Table 5 presents the defuzzified weights of the main attributes. Geometric means are calculated by using Eq. 23. Normalized weights are obtained based on Eq. 24. Defuzzified weights are calculated by using Eq. 26.

Table 5
Calculation of defuzzified weights of the main attributes

	Geometric Means	**Normalized Weights**	**Defuzzified Weights**
Geographical location	(0.508,1.266,1.364,2.141)	(0.041,0.193,0.263,0.782)	0.213
Cost	(1,1.637,1.83,3.956)	(0.082,0.249,0.361,1)	0.280
Transport connectivity	(0.467,0.746,1.019,1.968)	(0.038,0.114,0.201,0.719)	0.169
Labor availability	(0.253,0.423,0.6,1)	(0.021,0.064,0.119,0.365)	0.091
Stable government	(0.508,0.989,1.752,3.201)	(0.041,0.151,0.346,1)	0.247

Tables 6-10 present the pairwise comparison matrices of the sub-attributes with respect to the main attributes *geographical location*, *cost*, *transport connectivity*, *labor availability*, and *stable government* respectively.

Table 6
Pairwise comparison of sub-attributes using HFLTS w.r.t. geographical location

w.r.t. Geographical Location	Proximity to urban facilities	Proximity to disaster areas	Closeness to other warehouses	Warehouse security
Proximity to urban facilities	EE	Betweeen ALI and VLI	Betweeen EE and EHI	Betweeen ESLI and WLI
Proximity to disaster areas		EE	Betweeen VSHI and AHI	Betweeen WHI and ESHI
Closeness to other warehouses			EE	Betweeen ESLI and ELI
Warehouse security				EE

From Table 6, the trapezoidal fuzzy weights of the sub attributes with respect to *Geographical Location*, are obtained as (0.039,0.056,0.086,0.253), (0.246,0.502,0.823,1), (0.03,0.063,0.087,0.192), and (0.068,0.165,0.278,0.761), respectively.

Table 7
Pairwise comparison of sub-attributes using HFLTS w.r.t. cost

w.r.t. Cost	Storage cost	Investment cost	Labor price	Replenishment cost
Storage cost	EE	Betweeen WLI and ELI	Betweeen EHI and ESHI	WHI
Investment cost		EE	Betweeen ESHI and VSHI	Betweeen WHI and ESHI
Labor price			EE	Betweeen WLI and ELI
Replenishment cost				EE

From Table 7, the trapezoidal fuzzy weights of the sub attributes with respect to *Cost*, are obtained as (0.075,0.207,0.428,0.924), (0.148,0.315,0.778,1), (0.027,0.056,0.126,0.289), and (0.046,0.081,0.185,0.568), respectively**.**

Table 8
Pairwise comparison of sub-attributes using HFLTS w.r.t. transport connectivity

w.r.t. Transport Connectivity	Availability of seaport and airport	Near to (potential) beneficiaries	Adequate warehouse facilities	Adequate warehouse infrastructure
Availability of seaport and airport	EE	EHI	Betweeen EHI and WHI	Betweeen EHI and ESHI
Near to (potential) beneficiaries		EE	Betweeen EE and EHI	Betweeen EHI and WHI
Adequate warehouse facilities			EE	Betweeen EE and WHI
Adequate warehouse infrastructure				EE

From Table 8, the trapezoidal fuzzy weights of the sub attributes with respect to *Transport Connectivity*, are obtained as (0.13,0.266,0.487,1),(0.099,0.206,0.364,0.774), (0.066,0.157,0.276,0.588), and (0.036,0.117,0.214,0.393), respectively.

Table 9
Pairwise comparison of sub-attributes using HFLTS w.r.t. labor availability

w.r.t. Labor Availability	Trained and qualified personnel	Flexible customs regulations	Population density	Climate
Trained and qualified personnel	EE	Betweeen WHI and VSHI	Betweeen EE and EHI	Betweeen ESHI and VSHI
Flexible customs regulations		EE	Betweeen ELI and EE	Betweeen EHI and WHI
Population density			EE	Betweeen WHI and ESHI
Climate				EE

From Table 9, the trapezoidal fuzzy weights of the sub attributes with respect to *Labor Availability*, are obtained as (0.158,0.413,0.546,1), (0.053,0.124,0.198,0.543), (0.091,0.246,0.332,0.778), and (0.028,0.058,0.113,0.276), respectively.

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Table 10
Pairwise comparison of sub-attributes using HFLTS w.r.t. stable government

w.r.t. Stable Government	Cooperation with logistics agents	Political and economical stability	Existence of other agents (NGOs)	IT/ Communication
Cooperation with logistics agents	EE	Betweeen WLI and ELI	Betweeen ELI and EHI	ESHI
Political and economical stability		EE	Betweeen WHI and ESHI	ESHI
Existence of other agents (NGOs)			EE	Betweeen EHI and WHI
IT/Communication				EE

From Table 10, the trapezoidal fuzzy weights of the sub attributes with respect to *Stable Government*, are obtained as (0.077,0.193,0.364,0.791), (0.152,0.334,0.716,1), (0.054,0.114,0.243,0.728), and (0.029,0.058,0.109,0.213), respectively.

The next step is to obtain the pairwise comparison matrices of alternatives with respect to each sub-attribute. In our case, there are 20 matrices of such comparisons. Due to the space constraints we only present one of them. Table 11 gives the pairwise comparison of alternatives using HFLTS with respect to *proximity to urban facilities.*

Table 11
Pairwise comparison of alternatives using HFLTS w.r.t. proximity to urban facilities

w.r.t. proximity to urban facilities	HLW1	HLW2	HLW3	HLW4	HLW5
HLW1	EE	Betweeen VLI and WLI	Betweeen WHI and ESHI	Betweeen ESLI and WLI	Betweeen WHI and VSHI
HLW2		EE	Betweeen ESHI and VSHI	Betweeen WLI and ELI	Betweeen WHI and ESHI
HLW3			EE	Betweeen VLI and ESLI	Betweeen ESLI and WLI
HLW4				EE	ESHI
HLW5					EE

Table 12 shows the trapezoidal fuzzy weights of the main and sub-attributes all together.

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Table 12
Trapezoidal fuzzy weights of main and sub-attributes

Main Attribute	**Weight**	**Sub-attribute**	**Weight**
Geographical location	(0.041,0.193,0.269,0.782)	Proximity to urban facilities	(0.002,0.011,0.023,0.198)
		Proximity to disaster areas	(0.02,0.097,0.221,0.782)
		Closeness to other warehouses	(0.001,0.012,0.023,0.15)
		Warehouse security	(0.001,0.032,0.075,0.595)
Cost	(0.082,0.249,0.361,1)	Storage cost	(0.006,0.052,0.155,0.924)
		Investment cost	(0.012,0.078,0.281,1)
		Labor price	(0.002,0.014,0.045,0.289)
		Replenishment cost	(0.004,0.02,0.067,0.568)
Transport connectivity	(0.038,0.114,0.201,0.719)	Availability of seaport and airport	(0.005,0.03,0.098,0.719)
		Near to (potential) beneficiaries	(0.004,0.023,0.073,0.557)
		Adequate warehouse facilities	(0.003,0.018,0.055,0.423)
		Adequate warehouse infrastructure	(0.001,0.013,0.043,0.283)
Labor availability	(0.021,0.064,0.119,0.365)	Trained and qualified personnel	(0.003,0.026,0.065,0.365)
		Flexible customs regulations	(0.001,0.008,0.024,0.198)
		Population density	(0.002,0.016,0.04,0.284)
		Climate	(0.001,0.004,0.013,0.101)
Stable government	(0.041,0.151,0.346,1)	Cooperation with logistics agents	(0.003,0.029,0.126,0.791)
		Political and economical stability	(0.006,0.05,0.248,1)
		Existence of other agents (NGOs)	(0.002,0.017,0.084,0.728)
		IT/Communication	(0.001,0.009,0.038,0.213)

Table 13 shows the final defuzzified weights of the alternatives with respect to subattributes. According to these results, the prioritization of the alternatives is Bursa (0.261) > Kocaeli (0.232) > Corlu (0.191) > Luleburgaz (0.171) > Gonen (0.146). Turkish humanitarian relief organization should establish the first two warehouses in Bursa and then Kocaeli.

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Table 13
Weights of the alternatives

	Alternative Scores				
Sub-attribute	**Bursa**	**Corlu**	**Gonen**	**Kocaeli**	**Luleburgaz**
Proximity to urban facilities	0.02	0.038	0.007	0.039	0.015
Proximity to disaster areas	0.085	0.093	0.131	0.177	0.037
Closeness to other warehouses	0.027	0.016	0.008	0.031	0.005
Warehouse security	0.116	0.035	0.016	0.081	0.045
Storage cost	0.055	0.068	0.094	0.025	0.189
Investment cost	0.134	0.22	0.093	0.07	0.225
Labor price	0.028	0.036	0.026	0.022	0.06
Replenishment cost	0.108	0.043	0.062	0.092	0.032
Availability of seaport and airport	0.13	0.05	0.089	0.144	0.06
Near to (potential) beneficiaries	0.102	0.063	0.041	0.106	0.02
Adequate warehouse facilities	0.073	0.05	0.034	0.082	0.014
Adequate warehouse infrastructure	0.059	0.015	0.025	0.036	0.011
Trained and qualified personnel	0.08	0.043	0.028	0.061	0.014
Flexible customs regulations	0.013	0.021	0.033	0.006	0.04
Population density	0.049	0.032	0.015	0.059	0.008
Climate	0.004	0.011	0.019	0.007	0.018
Cooperation with logistics agents	0.158	0.093	0.06	0.136	0.034
Political and economical stability	0.226	0.171	0.076	0.118	0.174
Existence of other agents (NGOs)	0.136	0.091	0.052	0.136	0.052
IT/Communication	0.045	0.021	0.011	0.037	0.023
Normalized Total Score	**0.261**	**0.191**	**0.146**	**0.232**	**0.171**

7. Conclusion

A large number of high-impact natural and man-made disasters, such as floods, earthquakes, storms, and civil disturbance or war have occurred in dissimilar parts of the world in recent years. This condition triggered the need for well-organized stock-holding for humanitarian purposes. Recent studies in MCDM show that Hesitant Fuzzy Set (HFS) exposes a new viewpoint on fuzzy decision making. Contrary to ordinary fuzzy sets, HFSs characterize fuzziness by setting out all the possible values while assigning the membership degree of the elements of a set. Based on these new arguments, we proposed a hesitant fuzzy multi-attribute method to solve HL warehouse location selection problems.

Our model based on hesitant fuzzy AHP successfully evaluated alternative HL warehouse location alternatives. We extended Buckley's ordinary fuzzy AHP method to its hesitant fuzzy version since the other fuzzy AHP have been seriously criticized in the literature methods (Chang, 1996; van Laarhoven and Pedrycz 1983; etc.). Hesitant linguistic term sets provided the flexibility to elicit comparative linguistic expressions by using context-free grammar. The fuzzy linguistic scale is based on the AHP's classical 1-9 scale. Our hierarchy included 5 main attributes, 16

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sub-attributes and 5 HL warehouse location alternatives. This research yielded several useful managerial insights. First, the proposed method allows one to deal with incomplete information due to the vagueness of the criteria such as "cooperation with logistics agents" and "political and economic stability". Second, it provides a systematic approach for solving complex problems that involve many stakeholders. This systematic approach can be used to solve other decision making problems with the same characteristics. A limitation of the proposed method is the cumbersome calculations that are involved. However, this difficulty can be overcome by developing software for this purpose. For further research, other extensions of fuzzy sets such as intuitionistic fuzzy sets, type-2 fuzzy sets, multi fuzzy sets, etc. can be used in the proposed model above. The obtained results can be compared with our results.

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