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Evaluating Vaccine Temperature Monitoring Systems via Fuzzy Analytic Hierarchy Process

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ABSTRACT

Cold chain management is a specific part of supply chain management. Cold chain management deal with products that should be transported and stored in certain conditions. Monitoring the temperature in cold chain is one of the most critical and important factors. Effective temperature monitoring systems are a must have for a successful cold chain management in companies, so deciding on the best temperature monitoring system is a strategic decision. The aim of this study is to determine the best temperature monitoring system for vaccine storage in a warehouse. While there are many different criteria for selecting among different temperature monitoring systems, a multi criteria decision making methodology is used and we evaluated four different temperature monitoring systems by using fuzzy analytic hierarchy process (FAHP). Fuzzy numbers are used for the application of analytic hierarchy process (AHP), because fuzzy numbers enable the decision makers to deal better with the uncertain and vogue circumstances while selecting the best temperature monitoring systems. Electronic thermometer data logger system, wired data logger temperature monitoring system, wireless data logger temperature monitoring system and cloud-based data logger temperature monitoring system are chosen as alternatives. First, we determined 4 main and 14 sub-criteria that affect the selection process and then we applied fuzzy analytic hierarchy process for selecting the best temperature monitoring system. Cloud-based data logger temperature monitoring system is determined as the best alternative.

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1. Introduction

A vaccine is a biological preparation that improves immunity to a particular disease (http://www.who.int/topics/vaccines/en/). Vaccines are the best defense we have against serious, preventable, and sometimes deadly contagious diseases (http://www.vaccines.gov/basics/safety/index.html).

Vaccines lose their potency if exposed to excessive heat or freezing (www.unicef.org.). The World Health Organization (WHO) recommends that all vaccines except oral polio vaccine should be stored at between +2◦C and +8◦C at all immunization points (Kartoğlu et al., 2010; Matthias et al., 2007). Vaccines that are exposing to both high and sub-zero temperatures are widespread in both developed and developing countries at all levels of health systems (Kartoğlu et al., 2010). Because of their heat sensitive nature, vaccines' temperature should be monitored very carefully at every step during transportation and storage of the cold chain.

A cold chain is a temperature controlled supply chain, it is a concept resulting from specific needs related to the transformation and distribution of temperature-sensitive products. The cold chain includes all aspects of the transfer of food from the producer to the consumer. When a link of this cold chain fails, it inevitably results in a loss of quality and revenue, and, in many cases, leads to spoilage (Chen and Shaw, 2011).

Cold chain management is the process of planning, implementing and controlling efficient, effective flow and storage of perishable goods, related services and information from one or more points of origin to the points of production, distribution and consumptions in order to meet customers' requirements. It is the process of integrating the existing business activities, including special activities for perishable goods (Bogataj et al., 2005). To improve the quality monitoring and management system of the cold chain logistics processes, this issue has become a concern of government and enterprises and it is also an important topic for research (Aung and Chang, 2014). The purpose of cold chain management is managing activities related to perishable products like medicine, blood, diary, meat and so on, which must be distributed in a special time and kept in particular environment condition (Shabani et al., 2012). Cold chain management is a strategic issue in business. Determining on the right temperature monitoring system is the most critical factor for a successful cold chain management. It is a long term decision for companies. Implemented system should meet the firm's need for a long time period. The system should operate reliable and effectively. A successful system provides the firms a cost advantage. If the vaccines are not stored in appropriate conditions, they will spoil and this will add an extra cost to the firm. If the vaccines spoil, there will be delays to transport them to customers for the firm and the image of the firm will damage from customers perspective. To prevent the spoilage or the loss of vaccines , an effective temperature monitoring system is a must have for firms in the cold chain.

There are different types of temperature monitoring systems for vaccine storage. Stam or bi-metal thermometers are one of the first used devices for temperature monitoring. With these thermometers the temperature can be monitored when a worker checks the thermometer. When checked and a temperature value of between+2 C and +8 C is found, health workers may erroneously conclude that the vaccines are safe since this snapshot reading only provides a value when it is checked and by no means covers the rest of the daytime/nighttime period, so they can not be considered as an appropriate device (Kartoğlu et al., 2010). In parallel with the technological developments, new temperature monitoring systems have developed. In this study, electronic thermometer data logger, wired data logger, wireless data logger and cloud-based data logger temperature monitoring systems are chosen for evaluation.

In literature, there are some studies about vaccine cold chain management. Matthias et al.(2007) studied the freezing temperatures in the cold chain. They presented a literature review about it. Nelson et al. (2007) analyzed DTP-HB-Hib vaccine temperatures during shipments from central stores in Bolivia. The results showed that freezing occurred at almost every level of the distribution system. Techathawat et al. (2007) investigated cold chain temperatures in Thailand. Measles and Hepatit B vaccines on 48 randomly selected shipment routes are analyzed and they found exposure to freezing was more important problem. Kartoğlu et al. (2010) compared 30 day electronic temperature data logger with the thermometers. The study was done in Albenia for a 3 months period and they showed the superiority of 30 day electronic temperature data logger against thermometer. Zaffran et al. (2013) stated the current vaccine supply chain emphasized the importance of vaccine supply chain performance and presented a global plan for improvement. Llyod et al. (2015) presented a study conducted in Tunisia in 2012 that tested the impact of introducing several freeze prevention solutions to mitigate the risk of accidental freezing of vaccines. They found that , using new technologies continuous temperature monitoring combined with other technological interventions significantly reduced the prevalence of accidental exposure to freezing temperatures.

The aim of this paper is to determine the best temperature monitoring system for vaccine storage in a pharmaceutical warehouse for an effective and sustainable cold chain management. The problem is considered as a multi-criteria decision making problem because there are many different criteria that affect the selection process. Fuzzy numbers are integrated with AHP for selecting the best temperature monitoring system because decision makers can handle better with the uncertain criteria.

The rest of the paper is organized as follows: Section 2 explains the solution methodology, fuzzy AHP and the literature about fuzzy AHP. Section 3 presents the application of the best vaccine temperature monitoring device selection problem by using fuzzy AHP and Section 4 concludes the paper.

2. Methodology

Fuzzy AHP is used as the solution methodology to determine the best temperature monitoring system. In this section the methodology of AHP is given.

1.1. Fuzzy AHP

AHP is one of the most used multi-criteria decision making techniques in literature. AHP is introduced by Saaty and is widely used for complex multi-criteria problems that contain subjective judgment (Thengane et al., 2014; Somsuk and Laosirihongthong, 2014; Baysal et al., 2015). The aim of AHP is to provide weights for each criterion and alternatives (Baysal et al., 2015).

In real life, human assessments are always subjective and imprecise but traditional AHP doesn't take into account these uncertainty and imprecision of the decision makers (Chen and Hung, 2010). Fuzzy AHP that combines fuzzy numbers and classical AHP methodology, was developed for dealing with uncertain judgments. In fuzzy AHP , preferences are expressed as fuzzy sets or fuzzy numbers which reflect the vagueness of human thinking (Somsuk and Laosirihongthong, 2014).

2.2. Literature Review

Fuzzy AHP is an interdisciplinary methodology and has been used in many different sectors in business. Bruno et al. (2016) applied fuzzy AHP to a supplier selection problem. The methodology is applied to a real case company in the railway and transportation industry. Nguyen et al. (2015) used fuzzy AHP to evaluate complexity in transportation projects. Ezzabadi et al. (2015) prioritized criteria and sub-criteria with fuzzy AHP to find areas for improvement of projects in electricity company. Mangla et al. (2015) implemented fuzzy AHP to determine the priority of green supply chain risks of poly product manufacturing companies. They found that operational risks are the most important risks in green supply chain. Kabra et al. (2015) used fuzzy AHP to prioritize of the weights of coordination barriers in humanitarian supply chain management. The results show that the lack of top management commitment, improper organizational structure to create and share knowledge and lack of policy for coordination are the major barriers. Tasri and Susilawati (2014) determined the best renewable energy technology using fuzzy AHP. Hydro power was found the best renewable energy alternative. Calabrese et al. (2013) used fuzzy AHP to analyze the impact of intellectual capital components on information and communication technology service industry. Cho et al. (2012) implemented fuzzy AHP on a service supply chain measurement problem. They applied the methodology in hotel supply chain. Strategic, tactical and operational level performances are analyzed. Zheng et al. (2012) used fuzzy AHP to analyze the work safety in hot and humid environment. Cho and Lee (2011) studied a web based business process management system evaluation. The criteria are determined with Balanced Score Card and the evaluation of processes is made with fuzzy AHP.

When the literature is analyzed, it can be seen that fuzzy AHP has been used in various sectors from production to service sectors in business life. To the best of our knowledge fuzzy AHP has not been used in cold chain management in healthcare. There is a need to more studies in this topic. This study will fill the gap in this area.

2.3. The Steps of AHP

In this study, Buckley's (1985) fuzzy AHP methodology is used to select the best vaccine temperature monitoring system. As fuzzy numbers, triangular fuzzy numbers are used. The steps of the algorithm are listed below (Kahraman et al., 2014):

Step 1: Pair wise comparison matrices are constructed. Each element ($\tilde{C}_{ij}$) of the pair wise comparison matrix (C) is a linguistic term presenting the importance between two criteria.

$$\tilde{C}_k = \begin{bmatrix} \tilde{1} & \tilde{C}_{12} & \dots & \tilde{C}_{1n} \\ \tilde{C}_{21} & \tilde{1} & \dots & \tilde{C}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{C}_{n1} & \tilde{C}_{n2} & \dots & \tilde{1} \end{bmatrix} \text{ k= 1,2,…,K} \quad (1)$$

$\tilde{C}_k$ is a pair wise comparison matrix belonging to k_{th} expert. The linguistic terms and their fuzzy numbers' equivalent that are used for pair wise comparison are shown in Table 1. To aggregate decision maker's opinion, geometric mean is used.

Table 1: Linguistic Scale

Linguistic Expression	Fuzzy Number
Equally important (Eq)	(1,1,3)
Weakly important (Wk)	(1,3,5)
Essentially important (Es)	(3,5,7)
Very strongly important (Vs)	(5,7,9)
Absolutely important (Ab)	(7,9,9)

Source: Kahraman,C., Süder, A., Kaya, İ. Fuzzy multi criteria evaluation of health research investments, Technological and Economic Development of Economy,(2014), 20:2, 210-226

Step 2: Fuzzy weights are calculated.

$$\tilde{r}_i = \left[\tilde{C}_{i1} \otimes \tilde{C}_{i2} \otimes \ldots \otimes \tilde{C}_{in}\right]^{1/n} \tag{2}$$

$$\tilde{w}_i = \frac{\tilde{r}_i}{\tilde{r}_i \oplus \ldots \oplus \tilde{r}_n} \tag{3}$$

$\tilde{r}_i$ is the geometric mean of fuzzy comparison value of criterion I to each criterion and $\tilde{w}_i$ is the fuzzy weight of the i_{th} criterion.

Step 3: Fuzzy weights are defuzzified. Fuzzy numbers are converted into crisp numbers. In this paper Liou and Wang's (1992) total integral method is used. Liou and Wang (1992) proposed the total integral value method with an index of optimism $\omega \in [0,1]$. Let $\tilde{A}$ be a fuzzy number with left membership function $f^L_{\tilde{A}}$ and right membership function $f^R_{\tilde{A}}$. Then the total integral value is defined as follows:

$$E_\omega(\tilde{A}) = \omega E_R(\tilde{A}) + (1-\omega) E_L(\tilde{A}) \tag{4}$$

where

$$E_R(\tilde{A}) = \int_\alpha^\beta x f^R_{\tilde{A}}(x)dx \tag{5}$$

and

$$E_L(\tilde{A}) = \int_\gamma^\delta x f^L_{\tilde{A}}(x)dx \tag{6}$$

where $-\infty \le \alpha \le \beta \le \gamma \le \delta \le \infty$. For a triangular fuzzy number $\tilde{A} = (a,b,c)$ the total integral value is obtained by:

$$E_\omega(\tilde{A}) = \frac{1}{2}[\omega(a+b) + (1-\omega)(b+c)] \tag{7}$$

ω is taken as 0.5 for our problem.

Step 4: Consistency ratio is calculated for every pair wise comparison matrices. The consistency ratio (CR) should be less than 0,1. If the ratio is greater than 0,1 , the comparisons should be done again until the consistency ratio (CR) is less than 0,1. The formulation of consistency index (CI) and consistency ratio (CR) is shown below (Calabrese et al., 2013):

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{8}$$

$$CR = \frac{(CI \ - RI(n))}{100} \tag{9}$$

$\lambda_{\max}$ is s the largest eigenvalue of the comparison matrix, n is the dimension of the matrix and RI(n) is a random index that depends on n. The values of RI related to n is shown in Table 2.

Table 2: Random index (RI) values for different matrix dimensions

n	3	4	5	6	7	8	9
RI(n)	0,58	0,9	1,12	1,24	1,32	1,41	1,45

Source: Calabrese, A., Costa, R., Menichini, T. Using Fuzzy AHP to manage Intellectual Capital assets: An application to the ICT service industry, Expert Systems with Applications 40 (2013) 3747–3755.

Step 5: Final ranking is obtained and the best alternative is found.

3. Application

A pharmaceutical warehouse company wants to decide on a new vaccine temperature monitoring system. Three decision makers (3) are determined to select the most appropriate temperature monitoring system. Two decision makers are managers in pharmaceutical industry and one decision maker is an academician who studies about supply chain and cold chain management. Four alternative temperature management systems are determined. These are; USB data logger system, wired temperature monitoring data logger system, wireless temperature monitoring data logger system and cloud based temperature data logger system. Then the main and sub-criteria for selecting the best temperature monitoring system is determined. Four main criteria are determined by the decision makers. These are cost, warning type, technical features and ease of use. Under the 4 main criteria 14 sub-criteria are identified. The sub-criteria are listed below:

➢ **Cost**
- Purchasing cost
- Installation cost
- Annual cost

➢ **Alarm type**
- SMS
- Phone
- E-mail

➢ **Technical features**
- Wastage of energy
- Number of sensors
- Record time
- Physical life
- Measurable temperature range

➢ **Ease of use**
- Ease of traceability
- Ease of implementation
- Need of qualified workers

The hierarchical structure of the problem is shown in Figure 1.

Fuzzy AHP method is used to determine the best alternative because fuzzy sets give the decision makers more flexibility during the evaluation of alternatives. Decision makers evaluated the criteria and alternatives by using comparison matrices. After every matrix the consistency rate is checked and the matrices are revised when the consistency ratio is greater than 0,1. Obtained fuzzy weights are defuzzified and finally the best vaccine temperature monitoring system is determined. The flowchart of the solution procedure is shown in Figure 2.

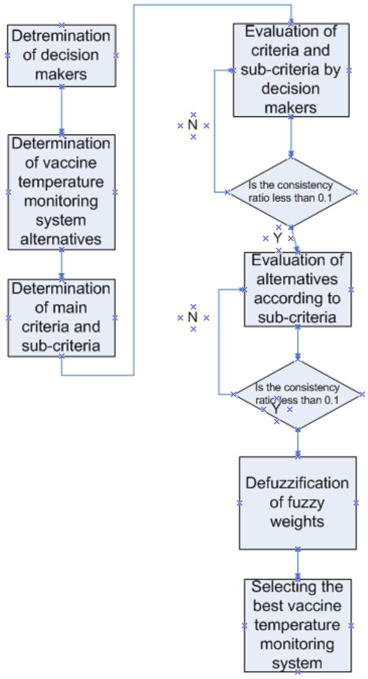

Figure 2 : The flowchart of the study

3.1. Vaccine Temperature Monitoring Alternatives

The firm decides to set up a new and safety continuous temperature monitoring system for its warehouse. According to firm's needs and technological developments, four temperature monitoring systems are determined. These are, electronic thermometer data logger system, wired data logger temperature monitoring system, wireless data logger temperature monitoring system and cloud based data logger temperature monitoring system. These systems are explained briefly below:

Electronic Thermometer Data Logger System

The electronic thermometer provides a 60-day temperature monitoring and there is no software needed to analyze the data. These type of data logger is equipped with a display monitor, bio-safe glycol filled vial (buffered probe) and connecting cable. The display monitor should be positioned outside the vaccine fridge unit. To analyze the data , detach it from the external probe, connect it to any computer via USB, and download the report like a removable memory stick. The bio-safe glycol filled bottle/probe should be centrally place inside the fridge unit along with the vaccine supply away from ceilings, walls, vents, fans and coils. Data logger has pre-set alarms to alert personnel for temperature excursions. The measurement interval of the device is between -30 °C and +55 °C (www.vdh.virginia.gov).

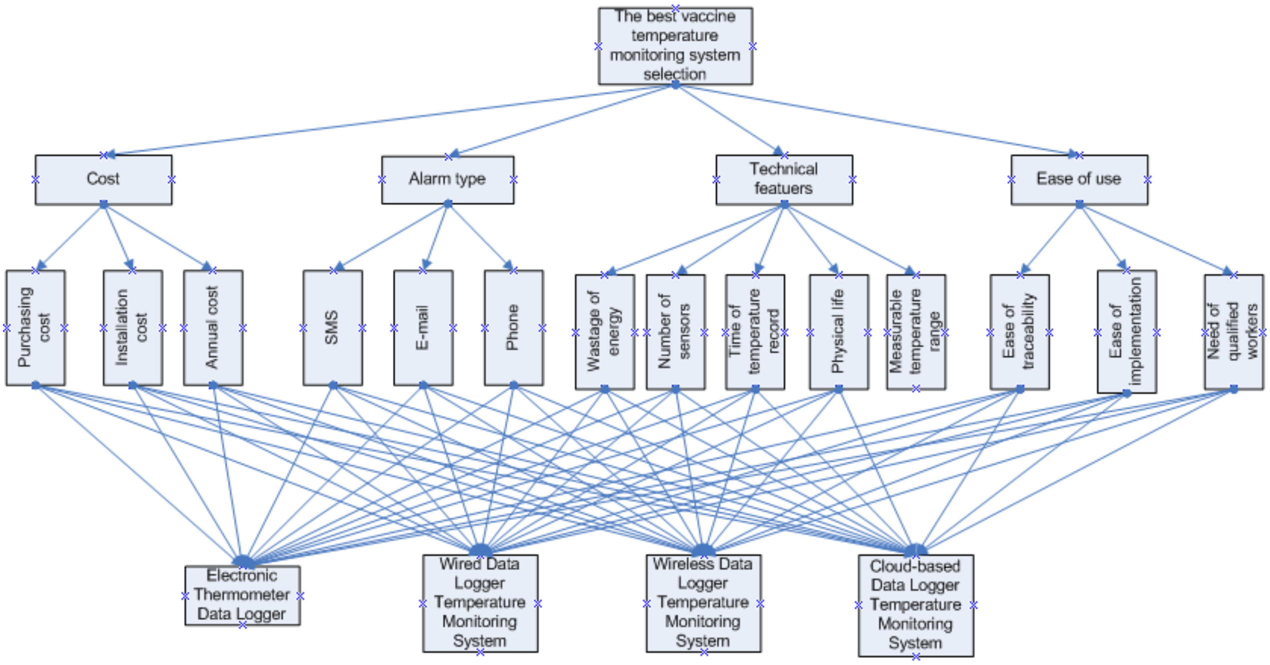

Figure 1: The hierarchy of the best vaccine temperature monitoring system selection

Wired Temperature Data Logger System

Wired sensors provide reliable data recording, however they can also require complex installation. Monitoring networks with wired sensors are also limited in the adaptability of the monitoring architecture. This complicates matters when equipment needs to be moved, or a warehouse needs to be reconfigured, potentially incurring additional costs (Technical supplement to WHO Technical Report Series, 2014). In the event of a loss of the network connection it will store up data until the connection is restored. In single account multiple monitors can be viewed . With the alarm settings alarms can be received via e-mail or cell phones (www.vfcdataloggers.com).

Wireless Data Logger Temperature Monitoring System

Wireless temperature monitoring systems are easy to install and use and they reduce cost and time required for installation and maintenance (Technical supplement to WHO Technical Report Series, 2014). Data logger works with a central server over Wifi. A main computer is needed to set up the system. Plugging in the device is enough to operate the system. In case of power loss, the interior battery of device will be put into use and measured temperatures are kept in memory of device. The temperatures can be read on LCD monitor and also can be tracked over internet. If the temperatures are out of range, it alarms the authorized personnel via SMS, e-mail or phone call (www.dorukan.com.tr).

Cloud-based Data Logger Temperature Monitoring System

Cloud-based temperature monitoring systems need no computer and installation. Because it doesn’t need a main computer, so the annual electric wastage decreases dramatically. When the device is turned on, it will start saving the data to a "cloud" server for access on the internet with user name and password. It alarms the people via SMS, e-mail or phone call. The situation of fridge door (open or close) also can be tracked. Data from multiple locations can be received from one device (www.nata.com.au, http://sensorium.com.tr, http://news.thomasnet.com).

3.2. Solution

First, 3 decision makers compared the main criteria with each other. Then the sub-criteria for every main criterion are compared and the local weights are calculated. Local weights are multiplied with related main criteria weights and overall global weights are obtained. The fuzzy linguistic comparison table for main criteria for 3 decision makers are shown in Table 3 and fuzzy weights and overall global crisp weights of main and sub-criteria are shown in table 4 and 5 respectively.

Table 3: Linguistic comparison matrix for main criteria

Decision maker 1				
	Cost	Alarm Type	Technical features	Ease of use
Cost	1	1/Eq	Eq	Ab
Alarm Type	Eq	1	Eq	Ab
Technical Features	1/Eq	1/Eq	1	Vs
Ease of use	1/Ab	1/Ab	1/Vs	1
Decision maker 2				
	Cost	Alarm Type	Technical features	Ease of use
Cost	1	1/Es	1/Es	Eq
Alarm Type	Es	1	Eq	Ab
Technical Features	Es	1/Eq	1	Vs
Ease of use	1/Eq	1/Ab	1/Vs	1
Decision maker 3				
	Cost	Alarm Type	Technical features	Ease of use
Cost	1	1/Eq	1/Wk	Es
Alarm Type	Eq	1	1/Eq	Vs
Technical Features	Wk	Eq	1	Ab
Ease of use	1/Es	1/Vs	1/Ab	1

Table 4: Fuzzy weights of main and sub-criteria

Criteria	Fuzzy weights
Cost	(0.094,0.183, 0.376)
Purchasing cost	(0.602, 0.805, 1.031)
Installation cost	(0.067, 0.095, 0.141)
Annual cost	(0.075, 0.1, 0.171)
Alarm Type	(0.219, 0.37, 0.782)
SMS	(0.202, 0.307, 0.525)
E-mail	(0.051, 0.073, 0.106)
Phone call	(0.398, 0.62, 0.905)
Technical Features	(0.177, 0.397, 0.68)
Wastage of energy	(0.185, 0.401, 0.904)
Number of sensors	(0.019, 0.035, 0.073)
Time of record	(0.111, 0.277, 0.613)
Physical life	(0.049, 0.121, 0.272)
Measurable temperature range	(0.073, 0.167, 0.422)
Ease of use	(0.03, 0.049, 0.085)
Ease of traceability	(0.562, 0.745, 0.988)
Ease of implementation	(0.064, 0.083, 0.123)
Need of qualified workers	(0.114, 0.172, 0.241)

The fuzzy weights are defuzzified by using Eq. (7) and final crisp weights are obtained.

According to fuzzy AHP weights alarm type is determined as most important main criteria with 0.392 points, then comes technical features as second with 0.372 points , cost as third with 0.188 points and ease of use as fourth important main criteria with 0.048 points.

Table 5: Crisp weights of main and sub-criteria

Criteria	Weight		Overall weight
Cost	0.188		
Purchasing cost		0.794	0.149
Installation cost		0.097	0.018
Annual cost		0.109	0.020
Alarm Type	0.392		
SMS		0.320	0.125
E-mail		0.072	0.03
Phone call		0.607	0.238
Technical Features	0.372		
Wastage of energy		0.401	0.149
Number of sensors		0.034	0.013
Time of record		0.271	0.101
Physical life		0.119	0.044
Measurable temperature range		0.175	0.065
Ease of use	0.048		
Ease of traceability		0.743	0.036
Ease of implementation		0.086	0.004
Need of qualified workers		0.171	0.008

Then, alternative vaccine temperature monitoring systems are compared according to every sub-criteria and after that the weights obtaining from every sub-criteria are summed for every alternative. Finally, the total points are calculated for four alternative monitoring systems. Table 6 indicates the evaluation of alternatives according to every sub-criteria.

An example for electronic thermometer temperature monitoring system is shown below:

[(0.149x0.710)+(0.018x0.325)+(0.020x0.357)+(0.125x0.039)+(0.03x0.049)+(0.238x0.044)+(0.149x0.444)+(0.013x0.050)+(0.101x0.036)+(0.044x0.038)+(0.065x0.123)+(0.036x0.047)+(0.004x0.631)+(0.008x0.056)]= **0.221**

The total values for other alternative temperature monitoring systems are calculated as the same way. Table 7 shows final ranking of alternatives.

Table 6: Evaluation of alternatives according to sub-criteria

	Electronic Thermometer Data Logger System	Wired Data Logger Temperature Monitor System	Wireless Data Logger Temperature Monitoring System	Cloud-based Data Logger Temperature Monitoring System
Purchasing cost	0.710	0.105	0.100	0.85
Installation cost	0.325	0.203	0.254	0.217
Annual cost	0.357	0.219	0.224	0.200
SMS	0.039	0.312	0.309	0.340
E-mail	0.049	0.093	0.389	0.469
Phone call	0.044	0.227	0.356	0.373
Wastage of energy	0.444	0.094	0.080	0.382
Number of sensors	0.050	0.256	0.319	0.375
Time of record	0.036	0.371	0.317	0.276
Physical life	0.038	0.268	0.320	0.374
Measurable temperature range	0.123	0.241	0.310	0.326

Table 7: Fuzzy AHP result

Alternatives	Total values	Ranking
Electronic Thermometer Data Logger Temperature Monitoring System	0.221	3
Wired Data Logger Temperature Monitoring System	0.208	4
Wireless Data Logger Temperature Monitoring System	0.259	2
Cloud-based Data Logger Temperature Monitoring System	0.312	1

According to fuzzy AHP results Cloud-based Data Logger Temperature Monitoring System is determined as the best vaccine temperature monitoring system for the firm. Wireless Temperature Monitoring System is the second best alternative. Electronic Thermometer Data Logger Monitoring System is the third best alternative and Wired Temperature Monitoring System is the fourth best alternative. The firm will implement Cloud-based Data Logger Temperature Monitoring System for its vaccine storage.

4. Results

One of the primary conditions of an effective cold chain maangement is to monitor the temperatures of products correctly. If the products are not stored in right conditons, they can spoil or lose its effectiveness and it will have negative impacts on human health. Therefore, temperature monitoring of products in the cold chain gains more importance to sustain the effectiveness of system and an effective temperature monitoring system is a must have for all partners in the cold chain. In this study, we determined on the best vaccine temperature monitoring system for a pharmaceutical warehouse. Electronic thermometer data logger, wired data logger temperature monitoring system, wireless data logger temperature monitoring system and cloud-based data logger temperature monitoring system are determined as alternative systems. While there are many critical factors for selecting the best system, one of the most used multi criteria decision making methodology fuzzy AHP is used as solution methodology. Fuzzy numbers are used to provide more flexibility during evaluation process. Cloud-based temperature monitoring system is determined as the best alternative for the firm. Cloud-based systems have long life cyle so they can be used for a long time period. Implementing and tracking the system is very easy. In real life, cloud-based temperature monitoring systems have been started to be used in companies, so the results are consistent with real life. This study will also helpful for managers in this area for decisions when implementing new systems. The vaccine cold chain has not been studied as a multi criteria decision making problem so far in literature, so this study will also fill the gap in this area.

In future research, different multi-criteria decision making problems can be applied on the same problem, the numbers of decision makers can be extended and the results can be compared with each other.

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