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EVALUATION OF REAL-TIME INTELLIGENT SENSORS FOR STRUCTURAL HEALTH MONITORING OF BRIDGES BASED ON SWARA-WASPAS; A CASE IN IRAN

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Abstract. Now a day, earthquake engineers follow subjects such as structural health monitoring, warning announcement and prediction rather safe-making in the field of structure. In this regard, these three choices are of great goals of Iran in direction of many studies concentrated on. This research is centralized on real time health monitoring system of Iran bridges. In this regard, to evaluate smart real time health monitoring sensors, first all different types were determined using the library resources, and then all the important indices in evaluating these sensors were derived by interviewing experts in construction management fields. After that, to continue the survey, questionnaires were given to 18 experts to weight the effective indices. Through a decision-making method using new hybrid methodology based on SWARA and WASPAS, existential necessity degree of all indices and sensors were obtained and eventually the following result captured: applying piezoelectric sensors is optimal in smart health monitoring to be used in Iran bridges and optical fiber sensor was recognized as the second optimum option.

Keyword: real-time intelligent sensors, structural health monitoring, damage assessment, SWARA, WASPAS.

1. Introduction

According to the fact that, 31 types out of more than 40 natural disasters have been recorded in Iran such as destructive earthquakes and floods, studying the critical conditions is necessary (Bitarafan *et al.* 2012). Now a day, earthquake engineers follow subjects such as structural health monitoring, warning announcement and prediction rather safe-making in the field of structure. In this regard, the need for design and construction of smart systems with structural form, and combinational and behavioral adaption capability with environmental conditions in recent decades has been increased (Bae *et al.* 2013; Farshad 1995; Mehrani *et al.* 2009). According to what mentioned, and also exhaustion of existing infrastructures, application of structural health monitoring system that is one of the smart systems in structures can culminate to reduction of costs of repair and retention (Dibley *et al.* 2012). Usage of smart structure systems can be categorized into three fields of study including structural health monitoring, control and adaptability and artificial intelligence system.

To ensure structural integrity and safety, civil structures have to be equipped with Structural Health Monitoring (SHM) (Chang 1997), which aims to develop automated systems for the continuous monitoring, inspection, and damage detection of structures with minimum labor involvement. The focus of this research is on Iran bridges real time health monitoring. It's crystal clear that the ocular study of a majority of the bridges requires investing time and a lot of money. Besides, despite all studies done by bridge experts and based on standard methods, yet most of the restrictions and defects related to bridge management and evaluation based on which aim is followed, are considerable. Considering this issue in Iran,

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the main aim of the research is the determination of all sensors used in bridge health monitoring and obtaining the optimal sensor based on the important indices in this area. Dozens of researches have been done on smart sensors up to now. Bitarafan *et al.* (2013) studied on Selecting the Best Design Scenario of the Smart Structure of Bridges for Probably Future Earthquakes.

In previous studies, designing sensors was focused in order to be utilized in structural health monitoring systems. However, the creative aspect of this recent study is appraisement of all types of sensors, considering important indices, to be used in Iran bridges. In this article, first, performance methodology is evaluated, results analysis is explained and then all types of sensors are identified, effective indices in appraisement process are derived and finally the results are concluded associated with the new hybrid methodology based on SWARA-WASPAS. The main steps of the research are shown in Fig. 1.

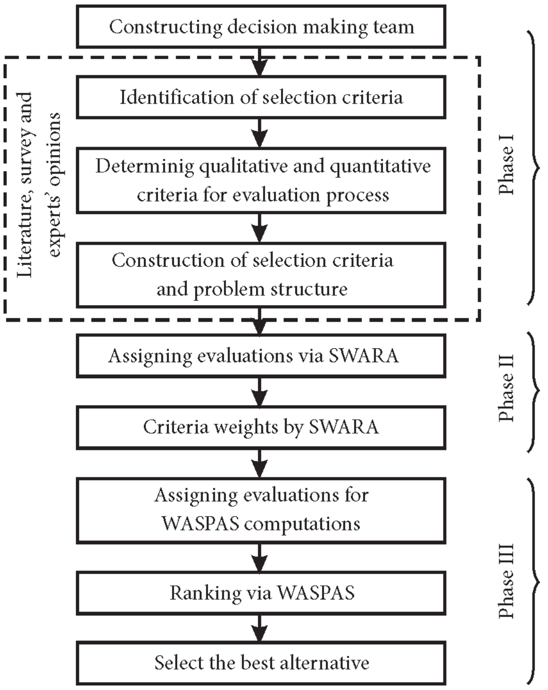

Fig. 1. Schematic representation of the process proposed for real-time intelligent sensors for structural health monitoring of bridges selection process

2. Online smart sensors for structural health monitoring

Types of real-time intelligent sensors are as follows:
- Piezoelectric (PZT) sensors;
- Optical fiber sensors;
- Self-Diagnosing Fiber Reinforced Composites;
- Magnetostrictive sensor technology.

2.1. Piezoelectric sensors (A_1)

Piezoelectric is an electromechanical phenomenon in which there exists a coupling between the elastic and the electric fields in the piezoelectric. Pressures generate voltage in a piezoelectric material (Farshad 1995). Smart PZT transducers, acting as both actuators and sensors in a self-analyzing manner, can be very effective for non-parametric health monitoring of structural systems (Yun *et al.* 2011). There are various types of piezoelectric materials: piezoelectric ceramics, piezoelectric polymers, and piezoelectric composites (Sun *et al.* 2010). More recently, piezoelectric sensors were introduced into SHM of civil engineering structures as an active sensing technology based on the measurement of electrical impedance and elastic waves (Sun *et al.* 2010).

The most important studies on the application of piezoelectric sensors in the bridge are the following:
- Park *et al.* (2006a, b) used Lamb wave method besides the electrical impedance method to detect damages in a steel bridge component.
- Soh *et al.* (2000) carried out an impedance-based health monitoring and damage detection using PZT patches on a prototype reinforced concrete (RC) bridge.

Advantages and disadvantages of this sensor include:

a. Fiber Optical System (FOS) systems can be connected to structures, easily and laid in different locations.

b. The qualitative nature of this technique makes it very accessible for everyone since it does not require any background knowledge in order to interpret the simple output (Electrical Impedance-Based SHM Method) (Sun *et al.* 2010).

c. Wide temperature range.

d. The PZT transducers can be very attractive and economical for large civil-infrastructures since a limited number of PZT transducers may be required near the damage critical locations (Yun *et al.* 2011).

e. It is a qualitative method because various types of damage such as cracks, corrosion and delamination all affect the mechanical impedance similarly which makes the distinction between each type of damage very difficult (Electrical Impedance-Based SHM Method) (Sun *et al.* 2010).

f. A large number of piezoelectric sensor elements could be used without greatly increasing the mass of the structure.

2.2. Optical fiber sensors (A_2)

Optical sensor, as their name implies, are materials which are sensitive to light. In addition, they are capable of converting the light energy to other energy form (Farshad 1995). OFS systems contain numerous benefits in structural health monitoring (Yun *et al.* 2011). Generally, they are able to apply on any kind of structures such as building, bridges, dams and etc. to gain information about temperature, fissure, crack and etc. in order to be utilized for safety assessment of structures (Sun *et al.* 2010).

Currently, many bridges around the world have been instrumented with OFS sensing system (Sun *et al.* 2010) that are listed below:
- The Beddington Trail Bridge in Calgary, Canada (Measures *et al.* 1995).

– Two bridges in Winterthur, Switzerland (Bronnimann *et al.* 1999).
– The Versoix Bridge in the USA (Inaudi *et al.* 2002).
– A Long steel truss bridge spanning the Winooski River in Waterbury, Vermont (Fuhr *et al.* 2000).
– A bridge monitoring in mainland China (Ou, Zhou 2008).

Advantages and disadvantages of this sensor include:
a. FOS systems can be connected to structures, easily and laid in different locations.
b. These systems are protected from electromagnetic disorders.
c. The sensors of FOS possess greatly high sensitivity and their size in changeable from mm to km.
d. Durability of OFSs has drawn much interest from the structural engineers, especially in the field of long-term structural health monitoring.
e. The cost of these systems is estimated too much.
f. They are fragile in some configurations (Sun *et al.* 2010).
g. The damage is difficult to repair when embedded (Sun *et al.* 2010).
h. The optical connection parts, which connect the embedded optical fibre with the outer data recording system, are also weak elements of the FOS system (Sun *et al.* 2010).

2.3. Magnetostrictive sensor technology (A_3)

Ferromagnetic materials have the property of being mechanically deformed when placed in a magnetic field. This phenomenon is called the magnetostrictive (Sun *et al.* 2010) and was first reported by Joule in 1847. The magnetostrictive sensor (MsS) is a type of transducer which can generate and detect time-varying stresses or strains in ferromagnetic materials (Kwun, Bartels 1998).

Advantages and disadvantages of this sensor include:
a. High sensitivity (Prieto *et al.* 2000).
b. Can be utilized for the generation and detection of mechanical stresses, deformations, and oscillations (Krautkramer, Krautkramer 1990).

2.4. Self-Diagnosing Fiber Reinforced Composites (A_4)

Self-diagnosing (or self-monitoring) fiber reinforced composites contain an electrical conductive phase such as carbon fiber and conductive powder in the cement or polymer matrix (Sun *et al.* 2010).

It has been reported that the electrical resistance change in carbon-fiber-reinforced plastics (CFRP) can be used to monitor the occurrence of fatal fracture in these materials (De Vries *et al.* 1995; Quirion, Ballivy 2000; Zhang *et al.* 2002).

Advantages and disadvantages of this sensor include:
a. The technique of SHM using self-diagnosing fiber reinforced composites as sensors is a simple technology (Sun *et al.* 2010).
b. They work as both structural materials and sensing materials.
c. Carbon fibers have not only provided smart abilities, but also improved the mechanical properties of concrete.
d. They have the abilities to monitor their own strain, damage and temperature.

3. Methodology

This study aims to evaluate the real-time intelligent sensors for structural health monitoring of bridges in Iran. First, real-time intelligent sensors are identified using library resources. Then, all of the proposed indicators to assess the composition of real-time intelligent sensors are extracted by interviewing experts in the field of structural engineering, earthquake engineering and construction management (based on Table 1). In the next step, a questionnaire was given to 18 experts in order to weight effective indices based on their viewpoints then SWARA-WASPAS research is analyzed applying the new hybrid MCDM method. SWARA is applied for evaluating and weighting criteria and WASPAS for evaluating alternatives of research.

3.1. Data gathering

At the first step, top managers having high experience of earthquake engineering and a group of experts in civil engineer and economy participated in a conference meeting for decision making in this area and with a preliminary work the decision making team determined four important criteria for reconstructing damaged areas in natural crises. Information about experts is shown in Table 1.

3.2. Step-wise weight assessment ratio analysis (SWARA) method

This method presented by Keršuliene *et al.* (2010) for evaluating and weighting of criteria. This method generally has a different perspective in this area of science. There are different methods for evaluating criteria like: AHP, ANP and FARE. Based of Hashemkhani Zolfani and Šaparauskas (2013) and Hashemkhani Zolfani and Bahrami (2014) this method is suitable for decision making in high level of make decisions and also instead of policy making.

Based on Keršulienė *et al.* (2010) and Keršulienė and Turskis (2011) importance of opinions of experts is more than other methods because they should make decisions about priority of criteria. The best advantage of this

Table 1. Background Information of Experts

Variable	Items	No	Variable	Items	No
1) Earthquake engineer	Bachelor	–	3) Structure engineer	Bachelor	–
	Master	4		Master	2
	Ph.D.	3		Ph.D.	5
2) Economic Experts	Bachelor	–	4) Top Managers	Bachelor	–
	Master	1		Master	2
	Ph. D.	–		Ph.D.	1

method is ability to make decision based on priorities of policies instead of calculating the importance of criteria.

The all developments of decision making models based on SWARA method up to now are listed below:

- Hashemkhani Zolfani and Šaparauskas (2013). Prioritizing Sustainability Assessment Indicators of Energy System;
- Hashemkhani Zolfani *et al.* (2013a). Design of products;
- Hashemkhani Zolfani *et al.* (2013b). Selecting the optimal alternative of mechanical longitudinal ventilation of tunnel pollutants;
- Hashemkhani Zolfani *et al.* (2013c). Investigating on the success factors of online games based on explorer;
- Alimardani *et al.* (2013). Supplier selection in agile environment;
- Hashemkhani Zolfani and Bahrami (2014). Investment Prioritizing in High Tech Industries;
- Ruzgys *et al.* (2014) integrated evaluation of external wall insulation.

The procedure for the criteria weights determination is presented in Fig. 2.

3.3. Weighted Aggregates Sum Product Assessment (WASPAS)

One of the latest methods in MADM fields is WASPAS and has presented based on Weighted Sum Model (WSM) and Weighted Product Model (WPM). This method has more accuracy in comparing to accuracy of one of WSM and WPM and proved by innovators of method (Zavadskas *et al.* 2012). This method is developed these years by other scholars in this short period of time around the world.

WASPAS calculation is based on these steps:

3.3.1. Normalized decision making matrix based on:

$$\bar{x}_{ij} = \frac{x_{ij}}{\underset{i}{opt}\, x_{ij}}, \text{ where } i = \overline{1,m};\ j = \overline{1,n}, \tag{1}$$

if *opt* value is max.

$$\bar{x}_{ij} = \frac{\underset{i}{opt}\, x_{ij}}{x_{ij}}, \text{ where } i = \overline{1,m};\ j = \overline{1,n}, \tag{2}$$

if *opt* value is min.

3.3.2. Calculating WASPAS weighted and normalized decision making matrix for summarizing part:

$$\bar{\bar{x}}_{ij,sum} = \bar{x}_{ij} q_j, \text{ where } i = \overline{1,m};\ j = \overline{1,n}. \tag{3}$$

3.3.3. Calculating WASPAS weighted and normalized decision making matrix for multiplication part:

$$\bar{\bar{x}}_{ij,mult} = \bar{x}_{ij}^{q_j}, \text{ where } i = \overline{1,m};\ j = \overline{1,n}. \tag{4}$$

3.3.4. Final calculating for evaluating and prioritizing alternatives based on:

$$WPS_i = 0.5 \sum_{j=1}^{n} \bar{\bar{X}}_{ij,sum} + 0.5 \prod_{j=1}^{n} \bar{\bar{X}}_{ij,mult},$$
$$\text{where } i = \overline{1,m};\ j = \overline{1,n}. \tag{5}$$

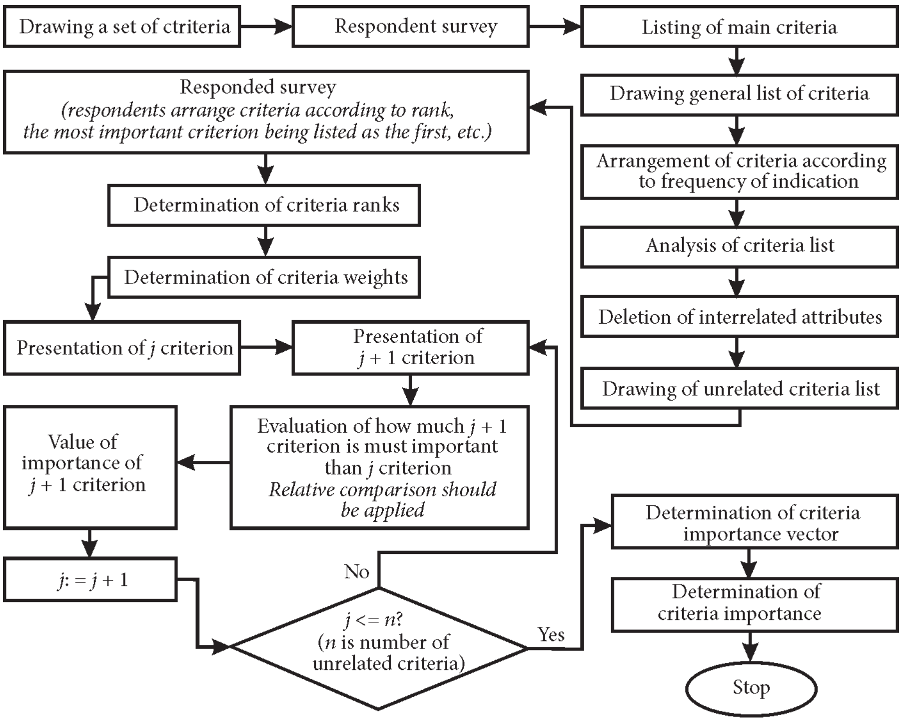

Fig. 2. Determining of the criteria weights based on (Keršulienė, Turskis 2011)

The all researches based on the WASPAS method up to now are described in several sources:

– Zavadskas *et al.* (2012) – developing WASPAS as a new methodology;
– Zavadskas *et al.* (2013) – Verification of robustness of methods;
– Dėjus and Antuchevičienė (2013) – Assessment of health and safety solutions at a construction site;
– Vafaeipour *et al.* (2014) – Assessment of regions priority for implementation of solar projects;
– Šiožinytė and Antuchevičienė (2013) – Solving the problems of daylighting buildings.

4. Determine effective indicators for the selection

Indices influencing the assessment of real-time intelligent sensors for structural health monitoring of bridges in Iran have been identified from the perspective of civil defense, and deciding indices are included from a set of defending and executing characteristics which have been regarded in Table 2.

Table 2. Indicators influencing on online intelligent sensors for structural health monitoring of bridges in Iran

Indicators influencing on online intelligent sensors for structural health monitoring of bridges in Iran	
C_1	Performance damage detection
C_2	Possibility of localization of sensor technology
C_3	Performance costs
C_4	Performance speed
C_5	Maintenance

5. Results of research

In this section, results of research are presented in Tables 3–8. Table 3 shows the result of SWARA method and Tables 4–8 are about WASPAS method results. The experts are participated in all part of this section.

According to the results of SWARA calculations, the performance damage detection is the most important criterion in evaluating the real-time intelligent sensors for structural health monitoring of bridges. It is followed by the performance costs as the second most important criterion, maintenance, performance speed and the possibility of localization of sensor technology are placed as the third, fourth and fifth priorities, respectively.

Table 4 presents judgment matrix and final weight of each decision making matrix.

Table 5 presents judgment matrix and the final weight of each WASPAS normalized decision making matrix.

Table 6 presents judgment matrix and the final weight of each WASPAS weighted and normalized decision making matrix for summarizing part.

Table 3. Final results of SWARA method in weighting criteria

Criterion	Comparative importance of average value S_j	Coefficient $k_j = s_j + 1$	Recalculated weight $w_j = \frac{x_{j-1}}{k_j}$	Weight $q_j = \frac{w_j}{\sum w_j}$
C_1		1	1	0.270
C_3	0.1861	1.1861	0.844	0.228
C_5	0.1806	1.1806	0.715	0.194
C_4	0.150	1.150	0.622	0.168
C_2	0.200	1.200	0.519	0.140

Table 4. Decision making matrix

	C_1	C_2	C_3	C_4	C_5
q	0.270	0.140	0.228	0.168	0.194
	Max	Max	Max	Min	Max
A_1	7	6	6	6	7
A_2	8	7	8	8	6
A_3	6	7	7	6	8
A_4	5	5	7	7	7

Table 5. WASPAS normalized decision making matrix

	C_1	C_2	C_3	C_4	C_5
q	0.270	0.140	0.228	0.168	0.194
	Max	Max	Max	Min	Max
A_1	0.875	0.858	0.75	1	0.875
A_2	1	1	1	0.750	0.750
A_3	0.750	1	0.875	1	1
A_4	0.625	0.715	0.875	0.858	0.875

Table 6. WASPAS weighted and normalized decision making matrix for summarizing part

	C_1	C_2	C_3	C_4	C_5
A_1	0.2363	0.1201	0.1710	0.1680	0.1698
A_2	0.2700	0.1400	0.2280	0.1260	0.1455
A_3	0.2025	0.1400	0.1995	0.1680	0.1940
A_4	0.1688	0.1001	0.1995	0.1441	0.1698

Table 7. WASPAS weighted and normalized decision making matrix for multiplication part

	C_1	C_2	C_3	C_4	C_5
A_1	0.9646	0.9788	0.9365	1	0.9744
A_2	1	1	1	0.9528	0.9457
A_3	0.9253	1	0.9700	1	1
A_4	0.8808	0.9541	0.9700	0.9746	0.9744

Table 8. The results of WASPAS

	$0.5\sum_{j=1}^{n}\bar{\bar{X}}_{ij,sum}$	$0.5\sum_{j=1}^{n}\bar{\bar{X}}_{ij,mult}$	WSP_i	Ranking
A_1	0.4326	0.4308	0.8633	1
A_2	0.4548	0.2274	0.6821	2
A_3	0.4520	0.2260	0.6780	3
A_4	0.3911	0.1956	0.5867	4

Table 7 presents judgment matrix and the final weight of each WASPAS weighted and normalized decision making matrix for multiplication part**.**

Final evaluating of alternatives is presented in Table 8.

6. Conclusions

1. Prediction and early warning announcement during the crisis, as two important segments, can play the main roles to reduce civilian casualties and losses in the crisis management. Therefore, one of the significant choices in this course is conversion of existing structures into smart structures.

2. Managing critical situations is a difficult problem for all managers and decision makers. The possibility of selecting an appropriate method which can consider all the criteria of reconstructing the damaged areas can be useful for decision makers in managing crises. Crisis management needs a team of experts from different areas, including structure engineer, economic experts, earthquake engineer, as well as top managers. Therefore, eighteen experts from these scientific fields participated in this research. Now a day, earthquake engineers follow subjects such as structural health monitoring, warning announcement and prediction rather safe-making in the field of structure. In this regard, in recent decades, most researchers of earthquake-prone countries have focused on smart structures technology.

3. These structures own natural or acquired capability in responding exteroceptives and capability of form, combination and behavior adaption with environmental conditions. One of the most vital organs of these smart structures is the sensor. As mentioned above, todays these sensors are extremely useful in health monitoring of even the biggest bridges. In this regard, all types of real time sensors in order to be utilized in Iran vital bridges are studied in this research. To evaluate and select the optimal case, SWARA-WASPAS method has been applied since SWARA-WASPAS method is highly capable as an efficient, low cost and accurate method in selecting the optimal case in group decision-makings. This method as a powerful management tool can give the best option with minimum time and cost. It's obvious that accurate data can raise the accuracy of the technique. Considering the accuracy of SWARA-WASPAS method, studying the general data and asking experts' opinions, the optimal choice is obtainable. By implementing this method, it can be concluded that the best index among all indices is performance damage detection and performance speed, maintenance, performance cost and possibility of localization of sensor technology follow the main index in a sequential order. Among all real time health monitoring sensors, piezoelectric sensors were selected as the optimal structural health monitoring method and optical fiber sensors, magnetostrictive sensor technology and self-diagnosing fiber reinforced composites are sequentially ordered as the next optimum choices.

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