A consensus-based AHP for improved assessment of resilience engineering in maintenance organizations

Ali Azadeh^{1*}, Seyed Mohammad Asadzadeh², Mehrab Tanhaeean²

¹*Department of Industrial Engineering, College of Engineering, University of Tehran, P.O.: Box 14395-515 Tehran, Iran*

²*Faculty of Engineering, College of Farabi, University of Tehran, Qom, Iran*

Abstract

Resilience engineering (RE) is a new approach to measuring and maintaining safety in complex systems. The focus of RE is not on errors rather than on understanding and supporting normal work and what goes right. Using analytical hierarchy process (AHP), the present study aims to devise a validated method for improved assessment of RE in maintenance organizations. A standardized questionnaire containing RE and Performance Shaping Factors (PSFs) for generic maintenance operators is designed to collect data from employees in 11 regional maintenance departments of a large public gas company. Holding regular discussion sessions with experts in the field, the AHP is then built up based on the consensus emerged from the discussions. To form the middle-level criteria of the analytical hierarchy, RE items are clustered into 6 new categories using a verified k-means clustering. Given the large number of RE items in some categories, a complete sensitivity analysis is then performed by data envelopment analysis (DEA) to identify the most important items as the final level criteria. The designed AHP is used to assess RE in the 11 regional maintenance departments. For verification and validation of the proposed AHP, the linear relationship between AHP-based RE assessment and PSFs assessment is tested for its significance. The results confirm the close relationship between RE and PSFs.

* Corresponding Author; Email: aazadeh@ut.ac.ir,

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1. Introduction

It is obvious that finding a right way and planning an effective strategy to increase intra-organizational knowledge about safety, reduce severe injuries caused by internal and external sources and increase the resilience of its desired configurations is one of the appropriate preventive measures against financial, casualty and credit losses in the small and large industries. RE has a prominent role in returning the system to a normal condition after a period of trouble or difficulty (Linh T.T. Dinh et al., 2012). It is also an approach to gain control of external problems and constraints and anticipate risks in the near future (G.H.A. Shirali et al., 2012).

The term resilience is originally derived from the Latin word *resiliere*, meaning jump back. This common language usage describes an ability to easily or quickly bounce back from a crisis (Seyedmohsen Hosseini et al., 2016). The American Society of Mechanical Engineers (2009) defines resilience as the ability of a system to control internal and external disruptions with the aim of continuing its operation. RE actually gives a new insight into safety and focuses on what we want. It has made organizations with a complex human and technological system take advantage of RE. A large number of studies has recently referred to RE as a strategic concept to improve complex systems, including nuclear power plants (Carvalho et al., 2008), healthcare systems (Jeffcott et al., 2009), aviation (Dekker et al., 2008), process industry (Shirali et al., 2013), industrial processes (Dinh et al., 2012), electricity distribution networks (Tarcisio Abreu Saurin et al., 2013; Tarcisio Abreu Saurin et al., 2014), and petrochemical plants (Azadeh et al., 2014; Azadeh et al., 2014; Azadeh and Salehi, 2014; Vugrin et al., 2011). In these organizations, efficiency depends heavily on manpower,

technology and environment, and RE establishes a strong association between human factors, control theory and safety engineering (Azadeh et al., 2015). RE is the natural ability of a system to be in operation under unexpected conditions (Hollnagel et al., 2007). Accordingly, organizational resilience is the natural ability to maintain or improve steady state stability, making it possible for organizations to normally operate in the face of serious challenges (Sheffi, 2005).

A proper operationalization of RE principles and concepts requires identification of factors as well as development of techniques to assess RE. Hollnagel(2007) determined management commitment, learning culture, reporting culture, awareness, preparedness, and flexibility, as the main factors of RE, to assess organizational resilience. Other studies also referred to the same sort of factors to assess RE(; Azadeh et al., 2014; Azadeh et al., 2014; Azadeh and salehi, 2014; Seyedmohsen Hosseini et al., 2016; Shirali et al., 2012; Shirali et al, 2013). A brief description of factors identified by Hollnagel(2007) is as follows.

- *Management commitment*: top managers have a duty to address concerns and issues affecting the efficiency of human work and resolve them (Wreathall, 2006). Improving safety along with reducing cost and increasing profitability needs to be the main objective of organizations (Costella et al., 2009).
- *Reporting culture*: given the fact that trying to put the blame on somebody is regarded as an unacceptable form of behavior, safety issues should be reported by organizations. The lack of a popular reporting culture in organizations significantly decreases operators' tendency to report issues and problems (Wreathall, 2006).
- *Learning culture*: there are important lessons to be learned from adverse events such as incidents, injuries and losses of performance. Also, valuable lessons drawn from the

normal work need to be taught others in such a way that everyone knows how to operate safely (Saurin and Carim Junior, 2011).

- *Awareness*: the efficiency of human work is assessed by managers through the collected information. All employees should be aware of the defensive position of system (Wreathall, 2006).
- *Preparedness*: the system is always anticipating various threats and offering solutions for them (Hollnagel et al., 2007).
- *Flexibility*: the system needs to be capable of adapting to different situations and changing its behavior and attitudes in order to be successful under critical conditions (Hollnagel et al., 2007).

In this study, a new and unique approach is developed in terms of the factors mentioned above to assess organizational resilience in regional maintenance departments of Tehran province Gas Company. This paper contributes to the field of RE by introducing an integrated Clustering-DEA-AHP approach to address both the problems of multi-variability and data redundancy when using qualitative questionnaires for RE assessment. The clustering part of the proposed approach puts the RE questionnaire items into new categories which are regarded as new resilience factors in the maintenance departments. In the second part of the proposed approach an input-free DEA model is formulated to assess each new resilience factor in the 11 maintenance departments (as DMUs) based on those items that fell into each category (as DEA outputs). DEA calculates the relative importance of each item in a category relative to other items in the same category. This allows for identification of items with the highest importance. At the third part of the proposed approach, an AHP is constructed based on the categories and items resulted from clustering and DEA, respectively. The overall resilience score is located at the top level of the hierarchy. The second

level consists of new maintenance resilience factors, resulted from clustering. Refined after application of DEA, the remaining items from each category form the third level of the hierarchy. AHP is the most comprehensive system designed for multiple criteria decision making and has many industrial applications. It can be very helpful for top managers in the maintenance departments to assess resilience.

The ultimate goal of RE is to improve safety and this fact can be served as a basis to validate any technique aimed at RE assessment. Accordingly, the results of the proposed AHP are validated with the results of PSFS survey performed in the same maintenance departments. The PSFs of maintenance operators are normally used to identify and analyze risks affecting the human errors and the workplace safety. Careful and detailed examination of human factors and errors may help reduce the frequency of unsafe behaviors, accidents and injuries, and improve the performance of health and safety in the workplace (Azadeh et al., 2011). Improving the health and safety of employees should be a main priority, especially in high-risk organizations such as the sample under study. The positive effect of ergonomics on workplace has also been shown in other studies (Ayoub, 1990; Blanchard and Fabrycky, 1990; Shikdar and Sawaged, 2004). It has been proved that the lack of ergonomic principles creates mental stresses and physical problems, reduces efficiency, and makes the quality of work poor (Burri and Helander, 1991; Cabrero-Canosa et al., 2003; Caldwell et al., 1998).

The rest of the paper is organized as follows. Section 2 presents an outline of the proposed Clustering-DEA-AHP approach as well as the methodology of the approach. Section 3 demonstrates an experiment with the proposed approach in the maintenance departments. And finally, Section 5 concludes the study.

2. The proposed integrated Clustering-DEA-AHP approach

The proposed integrated Clustering-DEA-AHP approach of the study is outlined in Figure 1. Figure 1 provides step by step directions on how to conduct the present study.

Figure 1: An outline of the proposed Clustering-DEA-AHP approach

This approach at the first step designs a standard questionnaire containing RE and PSFs to assess the efficiency of human work. The questionnaire then is tested for its content validity. In the next step, data are collected by administering questionnaire to the employees of 11 maintenance departments. The Cronbach's alpha coefficient is used to verify reliability. If the questionnaire is not verified for its validity or reliability, its items will be modified with respect to experts' opinion or existing literature, and more data will be collected. The verified results of the questionnaire survey then further analyzed by the use of k-means clustering. Items pertaining to the RE part of the questionnaire, are clustered into new categories (named as new maintenance resilience factors). These new maintenance resilience factors are regarded as the second-level set of criteria in the AHP. Before going further into the next steps of the proposed approach, the results of k-means clustering are compared with the results of another clustering technique (namely fuzzy c-means) to test the robustness and accountability of its results. If the clustering results of k-means are not verified by FCM, then appropriate modification in k-means parameters including the desired number of clusters are applied until a robust clustering is achieved. It should be noted that the answers of all employees in a given maintenance departments are averaged to form an 11-dimensional data set, as the input matrix to both k-means and FCM.

The clustering part of the proposed approach puts the RE questionnaire items into new categories which are regarded as new resilience factors in the maintenance departments. In the second part of the proposed approach an input-free DEA model (DEA without inputs) is formulated to assess each new resilience factor in the 11 maintenance departments (as DMUs) based on those items that fell into each category (as DEA outputs). DEA calculates the relative importance of each item by eliminating the item from the set of items in the category and re-calculation of DEA

efficiencies. The amount of change that eliminating an item could cause in the DEA efficiency scores is regarded as a measure for the item's importance. An unimportant or trivial item is the item that its absence causes no change in DEA efficiencies. The magnitude of change in DEA efficiency scores is quantified by Spearman correlation between efficiency scores before and after eliminating the item. This allows for identification of items with the highest importance (final-level hierarchy).

By now, the structure of AHP for RE assessment is formed. However, the practical application of this AHP for RE assessment requires pair-wise comparisons of its items and factors in different levels of the hierarchy that allows calculation of relative weights of the items and factors. In this study, a consensus-based survey of experts in the field is used for pair-wise scoring. After identification of the AHP hierarchy, the new maintenance resilience factors with their associated important items are demonstrated to a panel of experts and they are asked to express their opinion on the relative pair-wise scoring of factors and items. In the case of conflicting opinions, discussions between experts are triggered and continued until a consensus is achieved. The final outputs of this stage are AHP-based RE scores in the maintenance departments. These scores are indications of the level of the maintenance employees' collective understanding and practical implications of the RE concepts and principles.

At the final step of the proposed approach, the results of AHP-based RE scoring are tested for their validity based on their correlation with the PSFs. Here the rationale for such correlation analysis is that, should a method be an appropriate method for RE assessment, its results then should show significant correlation with other aspects of safety because the ultimate goal of RE is to promote safety. The remaining of this section presents the methodology of the techniques used in the proposed approach.

2.1. *k*-means clustering

k-means clustering is a simple unsupervised learning algorithm to resolve the clustering problems (Naldi and Campello, 2015; MacQueen, 1967). k-means is recently considered as one of the top 10 data mining algorithms due to its simplicity, scalability and easy adaptation to different applications (Wu, 2009). Accordingly, RE questions are categorized by implementing this algorithm through the following stages:

1. Points are selected as the cluster centers, being equal to the number of clusters.
2. Each data set is allocated to a cluster whose center has the shortest distance from it.
3. A mean point as the center is calculated for each cluster.
4. Stages 2 and 3 are repeated until no change occurs in the center of clusters.

The objective function of algorithm is defined as a minimizing function:

$$J = \sum_{i=1}^N \sum_{j=1}^C \|x_i - c_j\|^2 \quad (1)$$

where $\|*\|$ is the measure of distance between points and c_j as the j^{th} cluster center.

2.2. FCM

FCM algorithm developed by Dunn(1973) is also one of the basic clustering techniques, making it possible to allocate data points to two or more clusters (Liyong Zhang et al., 2016). It is used for pattern recognition and clustering tasks. The objective function of algorithm is a minimization function:

$$J = \sum_{i=1}^N \sum_{j=1}^C u_{ij}^m \|x_i - c_j\|^2 \quad (2)$$

where $\|*\|$, m , u_{ij} , and x_i are the measure of distance between points and c_j as the j^{th} cluster center, a real number greater than 1, membership degree of x_i in cluster j , and sample i , respectively. Fuzzy algorithm finds the optimal solution with repetition. u_{ij} and c_j can be rewritten as follows.

$$u_{ij} = \sum_{k=1}^C \left(\frac{\|x_i - c_j\|}{\|x_i - c_k\|} \right)^{\frac{-2}{m-1}} \quad (3)$$

$$c_j = \frac{\sum_{i=1}^N u_{ij}^m x_i}{\sum_{j=1}^N u_{ij}^m} \quad (4)$$

Repetition stops for $\max_{ij} \{|u_{ij}^{k+1} - u_{ij}^k|\} < \varepsilon$, where ε is the end of a number between zero and one.

2.3. DEA

DEA is a quick-and-easy tool to assess the efficiency of DMUs. It distinguishes between efficient and inefficient ones. Managers and decision makers may be able to improve their systems using the results obtained from DEA (Charnes et al., 1978; Zou and Wei, 2009). It is also used to calculate the efficiency score of multiple-input or multiple-output factors (Serrano Cinca et al., 2006). In fact, DEA is a nonparametric approach with linear programming (Azadeh et al., 2014) to assess the relationship between DMUs with multiple inputs and outputs.

Since the items in each category are assessing the quality of resilience from the viewpoint of the concept being carried by that category, all the items are regarded as DEA outputs. In other words, the resiliency score that a department would get from a category is positively related to the

scores it gets from the items in a category. Accordingly, the items in each category are considered as DEA outputs and the DEA model should be constructed without any inputs. Literally, the current study uses an output oriented DEA model with a dummy input to assess each of the new resiliency factors. The objective function of this output oriented model is defined to assess the efficiency of any maintenance departments. The derived DEA model is shown in the Equation set (5).

$$\begin{aligned}
& \text{Max } \theta \\
& \text{s. t. } \sum_{j=1}^n x_{ij} \lambda_j \leq x_{io} \quad , \quad i = 1 \\
& \theta y_{ro} \leq \sum_{j=1}^n y_{rj} \lambda_j \quad , \quad r = 1, \dots, m \\
& \theta \text{ is free and } \lambda_j \geq 0 \text{ for all } j
\end{aligned} \tag{5}$$

where m and n are the number of items per category and the number of DMUs, respectively. $x_{ij} = 1$ and y_{rj} represent the values of dummy input i and output r of the j^{th} DMU, respectively. Also, x_{io} and y_{ro} are the values of input i and output r of the objective DMU, respectively. When an input is a constant value, the model above is used to maximize its output.

2.4. AHP

AHP reflects the natural behavior of human thinking. It solves complex problems by decomposing them into a hierarchy of more easily comprehended sub-problems having decision alternatives at the lowest levels. Multiple-criteria decision analysis can be performed by AHP.

The AHP is normally implemented in four simple consecutive steps.

1. Hierarchical structure development. A decision problem is structured into a hierarchy of dependent factors and items with a goal.
2. Paired comparison. It makes a comparison between different elements in different levels of the hierarchy using the scale developed by Saaty (1987).
3. Weight determination. The weight of any factor and item is measured by the elements of eigenvector as follows:
 - A) The resulting matrix of paired comparisons in step 2 is considered as an input and stored as matrix A .
 - B) Starting from $i=1$, matrix $A^i \times I$ is calculated in which I is a matrix of order $m \times 1$ with m rows or columns.
 - C) Step 2 continues until $A^n \times I - A^{n-1} \times I \leq 10^{-4}$ is satisfied.
4. An integration of the relative weights to calculate the score of decision alternatives. The relative weight of each element should be multiplied by the weight of its higher elements to obtain the final weight.

3. Experiment

The study is conducted among a sample of 99 employees with different responsibilities in 11 maintenance departments of Tehran Gas Company. In developing countries due to lack of sophisticated data gathering systems, questionnaires are usually applied to collect standard data. This study uses a questionnaire containing RE and PSFs to investigate their relationship (Azadeh et al., 2015; Shirali et al., 2013). The designed 108-item questionnaire consists of three parts. Part 1 is assigned to demographic information (gender, age, education level, work experience, and employment status). Part 2 contains 96 questions, demonstrating RE factors in 6 categories of management commitment (1-19), reporting culture (20-34), learning culture (35-58), awareness

(59-73), preparedness (74-88) and flexibility (89-96). Part 3 contains 12 questions, examining the concepts of health (1-4), safety (5-8) and ergonomics (9-12). These questionnaires are distributed among the employees in 11 maintenance departments and finally 99 filled questionnaires are received from the employees. The number of respondents in each department varies between 5 and 11 with average of 9 responds. Respond to each item would be based on a six-point Likert scale (strongly disagree, disagree, slightly disagree, slightly agree, agree, strongly agree).

3.1. Validity and Reliability of the Questionnaire

In order to testing the content validity of questionnaire, the effort is directed to verifying questionnaires and making reference to previous research on the subject by experts. It helps to ensure the inclusion of all significant RE and PSFs in the questionnaire. Regular meeting with all the audience have been held to communicate the concept that each item of the questionnaire is aiming at. After making the necessary arrangements, all employees are asked to accurately fill in the questionnaire and in the case of any confusion or vagueness; the research team were trying to clear up the confusion not only to the respondent who raised it but also to the entire audience.

The reliability of the survey tool is tested by Cronbach's alpha coefficient. This coefficient is calculated for the items under each of the categories mentioned by Hollnagel (2007) including management commitment, reporting culture, learning culture, awareness, preparedness, and flexibility. Table 1 shows the Cronbach's alpha coefficient of RE categories calculated by SPSS software. It can be seen that the reliability of questionnaire items in the first four previous categories can be verified due to Cronbach's alpha coefficient above 0.7. However, this reliability cannot be verified for Preparedness and Flexibility. This suggests that the previous categories of RE items may not be appropriate for assessing resilience in maintenance departments and there is a need for new categories of items to be more consistent and robust for assessing RE in maintenance

departments. The next section introduces the use of clustering techniques to find a new set of verified resilience factors, applicable for RE assessment in maintenance departments.

Table 1: Cronbach's alpha coefficient of RE categories

Category	N of Items	Cronbach's Alpha
Management Commitment	19	0.92
Reporting Culture	15	0.75
Learning Culture	24	0.83
Awareness	15	0.70
Preparedness	15	0.61
Flexibility	8	0.53

3.2. New Resilience Factors by k-means

In this section, using a verified k-means clustering technique, the RE items are clustered into six new categories of concepts. A mean score is calculated for each answer choice to reduce the variability in scoring and increase the accuracy of clustering, which forms a 96×11 matrix (having 96 items, each assessed in 11 maintenance departments). The first question to answer is how many clusters should be considered in the clustering algorithms. Five to nine number of clusters have been examined and among them the value of 6 has been selected, based on the maximum consistency of k-means clustering results with fuzzy c-means clustering results.

Table 2 summarizes the obtained results. The level of similarity or overlapping between two algorithms also is shown in Table 2, suggesting the accuracy of new classes in k-means algorithm.

Table 2: The clustering results and their consistency

Cluster	Number of k-means items	Number of FCM items	Number of overlapping items	Percentage of overlapping
Cluster 1	16	18	14	87.5
Cluster 2	24	16	15	62.5
Cluster 3	20	21	18	90
Cluster 4	13	17	12	92.3
Cluster 5	12	13	12	100
Cluster 6	11	11	11	100

Having a closer and more precise look into the items of each cluster implies that each cluster contains a particular kind of items evoking certain concepts. After discussing with the panel of experts the similarity of the concepts that the items in each cluster are testing for, the following new factors are introduced to be new resilience factors in maintenance departments.

- Factor 1: mutual trust and transparency - employees must give a transparent report on their mistakes with no fear of punishment to improve the work performance and eliminating errors.
- Factor 2: a steady and persistent improvement in adaptive skills - the system requires special adaptations in different situations. In other words, it must be sufficiently flexible to adapt to improbable and unlikely events.
- Factor 3: a steady and persistent improvement in intelligent skills - employees must increase their awareness about safety and its risk factors by not only learning from mistakes or near misses but also from the normal works that usually go right.
- Factor 4: promotion of cooperation - staff and managers must gain valuable experience of not only mistakes but also appropriate actions and share it with others by increasing the amount of cooperation with all departments, especially information exchange.

- Factor 5: clarification of safe work procedures - the system can bring employees under control by offering them greater freedom of choice with an accurate description of work.
- Factor 6: employee empowerment - a steady increase in the knowledge of employees about work procedures and conditions sends employees out feeling more empowered to face serious threats.

3.3. Factors Refinement using DEA

Given the results obtained from k-means clustering, the number of questions is large in some categories. Therefore, a sensitivity analysis is performed by DEA to identify the more important questions. First DEA is run with all the items in a given category as DEA outputs. After eliminating the item under study from the list of DEA outputs, DEA is applied for the reduced list of outputs. The comparison of DEA efficiency scores before and after item elimination provides a basis to construct an importance index for the eliminated question. The rationale here is that if eliminating an item does not cause a significant change in DEA efficiencies, then the item is of little importance. Finally, the level of importance is achieved for each item of the new categories (Figure 2). In each category, items accounting for more than 85% of total computational importance are selected to be included in the AHP. The results of items refinement are presented in Appendix 1. In the next section, they are identified as the third-level criteria to the AHP.

Figure 2: Items relative importance in the new resilience factors

3.4. AHP Construction

Based on the results of both k-means and DEA sensitivity analysis, the analytical hierarchy of RE in maintenance departments is achieved (Figure 3). In this hierarchy, the new resilience factors are forming the second level and the remaining important items after DEA sensitivity analysis are placed in the third level. In our case study, we have 11 maintenance departments whose relative RE assessments are performed according to this hierarchy of criteria. It should be noted that in Figure 3, to avoid tidiness, some connections are not drawn. In fact, there is a connection between every department and all the items in the third level.

Figure 3: The AHP for Resilience of the Maintenance Departments

3.5. AHP Results

Paired comparisons are made between RE factors as well as between items of each factor using the scale developed by Saaty (1987) from 1 (for indifference) to 9 (for extremely preferred). A panel of experts who were contributing in all the stages of the AHP analysis is asked to express their score on paired comparisons. The final score for every paired comparison is achieved when a consensus between conflicting opinions is reached.

Based upon the paired comparison scores, the final relative weights of every factor and its associated items are calculated in Table 3.

Table 3: The results of weight calculation for RE factors and items

Factor	Trust and Transparency		Adaptive Skills		Intelligent Skills		Cooperation		Safe Work Procedures		Employee Empowerment	
Weight	0.16		0.22		0.22		0.18		0.11		0.11	
Items and their weights	Items	Weight	Items	Weight	Items	Weight	Items	Weight	Items	Weight	Items	Weight
	5	0.04	14	0.05	8	0.20	13	0.18	22	0.06	39	0.09
	9	0.14	50	0.02	19	0.05	16	0.14	28	0.17	40	0.09
	10	0.23	51	0.04	29	0.05	27	0.09	47	0.05	49	0.39
	18	0.10	53	0.06	36	0.16	46	0.09	55	0.11	77	0.10
	25	0.12	59	0.02	43	0.09	48	0.07	44	0.20	83	0.06
	32	0.07	66	0.19	45	0.06	57	0.25	90	0.16	88	0.27
	87	0.30	67	0.08	54	0.05	65	0.18	92	0.26		
			72	0.08	56	0.01						
			89	0.14	68	0.05						
			93	0.16	76	0.16						
			94	0.16	85	0.12						

The average scores of respondents in every department multiplied by the weights of items yields a score for each factor. Then, the factor scores multiplied by the factors' weights is calculated for a total RE assessment score (Table 4). The questionnaire items for PSFs assessment in

maintenance departments are presented in Appendix 2. A similar working procedure is followed to achieve the relative weights of PSFs and consequently the total PSFs assessment score in every department. Their final results are presented in the last column of Table 4.

Table 4: The results of AHP-based RE and PSFs assessment

Dep .	Trust and Transparency	Adaptive Skills	Intelligent Skills	Cooperation	Safe Work Procedures	Employee Empowerment	RE	PSFs
1	3.71	3.61	4.19	2.65	2.93	5.02	3.67	3.21
2	4.39	3.80	4.66	3.48	3.28	5.21	4.13	3.25
3	4.53	3.80	4.51	3.75	2.86	5.13	4.11	3.58
4	2.50	2.90	4.04	2.20	2.82	5.35	3.23	2.94
5	4.33	3.85	4.39	3.54	3.19	5.15	4.06	3.35
6	4.62	3.56	4.55	4.00	2.61	4.78	4.06	3.39
7	3.96	3.75	4.22	2.86	2.94	5.15	3.80	3.35
8	4.20	3.74	4.47	3.15	2.72	5.27	3.93	3.53
9	3.91	3.50	4.01	3.16	3.46	5.07	3.78	3.25
10	4.53	4.02	4.56	3.65	3.08	4.88	4.15	3.59
11	4.12	3.84	4.44	3.28	2.38	4.57	3.84	3.38

3.6. The Significance of AHP

In this section, the significance of AHP for total RE assessment in maintenance departments is tested based on the linear relationship between AHP-based RE scores and PSFs scores. First, the correlation coefficient between RE and PSFs scores is calculated. The Pearson correlation index of 81.2% shows a significant association between RE and PSFs. Second, the significance of linear regression between RE and PSFS scores are tested in Figure 4. It is assumed that the scores of RE and PSFS are independent and dependent variables of regression model, respectively. As seen, the estimated value of the regression coefficient is significant for RE. Overall, this significant correlation suggests that the proposed AHP can be considered as an appropriate method for RE

assessment because its results shows significant correlation with other aspects of safety and this is consistent with this underlying idea that the ultimate goal of RE is to promote safety.

Figure 4: The linear regression of PSFs and AHP-based RE scores

The results of regression analysis are further analyzed as follows. First of all, the data point in the left tale of the regression line (3.23, 2.94) seems to be an outlier and if this data point is discarded, the new regression estimation becomes very weak with $R^2=32\%$ but the sign of regression coefficient still remains positive (0.45) which is significant at 90% confidence level and suggests a positive correlation of PSFs with RE. Nonetheless, this data point has been examined further for possibility of being an outlier but there is no sign of being an unusual observation. This data point is related to the maintenance department#4 in our case study and a closer look at some recent incident records in this department prevents us to consider the mentioned data point as an outlier. Some facts are as follow:

- A delay in responding to gas leaks due to the unavailability of gas rings is one of the recent events that have occurred, to a greater extent, in the fourth gas field.

- The unavailability of gas rings and postponed site visits caused a lengthy delay in fighting the fire during three events occurred in the past year.
- There was a long delay in fighting the fire during another event caused by the locked gas rings in this field.
- In cold months, deep freeze due to high consumption and impurities in gas delivery networks also resulted in some gas cut-offs in the field that department #4 was responsible for. The cut-offs could have been prevented by timely replacement of filters.

It is also noted that the value of 66% for R^2 is not very high and only 66% of variation in PSFs is explained by the variation in RE scores. However, this regression model is significant at 99% confidence level. Table 5 presents the analysis of variance (ANOVA) for the regression model performed in Minitab. Moreover, the coefficient of RE in this model is significant at 99% confidence level.

Table 5: ANOVA test for the regression model

Source	DF	Sum of Squares	Mean Squares	F	P-value
Regression	1	0.231532	0.231532	17.15	0.003
Error	9	0.121486	0.013498		
Total	10	0.353018			

Finally, it should be noted that the main purpose of the regression analysis presented here is to show the positive and significant correlation between RE and performance shaping factors (PSFs). It can be seen in Figure 4 that there are some data points far from the regression line on the right side of Figure 4. Nevertheless, the linearity of the relation between RE and PSFs is not of vital importance here and what really matters is the fact that there is a significant positive correlation

between these two variables. It suggests that in those departments with a lower RE score, the level of PSFs is also low, and in those departments with a high RE score, the level of PSFs is also high.

5. Conclusions

RE is a new total approach to safety that its proper implementation in complex socio-technical systems can improve safety. The aim of the study was to devise a verified tool for the assessment of RE in maintenance organizations. The study also confirmed the close relationship between RE and human related PSFs, suggesting that services to promote resilience engineering will lead PSFs to be in a good condition so as human error can be reduced and safety can be improved. In the present study, a standard questionnaire containing RE and maintenance related PSFs was used to collect data from employees in 11 maintenance departments of a large public gas company. Although the initial questionnaire was designed based on standard items that have previously been used in the literature for RE assessment; however, this questionnaire needed to be customized in order to be efficiently used for RE assessment in maintenance organizations. To do so, RE questions were clustered into new factors using the k-means clustering. Furthermore, the large number of items describing some of the new RE factors made it necessary to perform a complete sensitivity analysis using DEA to identify the most important items of any factor. Finally, AHP was used to find the relative weights of RE factors and items. The designed AHP enabled calculation of total RE scores for every maintenance department. The proposed AHP of this paper exhibits new and unique features which make it more preferable for RE assessment in maintenance organization (Table 5).

Table 6: The unique features of the proposed AHP versus previous studies

Features↓ Studies→	This study	Azadeh et al.(2015)	Azadeh et al.(2015)	Heerera et al.(2011)	Azadeh et al.(2013)	Shirali et al.(2013)	Azadeh et al.(2014)
Validated AHP model	✓						
Identification of important items	✓						
Clustering on resilience data	✓			✓			
Questionnaire based assessment	✓	✓	✓	✓	✓	✓	✓
Identification of resilience factors in maintenance departments	✓						
RE and PSFs correlation analysis	✓	✓					

References

1. Azadeh, A., Alizadeh Bonab, N., Salehi, V., Zarrin, M. (2015). A unique algorithm for the assessment and improvement of job satisfaction by resilience engineering: Hazardous labs. *International Journal of Industrial Ergonomics*, 49 (2015) 68-77.
2. Azadeh, A., Ghaderi, S. F., Anvari, M., Izadbakhsh, H. R., Rezaee, M. J., & Raoofi, Z. (2013a). An integrated decision support system for performance assessment and optimization of decision-making units. *The International Journal of Advanced Manufacturing Technology*, 66(5-8), 1031-1045.
3. Azadeh, A., Haghighi, S.M., Salehi, V. (2015), Identification of Managerial Shaping Factors in a Petrochemical Plant by Resilience Engineering and Data Envelopment Analysis. *Journal of Loss Prevention in the Process Industries*, 36 (2015): 158-166.
4. Azadeh, A., Rouzbahman, M., Saberi, M., Fam, I.M., (2011). An adaptive neural network algorithm for assessment and improvement of job satisfaction with respect to HSE and ergonomics program: the case of a gas refinery. *Journal of Loss Prevention in the Process Industries*, 24 (4), 361-370.
5. Azadeh, A., Salehi, V. (2014). Modeling and Optimizing Efficiency Gap between Managers and Operators in Integrated Resilient Systems: The Case of a Petrochemical Plant. *Process Safety and Environmental Protection* , In press.
6. Azadeh, A., Salehi, V., Arvan, M., & Dolatkah, M. (2014). Assessment of resilience engineering factors in high-risk environments by fuzzy cognitive maps: A petrochemical plant. *Safety Science*, 68, 99-107.

7. Azadeh, A., Salehi, V., Ashjari, B., & Saberi, M. (2014). Performance evaluation of integrated resilience engineering factors by data envelopment analysis: The case of a petrochemical plant. *Process Safety and Environmental Protection* , 92(3), 231-241.
8. American Society of Mechanical Engineers (ASME). Innovative Technological Institute (ITI). Washington, D.C.: ASME ITI, LLC; 2009.
9. Ayoub, M. A. (1990). Ergonomic deficiencies: I. Pain at work. *Journal of Occupational and Environmental Medicine*, 32(1), 52-57.
10. Blanchard, B.S., Fabrycky, W.J. (1990). *Systems Engineering and Analysis*. Prentice Hall Englewood Cliffs, New Jersey.
11. Burri, G.J., Helander, M.G. (1991). A field study of productivity improvements in the manufacturing of circuit boards. *International Journal of Industrial Ergonomics*, 7 (3), 207e215.
12. Cabrero-Canosa, M., Castro-Pereiro, M., Grana-Ramos, M., Hernández-Pereira, E., Moret-Bonillo, V., Martin-Egana, M., & Vereas-Hernando, H. (2003). An intelligent system for the detection and interpretation of sleep apneas. *Expert Systems with Applications*, 24(4), 335-349.
13. Caldwell, N.H., Breton, B.C., Holburn, D.M. (1998). Remote instrument diagnosis on the Internet. *IEEE Intelligent Systems*, 13 (3), 70-76.
14. Carvalho, P. V., dos Santos, I. L., Gomes, J. O., Borges, M. R. (2008). Micro incident analysis framework to assess safety and resilience in the operation of safe critical systems: a case study in a nuclear power plant. *Journal of Loss Prevention in the Process Industries*, 21(3), 277-286.

15. Charnes, A., Cooper, W. W., Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research* , 2(6), 429-444.
16. Costella, M. F., Saurin, T. A., & de Macedo Guimarães, L. B. (2009). A method for assessing health and safety management systems from the resilience engineering perspective. *Safety Science*, 47(8), 1056-1067.
17. Dekker, S., Dahlstrom, N., Winsen, R. V., Nyce, J.M. (2008). Crew resilience and simulator training in aviation. Book Chapter, In: *Resilience Engineering Perspectives: remaining sensitive to the possibility of failure*, Editor: Hollnagel, Nemeth and Dekker, United Kingdom: Ashgate, pp. 119-125.
18. Dinh, L. T., Pasman, H., Gao, X., Mannan, M. S. (2012). Resilience engineering of industrial processes: Principles and contributing factors. *Journal of Loss Prevention in the Process Industries* , 25(2), 233-241.
19. Dunn J. C. (1973) A Fuzzy Relative of the ISODATA Process and Its Use in Detecting Compact Well-Separated Clusters. *Journal of Cybernetics*, 3, 32-57.
20. Jeffcott, S. A., Ibrahim, J. E., Cameron, P. A. (2009). Resilience in healthcare and clinical handover. *Quality and Safety in Health Care* , 18(4), 256-260.
21. Herrera, I. A., Hollnagel, E., Håbrekke, S. (2011). Proposing safety performance indicators for helicopter offshore on the Norwegian Continental Shelf. In *PSAM 10-Tenth Conference on Probabilistic Safety Assessment and Management*, 10.
22. Hollnagel, E., Woods, D. D., Leveson, N. (Eds.). (2007). *Resilience Engineering: Concepts and Precepts* . Ashgate Publishing, Ltd.
23. Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering & System Safety*, 145, 47-61.

24. Dinh, L. T., Pasman, H., Gao, X., Mannan, M. S. (2012). Resilience engineering of industrial processes: principles and contributing factors. *Journal of Loss Prevention in the Process Industries*, 25(2), 233-241.
25. Kumar, V., & Wu, X. (Eds.). (2009). *The top ten algorithms in data mining*. CRC Press.
26. MacQueen, J. B. (1967) Some Methods for classification and Analysis of Multivariate Observations, *Proceedings of 5-th Berkeley Symposium on Mathematical Statistics and Probability*, Berkeley, University of California Press, 1, 281-97.
27. Naldi, M. C., Campello, R. J. (2015). Comparison of distributed evolutionary k-means clustering algorithms. *Neurocomputing*, 163, 78-93.
28. Saaty, R.W. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical Modeling*, 9 (3), 161-176.
29. Saurin, T. A., Júnior, G. C. C. (2011). Evaluation and improvement of a method for assessing HSMS from the resilience engineering perspective: a case study of an electricity distributor. *Safety Science*, 49(2), 355-368.
30. Saurin, T. A., Wachs, P., Henriqson, É. (2013). RETRACTED: Identification of non-technical skills from the resilience engineering perspective: A case study of an electricity distributor. *Safety science*, 51(1), 37-48.
31. Saurin, T. A., Wachs, P., Righi, A. W., & Henriqson, E. (2014). The design of scenario-based training from the resilience engineering perspective: A study with grid electricians. *Accident Analysis & Prevention*, 68, 30-41.
32. Serrano Cinca, C., Mar Molinero, C., & Chaparro García, F. (2006). Behind DEA efficiency in financial institutions.

33. Sheffi, Y. (2005). The resilient enterprise: overcoming vulnerability for competitive advantage. MIT Press Books, 1.
34. Shikdar, A. A., Sawaged, N. M. (2004). Ergonomics, and occupational health and safety in the oil industry: a managers' response. *Computers & Industrial Engineering*, 47(2), 223-232.
35. Shirali, G. H. A., Motamedzade, M., Mohammadfam, I., Ebrahimipour, V., Moghimbeigi, A. (2012). Challenges in building resilience engineering (RE) and adaptive capacity: A field study in a chemical plant. *Process safety and environmental protection*, 90(2), 83-90.
36. Shirali, G. A., Mohammadfam, I., Ebrahimipour, V. (2013). A new method for quantitative assessment of resilience engineering by PCA and NT approach: A case study in a process industry. *Reliability Engineering and System Safety*, 119, 88-94
37. Vugrin, E. D., Warren, D. E., Ehlen, M. A. (2011). A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. *Process Safety Progress*, 30(3), 280-290.
38. Wreathall, J. (2006). Properties of resilient organizations: an initial view. *Resilience engineering concepts and precepts*. In: Hollnagel, E., Woods, D., Leveson, N. (Eds.), *Resilience Engineering: Concepts and Precepts*. Ashgate, Aldershot, UK, pp. 275–286
39. Zhang, L., Lu, W., Liu, X., Pedrycz, W., Zhong, C. (2016). Fuzzy C-Means clustering of incomplete data based on probabilistic information granules of missing values. *Knowledge-Based Systems*, 99, 51-70.
40. Zou, L. L., & Wei, Y. M. (2009). Impact assessment using DEA of coastal hazards on social economy in Southeast Asia. *Natural Hazards*, 48(2), 167-189.

Appendix 1: The final factors and items for RE assessment in maintenance departments

New Resilience Factor	Item #	Item Description
Mutual Trust and Transparency	5	How to express appreciation of subordinates is extremely important.
	9	When I conduct successful campaigns to tackle problems threatening health and safety in an arbitrary way, my superior appreciates me.
	10	My superior is always aware of all crises and risks threatening his work environment.
	18	My manager has necessary knowledge and expertise to control my work.
	25	It is easy to give superior a report on workplace safety events.
	32	There is high motivation for working together in my work environment.
	87	In our organization, safety is always considered as an important issue and discussed in top-level management.
Improvement in Adaptive Skills	14	My manager develops a variety of training programs to improve the safety of maintenance and repair operations, but he does not put emphasis on their implementation.
	50	I think that my colleagues make active attempt to create a learning culture.
	51	Training programs developed by our organization are good to behave safely.
	53	I have received any necessary training to carry out my work well and safely.
	59	I notice my superior's behavior change every day.
	66	If there is any contradiction between safety and maintenance and repair operations, organization gives top priority to safety.
	67	I usually have enough time to carry out my work well.
	72	It is practical and simple to follow instruction set in urgent cases provoking a rapid reaction.
	89	I have an immediate access to alternate resources such as facilities, time, etc. to deal with improbable and unlikely events.
	93	In our organization, there are necessary equipment and effective methods to respond to sudden changes.
	94	I work in an organization which is capable of adapting to stressful situations arising from internal and external pressures.
Improvement in Intelligent Skills	8	When the safety of maintenance and repair operations is threatened by a factor, I am able to counter any possible threat.
	19	My manager has enough time to monitor my activities.
	29	Right decisions on workplace safety events need to be made in close cooperation with each other.
	36	I have enough time to think about my business plans.
	43	Intra-organizational discussions about risk or safety result in preventive measures against workplace safety events.
	45	There is a direct association between the level of reporting and the received training and learning programs.
	54	I am capable of finding a way to gain valuable experience of my mistakes at work.
	56	Manuals are not to use but to provide clear guidance.
	68	Health and safety performance is deeply influenced by organization's budget.
	76	I have the ability to carry out my work well under unpredictable conditions.
Promotion of	85	Improbable and unlikely events often occur in my workplace.
	13	Our organization provides necessary equipment and resources to maintain health and safety performance at a high level.

Cooperation	16	After occurring adverse events, the first priority in management is not to put the blame on somebody but to find and remove major obstacles.
	27	Employees may have a profound effect on the decisions of their superior in my work environment.
	46	Our organization spends the vast amounts of money on training and learning programs.
	48	Within our dominant organizational culture, the entire system is responsible for errors and mistakes, not certain people
	57	Safety guidelines and procedures are regularly updated in my workplace
	65	Our organization gives any details about what to be carried out.
Clarification of Safe Work Procedures	22	After receiving a report on workplace safety events, my superior blames and punishes offenders in my work environment
	28	When employees feel that some work has a negative effect on safety, they are free to avoid it.
	47	In our organization, people take responsibility for making their mistakes.
	55	The information in the instruction manual is already out-of-date and not useful to work safely.
	44	I have to carry out my work even if I have low awareness about it.
	90	the permission of superior is essential to make a decision in a critical condition.
Employee Empowerment	92	Maintenance and repair operations take shorter time than expected to be carried out in our organization.
	39	Faults must be analyzed carefully and their causes must be explained to others to gain valuable experience of them.
	40	When an error or a mistake having a negative effect on the performance of health and safety in the system is repeated, a special group of top managers is formed to discuss its details.
	49	We are sure that an event would not occur in the future if it has not occurred in the past.
	77	In urgent cases, the entire system attempt to eliminate any risk that may exist.
	83	It is necessary for employees to receive a substantial reward for anticipating future problems and risks.
	88	Health and safety programs necessitate providing background and complementary information to counter any possible threat in the near future.

Appendix 2: The questionnaire items for PSFs assessment in maintenance departments

Item #	Item Description
1	There is reasonable time to rest during a shift.
2	We suffer from significant pollution at work.
3	Our organization has achieved the employee health-related international standards
4	There is awful sound or smell in my workplace.
5	I am eager to increase my knowledge about new technology and software in the field of my work.
6	Our organization provides the perfect opportunity for employees' familiarity with work-related technology and software.
7	Safety equipment usage is an absolute necessity in my workplace.
8	Our organization constantly upgrades safety equipment.
9	I have access to special tools to carry out technical work.
10	Seat height is proportional to the height of my desk at work.
11	There is sufficient space to refresh by walking.
12	There is a good light to perform tasks in my work environment.