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The Use of Fuzzy Analytic Hierarchy Process (Fuzzy AHP) for Inspection Mechanisms Selection Towards Automated Inspection System Development: A Case Study

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Abstract: This paper presents an application of Fuzzy Analytic Hierarchy Process (Fuzzy AHP) method for inspection mechanisms selection towards automated inspection system development. A case study from the adhesive tape-based manufacturing industry was used to show the applicability of the method. The Fuzzy AHP method applied in this paper consists of four steps; hierarchy structure development, criteria weighting, alternative weighting and final score of the alternative. The four criteria (cost, reliability, durability and minimal lagging) and three alternatives (pressure strips, profiling pressure and image) are firstly defined in the development of the hierarchy structure. Based on the evaluation process of criteria and alternative weighting, the final score of each alternative is obtained. The final result shows that the alternative of the image gives the highest score at 0.706, followed by profiling pressure and pressure strips at 0.645 and 0.081, respectively. Therefore, the alternative of the image is highly recommended to be used as the inspection mechanism for automated inspection system development.

Keywords: Fuzzy AHP, inspection mechanism, case study

1. Introduction

In project management, selecting the best option with multiple criteria consideration is a crucial decision-making process to optimise the benefits of the project. Scientifically, this decision-making process can be classified as a multi-criteria decision-making (MCDM) structure. In other words, the decision-making process is carried out in a systematic way by considering multiple criteria towards selecting the best alternative. Thus, guide high reliability of decision to be recommended.

In the literature, several methods are introduced and applied to solve varieties of MCDM problems (Aruldoss, Lakshmi & Venkatesan, 2013). One of them is the fuzzy analytic hierarchy process (fuzzy AHP) method. The fuzzy AHP is an expanded version of a classical AHP method (Saaty, 1980) by considering the fuzzy environments. Under this method, the evaluation process of criteria and alternative weighting is carried out based on pre-defined fuzzy linguistic values (Petkovic, 2012). In other words, the integration of the fuzzy computational process into the AHP method considers the uncertainty of expert judgment during scale criteria value selection, thus providing a better evaluation process of criteria.

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Some recent studies related to the application of Fuzzy AHP are as follows. Natasa & Prascevic (2017) solved a ranking and selection problem of project status in construction project management using the fuzzy AHP method. Jain et al. (2018) applied Fuzzy AHP to solve a supplier selection problem in the Indian automotive industry. Mondragon et al. (2019) compared the results between AHP and Fuzzy AHP applications to solve the problem of technology and supplier selection in the textile industry. Averill (2020) discussed the usefulness of the Fuzzy AHP application in the material finishing industry. The study intends to select the best solvent for cleaning equipment to be used in oxygen service and for cleaning metal parts prior to further finishing treatment. Kazimieras Zavadskas et al. (2020) presented the optimal supplier selection problem by applying fuzzy AHP method. Their study considered five suppliers and nine pre-defined criteria to be evaluated using the method. Banadkouki & Lotfi (2021) combined the application of Fuzzy AHP and Fuzzy TOPSIS to solve a selection problem of computer-integrated manufacturing (CIM) technologies. Their study found that computer-aided process planning is the best CIM technology. Jasiulewicz-Kaczmarek et al. (2021) combined multiple applications of MCDM methods, including fuzzy AHP, to evaluate maintenance factors affecting sustainable manufacturing practice. Ten related factors of maintenance practice were taken into account in their study. Bakir & Atalik (2021) applied fuzzy AHP and fuzzy Marcos approach to evaluate the quality of e-service in the airline industry from a customer perspective. Dastorani (2022) presented a desertification assessment in the Sabzevar area in Iran based on fuzzy AHP application method. The results from this assessment significantly contribute to the sustainable development program, thus being able to avoiding severe desertification effects issue. These literature studies found that the application of fuzzy AHP is extensive for many different scopes of problems and industries. However, as far as authors' are concerned, the application of fuzzy AHP related to design problem is currently limited.

Therefore, this paper presents a research project applying the fuzzy AHP method to solve a related design problem. Specifically, a problem of inspection mechanisms selection towards automatic inspection system development is focused of the presented paper.

This paper is organised as follows. Section 2 presents the case study overview, where a precise and concise background of the case study company and the related motivations are given. Section 3 describes the step-by-step procedure of fuzzy AHP application. In Section 4, the results and discussion is presented according to the fuzzy AHP procedure described in the previous section. This paper ended with conclusions and some related future works are then included.

2. Case Study Overview

The case study presented in this research project is carried out in a manufacturing area located in Penang, Malaysia. The company is an adhesive tape-based manufacturing industry that produces various adhesive tapes for domestic and industrial applications. Fig. 1 illustrates the entire process of adhesive tape production in the company.

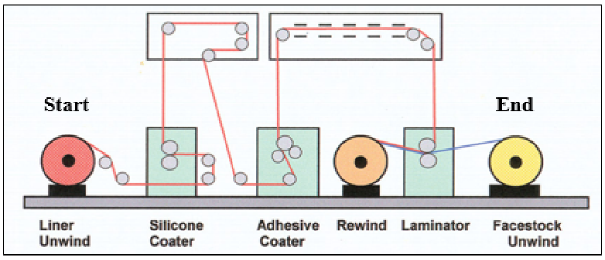

Fig. 1 - Adhesive tapes production processes

The case study is focused on the lamination process due to the high defects that occurred during this process. The initial defects analysis reveals that the bubble trap, poor bonding and adhesive picking are the three major defects that contribute to 88% of overall defects in this process. The root cause analysis found that these three defects have shared the exact root cause, which is due to the misalignment of the nip rollers of the lamination machine.

These findings align with the current practice of the machine operators at this workstation (lamination process), where the adjustment on the right/left bolts of nip rollers is carried out manually by the operator when the defects occur (see Fig. 2). From a strategic point of view, this current practice is classified as a reactive strategy, where the problem is solved after it happens. Consequently, the company has received many customer complaints due to these defects. This directly creates an unhealthy business condition, where the company have to do many rework process and pay for the delay of the product delivery to the customers.

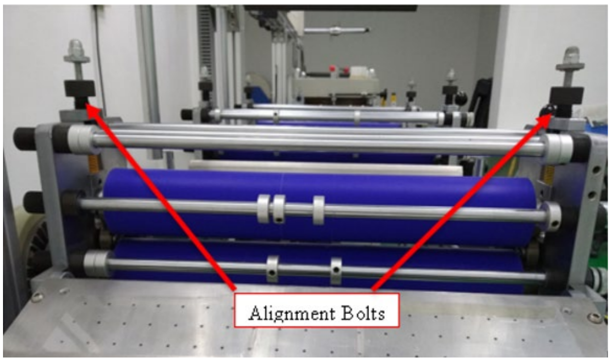

Fig. 2 - Alignment bolts of nip rollers

Since this problem is continued to occur for a few years without an effective and sustainable solution, the top management of the company looks for a better solution. The company aims to adopt an automated inspection system for the lamination machine. This automated system should be able to monitor and inspect the lamination process continuously; thus the mentioned defects problem can be avoided or at least significantly reduced.

This improvement project is then called the development of an automated inspection system (AIS). The company intends to develop this system using its resources and expertise to reduce development costs. However, they allowed a strategic collaboration with high education institutions to systematically and scientifically guide the AIS development process. Therefore, a team that consists of the company's workers and researchers from Penang Skills Development Centre (PSDC) and Universiti Malaysia Perlis (UniMAP) have been formed.

One of the essential processes toward AIS development is to select the inspection mechanism. Thus, it will ensure the final AIS will work at optimal effectiveness and efficiency levels.

The project team have finalised the four key criteria for the selection of inspection mechanism there are cost, reliability, durability and minimal lagging. The precise and concise descriptions for each of these criteria are given in Table 1.

Table 1 - Criteria descriptions

Criteria	Description
Cost (C)	Refer to the cost of related devices (hardware) and software development to ensure the mechanism is functioning as intended. It also includes the expected cost of maintenance.
Reliability (R)	The ability of the mechanism to support the AIS to function without failure (no defect escapee scenario).
Durability (D)	The ability of the mechanism to support the AIS to function continuously (long time) with consistent performance of defect identification. Also, without requiring frequent adjustment or setup due to physical misalignment issues (e.g. vibration effects of the adhesive production process).
Minimal lagging (ML)	The ability of the mechanism to support the AIS to operate without stopping or slowing down the production process.

In this paper, these four criteria are further used as the evaluation criteria for the AIS mechanism selection process. The development of the AIS is continued with the application of Fuzzy AHP to identify the optimal mechanism of AIS systematically.

3. Fuzzy AHP Procedure

In this study, the Fuzzy AHP was applied based on the steps as shown in Figure 3. The detailed descriptions of the steps are presented in Musman & Ahmad (2018).

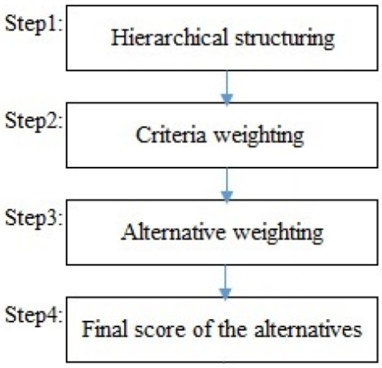

Fig. 3 - Fuzzy AHP procedure [8]

The summary of the fuzzy AHP procedure is as follows. The first step is the development of the hierarchy structure of the problem. Basically, the hierarchy structure consists of three elements. The first element is the problem statement. In this study, the problem is to identify the optimal AIS mechanism. The problem statement is stated in the top box of the hierarchy structure. The second element is the predefined criteria. As mentioned in Section 2, four criteria were considered; cost, reliability, durability and minimal lagging. The final element is alternatives. It refers to the options to be evaluated with respect to the predefined criteria, where it should be more than one option. The overall hierarchy structure of the problem is then illustrated.

The second step is criteria weighting, which is carried out based on a pairwise comparison matrix. The generic version of the pairwise comparison matrix is given in equation 1. The $(\tilde{d}_{ij}^{k})$, indicates the kth evaluator's preference of ith criteria over jth criteria, via fuzzy triangular numbers. Example, $(\tilde{d}_{12}^{1})$ $d12$ = (2, 3, 4). If there is more than one evaluator, the preferences of each evaluator $(\tilde{d}_{ij}^{k})$ are averaged.

$$\tilde{A}^k = \begin{bmatrix} \tilde{d}_{11}^k & \dots & \tilde{d}_{1n}^k \\ \dots & \dots & \dots \\ \tilde{d}_{n1}^k & \dots & \tilde{d}_{nm}^k \end{bmatrix} \qquad (1)$$

In this study, criteria weighting uses linguistic terms that correspond to triangular fuzzy numbers as given in Table 2 (Buckley, 1987). It is used to determine the relative importance weights for both the criteria and the alternatives.

Table 2 - Linguistic terms and the triangular fuzzy numbers (Buckley, 1987)

Scale	Definition	Fuzzy Triangle Score
1	Equal (E)	(1,1,1)
3	Moderate (M)	(2,3,4)
5	Strong (S)	(4,3,6)
7	Very Strong (VS)	(6,7,8)
9	Extremely Very Strong (EVS)	(9,9,9)
2	Intermediate Value Between 2 Scales	(1,2,3)
4		(3,4,5)
6		(5,6,7)
8		(7,8,9)

Under this step (Step 2), four specific criteria evaluations are carried out. The geometric fuzzy comparison values ($\tilde{r}_i$) are first determined. Based on Buckley [9], geometric fuzzy comparison values for each criterion is calculated using equation 2. Next, the fuzzy weight of a single criterion ($\tilde{w}_i$) is found by using equation 3 (Petkovic, 2012) [3], where *l*, *m* and *u* represent the triangular fuzzy numbers.

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{d}_{ij} \right)^{1/n}, i = 1,2,...,n \qquad (2)$$

$$\tilde{w}_i = \tilde{r}_i (*)(\tilde{r}_1 + \tilde{r}_2 + ... + \tilde{r}_n)^{-1}$$
$$= (lw_i, mw_i, uw_i) \qquad (3)$$

The relative non-fuzzy weight of the selected criterion (M_i) is calculated by taking the average of fuzzy numbers for each criterion as given in equation 4. Finally, by using non fuzzy weight of the criterion, the normalised weights of each criterion are calculated using equation 5 (Mondragon, Mastrocinque & Hogg, 2019).

$$M_i = \frac{lw_i, mw_i, uw_i}{3} \qquad (4)$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \qquad (5)$$

In the third step (alternative weighting), the same evaluation process presented in Step 2 is applied. Normalised non-fuzzy relative weights (N_i) of each alternative for each criterion are averaged and an individual score of each alternative is obtained. Finally in Step 4, the final score of all alternatives is summarised. The alternative with the highest score is highly recommended as the optimal selection.

4. Results and Discussion

This section presents the results and discussion of the application of Fuzzy AHP in the case study described in Section 2. Fig. 4 shows the hierarchical structure of the problem under study. The top-level of the hierarchy structure is stated as optimal AIS mechanism identification. The second level of the hierarchy structure is connected with the four mentioned criteria. There are three alternatives that are taken into account to be selected; pressure strip-based inspection, profiling pressure film-based inspection and image-based inspection.

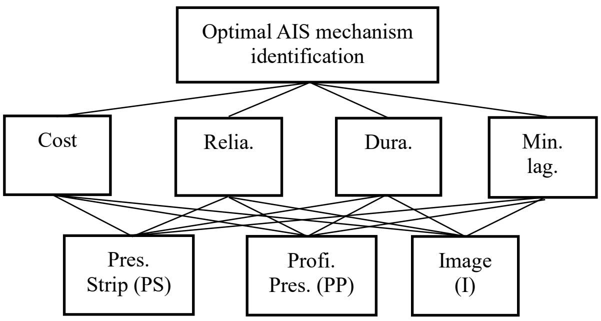

Fig. 4 - Hierarchy structure of the problem under study

The descriptions of each alternative are explained as follows. Alternative 1 is Pressure Strip (PS)-based inspection, which it requires the pressure strips to be run into nip rollers, as shown in Fig. 5. The pressure at fixed points of the nip roller is measured digitally. Alignment of the nip roller is performed by referencing the pressure readings obtained at points.

Table 3 - Criteria weighting evaluation

<<< More important					**Equally important**		**Less important >>>**			
M	**S**	**VS**	**EVS**	**Criteria**	**E**	**Criteria**	**M**	**S**	**VS**	**EVS**
(2,3,4)	(4,5,6)	(6,7,8)	(9,9,9)		(1,1,1)		(2,3,4)	(4,5,6)	(6,7,8)	(9,9,9)
				R	√	C				
		√		R		D				
				R	√	ML				
		√		C		D				
				C		ML		√		
				D		ML			√	

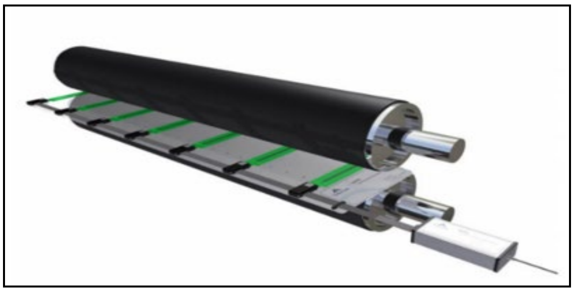

Fig. 5 - Pressure strip application

Alternative 2 is Profiling Pressure (PP) film-based inspection, which applies dual pressure films run into nip rollers as shown in Fig. 6. The pressure at dual points of the nip roller is profiled digitally. The profile facilitates the alignment of the nip roller on both ends of the nip roller.

Fig. 6 - Profiling pressure film application

Alternative 3 is an Image (I) -based inspection system, which incorporates the application of computer software and a camera to detect defects. The non-consistent surface pattern can be used as a guide for the alignment of nip rollers. Fig. 7 shows an example of an image when misalignment occurs.

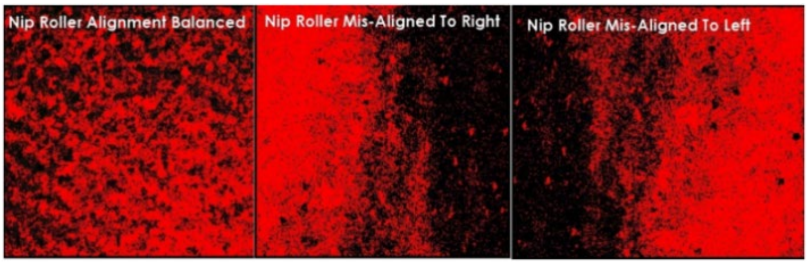

Fig. 7 - Example of image-based application

Based on the Fuzzy AHP procedure described in Section 3, the input data of criteria weighting is obtained collectively from team members (refers as evaluators) based on the format given in Table 3. It is carried out based on the collective preferences of the project team. Numbers of brainstorming sessions among project group members were performed to finalize the preferences (Table 3). The result of these collective preferences is then presented as the averaged pairwise comparison of the criteria is given in Table 4.

Table 4 - Pairwise comparison of the criteria

Criteria	C	R	D	ML
C	(1,1,1)	(1,1,1)	(6,7,8)	(1/4,1/5, 1/6)
R	(1,1,1)	(1,1,1)	(6,7,8)	(1,1,1)
D	(1/6,1/7, 1/8)	(1/6,1/7, 1/8)	(1,1,1)	(1/6,1/7, 1/8)
ML	(4,5,6)	(1,1,1)	(6,7,8)	(1,1,1)

Table 5 - Geometric means of fuzzy comparison value

Criteria	Triangular fuzzy numbers		
C	0.71	0.67	0.64
R	2.45	2.65	2.83
D	0.64	0.61	0.59
ML	2.21	2.43	2.63
Total	6.01	6.36	6.69
Total^{-1}	0.17	0.16	0.15
Increase Order	0.15	0.16	0.17

The geometric means of fuzzy comparison values of all criteria are shown in Table 5. In addition, the total values and the reverse values are also presented in the last row of Table 5; since the fuzzy triangular number should be in increasing order, the order of the numbers is changed into increasing order. Based on Table 6, fuzzy weight is calculated for each criterion. The mean (M_i) is calculated by taking the average of fuzzy numbers for each criterion and tabulated.

Table 6 - Averaged and normalised relative weight of criteria

Criteria	w_i			Mean (M_i)	Normalize (N_i)
C	0.11	0.11	0.11	0.11	0.11
R	0.37	0.42	0.48	0.42	0.42
D	0.10	0.10	0.10	0.10	0.10
ML	0.33	0.39	0.45	0.39	0.38

Following this, the normalised non-fuzzy relative weights (N_i) for criteria are calculated. The alternatives should be pairwise compared with respect to each criterion particularly. Thus, the analysis is repeated 3 more times for each criterion. Table 7 shows an example of an alternative weighing comparison according to cost, *C* criteria. Similar to criterion calculation methodology, the geometric means of fuzzy comparison values and relative fuzzy weights of alternatives for each criterion are calculated.

Table 7 - Alternative weighting comparison according to cost, *C* criteria

<<< More important					Equally important		Less important >>>			
M (2,3,4)	**S** (4,5,6)	**VS** (6,7,8)	**EVS** (9,9,9)	**Alternative**	**E** (1,1,1)	**Alternative**	**M** (2,3,4)	**S** (4,5,6)	**VS** (6,7,8)	**EVS** (9,9,9)
		√		I		PP				
				PP		PS		√		
				PS		I	√			

Table 8 shows the overall summary of the normalised (N_i) values of each alternative according to criteria. The normalised (N_i) values for alternative image (*I*), profiling pressure (*PP*) and pressure strips (*PS*) are calculated as 0.706, 0.645 and 0.081, respectively. Therefore, this result highly recommended that the alternative image (*I*) is the optimal inspection mechanism that can be used for AIS development.

Table 8 - Normalised (N_i) of each alternative according to each criterion

Criteria		**Alternatives (N_i) Score with Respect to Criterion**		
	Weights	**I**	**PP**	**PS**
C	0.11	0.65	0.07	0.28
R	0.42	0.63	0.30	0.06
D	0.10	0.75	0.18	0.06
ML	0.38	0.79	0.15	0.05
Total		**0.706**	**0.645**	**0.081**
Ranking		**1**	**2**	**3**

5. Conclusion

The application of fuzzy AHP method to solve an inspection mechanism selection problem is presented. This selection problem is structured of four predefined criteria and three alternatives. The method is applied based on four steps; hierarchy structure development, criteria weighting, alternative weighting and the final score of the alternative. The final evaluation result revealed that the alternative of the image gives the highest score at 0.706, thus recommending to the project team to select this alternative as the inspection mechanism for AIS development.

Based on the finding of the presented research work, three main future works are planned. First, design and develop the functionality flow of AIS based on the image mechanism. Second, acquire the related hardware devices and develop the related programming algorithms to support the efficiency and effectiveness of the AIS. Third, final AIS prototype development, including their validation process.

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