APPLICATION OF FUZZY AHP AND TOPSIS APPROACH FOR MULTI-OBJECTIVE SCHEDULING PROBLEMS IN ROBOTIC FLEXIBLE ASSEMBLY CELLS

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Abstract: *This study describes the application of the developed approach to the scheduling of the Robotic Flexible Assembly Cells (RFACs). The present study is a continuation of the paper titled “development of fuzzy AHP and TOPSIS approach for multi-objective scheduling problems in robotic flexible assembly cells”. In this paper, a realistic case study of RFACs is presented to examined and verified the developed approach via implement three phases: problem description; application of FAHP-FTOPSIS; and analysis of the results. The analysis showed the stability of the results for FAHP-FTOPSIS and also verified the robustness and the appropriateness of the proposed approach. This study also demonstrated that the proposed approach can be successfully used in the multi-objective optimisation of dynamic scheduling in RFAC.*

Key words: *Fuzzy AHP, Fuzzy TOPSIS, Scheduling, Robotics, Assembly cells*

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1. Introduction

Robotic flexible assembly cells (RFACs) are highly modern systems, structured with industrial robot(s), assembly stations and an automated material handling system, all monitored by computer numerical control [1, 2]. RFACs are capable of assembling a large variety of products in small to medium batch sizes [3]. The design of RFACs with multi-robots has two key advantages for industrial companies [4-7]. The first advantage is the assembly process needs robots with different characteristics such as end effectors, payload, repeatability, degrees of freedom and accuracy. The second advantage is employing end effectors as fixtures to allow reduction of complex orienting, because the assembly processes of products could require more than one direction of part insertion. With these advantages, employing multi-robots in the assembly cells obviously allows for increasing flexibility and reconfiguration capacity [8]. Nevertheless, the main problem of the RFACs is that more than one robot operating simultaneously in the same workplace needs a complex scheduling and control system to prevent collisions between them [9-11].

Recently, an intelligent approach for scheduling RFACs in a dynamic situation was developed [12]. In this approach, the simulation modelling was integrated with Taguchi optimisation method to study the influence of the scheduling factors on the performance of RFACs. Although the proposed approach is designed to deal with dynamic scheduling in RFACs, it is restricted to solving single-objective optimisation problems.

Therefore, the aim of this paper is to demonstrate the application of the proposed approach to a comprehensive decision problem for multi-objective optimisation of dynamic scheduling problems in RFACs. In order to achieve the stated aim, the following two steps have to be performed sequentially: Implement the proposed approach using fuzzy AHP-fuzzy TOPSIS (FAHP-FTOPSIS). Perform a sensitivity analysis and confirmation test to verify and validate the results obtained.

2. Case Study

The objective of this case study is to examine the robustness of the approach presented in previous paper. Three independent objective functions, makespan (C_{max}), total tardiness (TD) and number of tardy jobs (N_T) are considered. Tables 1 showed the three objective functions with their signal-to-noise (S/N) ratios. From these results, for single-objective scheduling, it can be seen that the optimum combination of scheduling factors is the one having the smallest objective function value (the highest S/N ratio). Nevertheless, for multi-objective scheduling, it can be concluded that the optimum combination of scheduling factors is not as straightforward as that of single-objective scheduling, because a higher S/N ratio for one objective response may correspond to a lower S/N ratio for another objective response. These results reveal that the optimum combination of scheduling factors is multi-criteria decision-making (MCDM) problem.

Alternatives	C_{max}	S/N	$\mu_{C_{max}}$	TD	S/N	μ_{TD}	N_{TD}	S/N	$\mu_{N_{TD}}$
$A_1 (SR_1 DR_1 U_1 K_1)$	38499	-91.71	0.32	10070	-80.061	0.35	4	-12.041	0.71
$A_2 (SR_1 DR_2 U_2 K_2)$	34736	-90.82	0.67	19124	-85.632	0.21	12	-21.584	0.25
$A_3 (SR_1 DR_3 U_3 K_3)$	31571	-89.99	1.00	50161	-94.007	0.00	22	-26.848	0.00
$A_4 (SR_2 DR_1 U_2 K_3)$	35387	-90.98	0.61	28904	-89.219	0.12	18	-25.105	0.08
$A_5 (SR_2 DR_2 U_3 K_1)$	32488	-90.23	0.90	5666.0	-75.066	0.48	2	-6.021	1.00
$A_6 (SR_2 DR_3 U_1 K_2)$	42356	-92.54	0.00	9909.0	-79.921	0.36	7	-16.902	0.48
$A_7 (SR_3 DR_1 U_3 K_2)$	33003	-90.37	0.85	2994.0	-69.525	0.62	6	-15.563	0.54
$A_8 (SR_3 DR_2 U_1 K_3)$	39999	-92.04	0.19	31792	-90.046	0.10	19	-25.575	0.06
$A_9 (SR_3 DR_3 U_2 K_1)$	36310	-91.20	0.52	542.00	-54.680	1.00	2	-6.021	1.00

Tab. 1. Simulation results with their normalisations

To simplify the complexity of the MCDM problem, it can be described as a hierarchical structure, as shown in Figure 1. This hierarchy contains three main elements: *overall goal*, *criteria* and *alternatives*.

Overall goal: the main goal is to solve the multi-criteria decision-making problem for optimisation of dynamic scheduling problems in RFAC.

Criteria: The criteria represent the objective functions to fulfil the overall goal. Three objective functions are considered in this problem. These objectives are classified into two types: time-based and due date-based objectives. The makespan (C_{max}), is in the first category while total tardiness (TD) and the number of tardy jobs (N_T) fall into the second category.

Alternatives: The decision alternatives represent the simulation experiments (feasible solutions) with respect to the multi-objective functions. These experiments are conducted under different combinations of scheduling factors: sequencing rule (SR), dispatching rule (DR), cell utilisation (U) and due date tightness (K),

After the MCDM problem is constructed as a hierarchical structure, a decision table of the alternatives with respect to the conflicting objectives is built. In the decision table, the S/N ratios for the three objective functions, makespan (C_{max}), total tardiness (TD) and number of tardy jobs (N_T) must be within the same range. In this case study, the value ranges of the three objectives are all different.

To avoid the different ranges, the values of the S/N ratio must be normalised. Since the three objectives are the ‘*smaller the better*’ type, the normalisation is determined using Equation (1). The normalisation values are between 0 and 1; 0 means the least desirable value while 1 denotes the best value. The simulation results of the three objective functions with their normalisations are shown in Table 1.

Fig. 1. The decision hierarchy

3. Application Using FAHP-FTOPSIS

In this section, the FAHP is applied to determine the weights of the multiple evaluation criteria to be used in the evaluation process, and the FTOPSIS is applied for evaluation of each alternative scheduling combination based on their overall performance in order to make a final decision.

3.1. Application of FAHP in determining weights of criteria

In Fuzzy Analytic Hierarchy Process (FAHP), the fuzzy comparison matrix is created by experts who have experience relevant to the related decision area. The experts decide how much one criterion dominates another. Hence, the experts are given the task of forming an individual pairwise comparison matrix by using triangular fuzzy number (TFN). In this research, TFN and the reciprocal scales are defined with the corresponding membership functions as shown in Figure 2 and Table 2 respectively. TFNs are used to overcome shortcomings of the nine-point scale in the traditional AHP. Table 3 presents the aggregate fuzzy comparison matrix with respect to the overall objective.

Linguistic scale for importance	Linguistic term	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just Equal		(1,1,1)	(1,1,1)
Equal importance	E	(1,1,3)	(1/3,1,1)
Moderate	M	(1,3,5)	(1/5,1/3,1)
Fairly strong	FS	(3,5,7)	(1/7,1/5,1/3)
Very strong	VS	(5,7,9)	(1/9,1/7,1/5)
Extremely preferred	EP	(7,9,9)	(1/9,1/9,1/9)

Tab. 2. Fuzzy evaluation scale for the weights

Fig. 2. Linguistic variables for the importance weight of each criterion

	Makespan (C_1)	Total tardiness (C_2)	Number of tardy jobs (C_3)
C_1	(1,1,1)	(1,3,5)	(1,3,5)
C_2	(1/5,1/3,1)	(1,1,1)	(1,1,3)
C_3	(1/5,1/3,1)	(1/3,1,1)	(1,1,1)

Tab. 3. The fuzzy comparison matrix of criteria

After the fuzzy comparison matrix is constructed, the weight of each criterion can be calculated as follows: Firstly, the values of the fuzzy synthetic extent of the three criteria are calculated as below by using Equation (5):

$$S_1 = (3.00, 7.00, 11.00) \times (19, 11.666, 6.733)^{-1} = (0.158, 0.600, 1.634)$$

$$S_2 = (2.20, 2.33, 5.00) \times (19, 11.666, 6.733)^{-1} = (0.116, 0.200, 0.743)$$

$$S_3 = (1.53, 2.33, 3.00) \times (19, 11.666, 6.733)^{-1} = (0.081, 0.200, 0.446)$$

Secondly, the degrees of possibility of S_i over S_j ($i \neq j$) are calculated by Equation (9).

$$V(S_1 \geq S_2) = 1.00,$$

$$V(S_1 \geq S_3) = 1.00,$$

$$V(S_2 \geq S_1) = \frac{(0.158 - 0.743)}{(0.200 - 0.743) - (0.600 - 0.158)} = 0.59,$$

$$V(S_2 \geq S_3) = 1.00,$$

$$V(S_3 \geq S_1) = \frac{(0.158 - 0.446)}{(0.200 - 0.446) - (0.600 - 0.158)} = 0.42,$$

$$V(S_3 \geq S_2) = 1.00$$

Thirdly, the minimum degree of possibility is determined using Equation (12) as follows:

$$m(C_1) = \min V(S_i \geq S_k) = \min (1.00, 1.00) = 1.00$$

$$m(C_2) = \min V(S_i \geq S_k) = \min (0.59, 1.00) = 0.59$$

$$m(C_3) = \min V(S_i \geq S_k) = \min (0.42, 1.00) = 0.42$$

Therefore, the weight vector is given by: $W_c = (1.00, 0.59, 0.42)T$. Finally, after normalising W_c , the normalised weight vectors of each of the three criteria can be determined as $W = (0.497, 0.295, 0.208)T$. The makespan (C_1) is determined as the most important criterion in the combinations of scheduling factors, followed by total tardiness (C_2); the number of tardy jobs (C_3) appears to be less significant. After the weights of each criterion are calculated, the last stage in FAHP is to identify the consistency of the linguistic values in the fuzzy comparison matrix.

In this study, the consistency ratio (CR) is calculated. The results obtained from the calculations based on the fuzzy comparison matrix are presented in Table 4. As can be seen from Table 4, the consistency ratio (CR) is less than 0.10. Thus, the weights are consistent and they are able to be used in the evaluation process.

Criteria	Weights (w)	$\lambda_{\max}$	CI	RI	CR
C_1	0.497	3.0921	0.0145	0.58	0.0251
C_2	0.295				
C_3	0.208				

Tab. 4. Results obtained from FAHP approach

3.2 Application of FTOPSIS in ranking of alternatives

In FTOPSIS, six stages are required for evaluating and ranking the alternatives.

Stage 1: Establish the fuzzy decision matrix by evaluating alternatives under each of the criteria using linguistic variables. The membership functions of these linguistic variables are shown in Figure 3. In this study, nine alternatives (scheduling factor combinations) must be evaluated with respect to each criterion, as shown in Table 1. The fuzzy decision matrix of the elements in is demonstrated in Table 4.

Fig. 3. Membership functions of linguistic variable set

Stage 2: Normalise the fuzzy decision matrix. Since the ranges of all the values belong to the closed interval $[0, 1]$, there is no need for normalisation.

Stage 3: Obtain a weighted decision matrix. This matrix can be established using the Equation (13) and the criteria weights calculated by fuzzy AHP. The weighted decision matrix is presented in Table 5.

Stage 4: Determine the fuzzy positive ideal solution ($FPIS, A^+$) and the fuzzy negative ideal solution ($NPIS, A^-$) using Equations 23 and 24. In this problem, C_1, C_2, C_3 are considered as benefit criteria, so $\tilde{v}_1^+ = (1,1,1)$ and $\tilde{v}_1^- = (0,0,0)$, as shown in Table 5.

Stage 5: Calculate the distance of each alternative (d_i^+, d_i^-) from $FPIS$ and $FNIS$ using Equations 27 and 28, as shown below as an example illustrating this calculation.

Stage 6: Calculate the closeness coefficient of each alternative using Equation 29. The final results obtained by the FTOPSIS are summarised in Table 6.

Alternatives	C_1	C_2	C_3
$A_1 (SR_1 DR_1 U_1 K_1)$	(0.2, 0.3, 0.4)	(0.3, 0.4, 0.5)	(0.6, 0.7, 0.8)
$A_2 (SR_1 DR_2 U_2 K_2)$	(0.6, 0.7, 0.8)	(0.1, 0.2, 0.3)	(0.2, 0.3, 0.4)
$A_3 (SR_1 DR_3 U_3 K_3)$	(0.8, 1.0, 1.0)	(0.0, 0.0, 0.2)	(0.0, 0.0, 0.2)
$A_4 (SR_2 DR_1 U_2 K_3)$	(0.5, 0.6, 0.7)	(0.0, 0.0, 0.2)	(0.0, 0.0, 0.2)
$A_5 (SR_2 DR_2 U_3 K_1)$	(0.8, 1.0, 1.0)	(0.4, 0.5, 0.6)	(0.8, 1.0, 1.0)
$A_6 (SR_2 DR_3 U_1 K_2)$	(0.0, 0.0, 0.2)	(0.3, 0.4, 0.5)	(0.4, 0.5, 0.6)
$A_7 (SR_3 DR_1 U_3 K_2)$	(0.7, 0.8, 0.9)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)
$A_8 (SR_3 DR_2 U_1 K_3)$	(0.1, 0.2, 0.3)	(0.0, 0.0, 0.2)	(0.0, 0.0, 0.2)
$A_9 (SR_3 DR_3 U_2 K_1)$	(0.4, 0.5, 0.6)	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)
Weight	0.497	0.295	0.208

Tab. 4. Fuzzy decision matrix for nine alternatives with three criteria

Alternatives	C ₁	C ₂	C ₃
A ₁	(0.099, 0.149, 0.198)	(0.088, 0.118, 0.147)	(0.124, 0.145, 0.166)
A ₂	(0.298, 0.347, 0.397)	(0.029, 0.059, 0.088)	(0.041, 0.062, 0.083)
A ₃	(0.397, 0.497, 0.497)	(0.000, 0.000, 0.059)	(0.000, 0.000, 0.041)
A ₄	(0.248, 0.298, 0.347)	(0.000, 0.000, 0.059)	(0.000, 0.000, 0.041)
A ₅	(0.397, 0.497, 0.497)	(0.118, 0.147, 0.177)	(0.166, 0.208, 0.208)
A ₆	(0.000, 0.000, 0.099)	(0.088, 0.118, 0.147)	(0.083, 0.104, 0.124)
A ₇	(0.347, 0.397, 0.447)	(0.147, 0.177, 0.206)	(0.083, 0.104, 0.124)
A ₈	(0.049, 0.099, 0.149)	(0.000, 0.000, 0.059)	(0.000, 0.000, 0.041)
A ₉	(0.198, 0.248, 0.298)	(0.236, 0.295, 0.295)	(0.166, 0.208, 0.208)
A ⁺	$\tilde{v}_1^+ = (1, 1, 1)$	$\tilde{v}_2^+ = (1, 1, 1)$	$\tilde{v}_3^+ = (1, 1, 1)$
A ⁻	$\tilde{v}_1^- = (0, 0, 0)$	$\tilde{v}_2^- = (0, 0, 0)$	$\tilde{v}_3^- = (0, 0, 0)$

Tab. 5. Weighted decisions for alternatives

$$d_1^+ = \sqrt{\frac{1}{3} [(1 - 0.099)^2 + (1 - 0.149)^2 + (1 - 0.198)^2]} + \sqrt{\frac{1}{3} [(1 - 0.088)^2 + (1 - 0.118)^2 + (1 - 0.147)^2]} + \sqrt{\frac{1}{3} [(1 - 0.124)^2 + (1 - 0.145)^2 + (1 - 0.166)^2]} = \mathbf{2.589}$$

$$d_1^- = \sqrt{\frac{1}{3} [(0 - 0.099)^2 + (0 - 0.149)^2 + (0 - 0.198)^2]} + \sqrt{\frac{1}{3} [(0 - 0.088)^2 + (0 - 0.118)^2 + (0 - 0.147)^2]} + \sqrt{\frac{1}{3} [(0 - 0.124)^2 + (0 - 0.145)^2 + (0 - 0.166)^2]} = \mathbf{2.102}$$

Alternatives	d_j^+	d_j^-	CC_j	Rank
A ₁	2.589	2.102	0.448	7
A ₂	2.532	2.323	0.478	5
A ₃	2.505	2.453	0.495	3
A ₄	2.670	2.287	0.461	6
A ₅	2.197	2.402	0.522	1
A ₆	2.746	2.018	0.424	8
A ₇	2.323	2.360	0.504	2
A ₈	2.869	2.094	0.422	9
A ₉	2.284	2.188	0.489	4

Tab. 6. FTOPSIS results

4. Analysis of Results and Discussion

Based on FAHP-FTOPSIS results, the alternative A_5 ($SR_2 DR_2 U_3 K_1$) is closest to the fuzzy positive ideal solution ($FPIS$) with a value of 2.197, and the alternative A_8 ($SR_3 DR_2 U_1 K_3$) is located farthest from the fuzzy negative ideal solution ($FNIS$) with a value of 2.869. The alternative A_3 ($SR_1 DR_3 U_3 K_3$) is located farthest from the $FNIS$ with a value of 2.453, and the alternative A_6 ($SR_2 DR_3 U_1 K_2$) is closest to the $FNIS$ with a value of 2.018.

According to the results in, it can be seen that the alternative A_5 ($SR_2 DR_2 U_3 K_1$) is the optimal combination of scheduling factors, with a relative closeness coefficient (CC_j) value of 0.522. The alternative A_7 ($SR_3 DR_1 U_3 K_2$) has a CC_j value of 0.504 and is ranked second in these results. The alternative A_3 ($SR_1 DR_3 U_3 K_3$) is ranked third with a CC_j value of 0.495. The worst alternative is A_8 ($SR_3 DR_2 U_1 K_3$) with a CC_j value of 0.422. Therefore, the descending order of the final ranking using FAHP-FTOPSIS is: $A_5 > A_7 > A_3 > A_9 > A_2 > A_4 > A_1 > A_6 > A_8$.

To conduct the sensitivity analysis for the results obtained by FAHP-FTOPSIS, change the weight of each individual criterion, and keep the summation total of all criteria weights equal to one. The decision-maker can assume different scenarios. *Scenario 0* shows the original weights' values as calculated by FAHP, whereas the other scenarios (*Scenario 1*, *Scenario 2* ... *Scenario n*) all show different weights values. For example, the total weight of the makespan (C_1), total tardiness (C_2) and number of tardy jobs (C_3) is equal to one ($0.497+0.295+0.208 = 1$); these original weights represent *Scenario 0*.

The other scenarios can be established for example by increasing C_1 to 0.55, increasing C_2 to 0.30 and decreasing C_3 to 0.15. Table 7 summarises the numerical results of three different scenarios.

Criteria	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Makespan (C_1)	0.497	0.55	0.50	0.45
Total tardiness (C_2)	0.295	0.30	0.20	0.35
Number of tardy jobs (C_3)	0.208	0.15	0.30	0.20

Tab. 7. the weight of individual criterion

Alternatives	Relative closeness coefficient (CC_j)			
	Scenario 0	Scenario 1	Scenario 2	Scenario 3
A_1 ($SR_1 DR_1 U_1 K_1$)	0.448	0.450	0.448	0.447
A_2 ($SR_1 DR_2 U_2 K_2$)	0.478	0.485	0.479	0.473
A_3 ($SR_1 DR_3 U_3 K_3$)	0.495	0.505	0.495	0.486

$A_4 (SR_2 DR_1 U_2 K_3)$	0.461	0.468	0.461	0.456
$A_5 (SR_2 DR_2 U_3 K_1)$	0.522	0.529	0.525	0.515
$A_6 (SR_2 DR_3 U_1 K_2)$	0.424	0.423	0.422	0.424
$A_7 (SR_3 DR_1 U_3 K_2)$	0.504	0.511	0.501	0.499
$A_8 (SR_3 DR_2 U_1 K_3)$	0.422	0.424	0.421	0.420
$A_9 (SR_3 DR_3 U_2 K_1)$	0.489	0.492	0.486	0.489

Tab. 8. Sensitivity analysis for FAHP-FTOPSIS based on first procedure

As shown in Figure 4, the final ranking in Scenario 0 is nearly the same as for all the other scenarios (Scenario 1, Scenario 2 and Scenario 3). For example, A5, A7, A2, A4 and A1 have the same rankings in all scenarios. In this example, even though the weights of the criteria (C1, C2 and C3) are each changed from the original weights, this has only a minor influence on the final ranking.

Fig. 4. Sensitivity analysis for FAHP-FTOPSIS

5. Conclusion

The research work described in previous paper, *development of fuzzy AHP and TOPSIS approach for multi-objective scheduling problems in robotic flexible assembly cells*, was devoted to develop a new approach based on FAHP-FTOPSIS for solving optimisation problems.

The objective of this paper, a hypothetical case study was applied to demonstrate the effectiveness of the developed approach that presented in previous paper. In order to achieve the stated objective, the following two steps have to be performed

sequentially: first; Implement the proposed approach using fuzzy AHP-fuzzy TOPSIS (FAHP-FTOPSIS); and then perform a sensitivity analysis and confirmation test to verify and validate the results obtained.

The results achieved in this paper illustrate that the final ranking in Scenario 0 is relatively less sensitive to the changes in fuzzy rules. Hence, it can be concluded that almost all of the changes in the weight of each criterion do not have significant influence on the final ranking. Thus, the sensitivity analysis reflects the stability of the results in *Scenario 0*, and demonstrates the robustness of the FAHP - FTOPSIS approach.

A further research can be suggested to continue the current work. This can be done by comparing the obtained results of the proposed FAHP-FTOPSIS with fuzzy decision support system (FDSS) to check the reliability and consistency of the proposed approach. The FDSS can be built using a MATLAB fuzzy logic toolbox.

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