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Using the Analytic Hierarchy Process in Engineering Education*

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The Analytic Hierarchy Process is introduced into undergraduate and postgraduate student projects to formalise the process of selection of 'hard' and 'soft' system components. This formal framework provides greater insight into a student's reasoning. This is of great benefit to the lecturer since it reveals the extent to which the student understands the objectives of the engineering exercise being tackled and the relative merits of the alternative solutions. Detailed examples are presented in a tutorial form.

THE NEED FOR THE ANALYTIC HIERARCHY PROCESS

ONE OF THE key skills required of an engineer is the ability to produce systems that satisfy users' requirements, by the correct selection, configuration, integration, operation and control of proprietary building blocks. These component parts can be physical entities such as computers and manufacturing machinery—the 'hard' system components. However, they can also be non-physical entities such as software, algorithms, control strategies and methods—the 'soft' systems components. If the wrong components are selected then the users' requirements will not be satisfied. If sub-optimal components are selected then the system solution will be sub-optimal. Clearly, selection is a critical element of the engineering process. Therefore, it is essential that it is systematic, formalized and accountable, so that it is amenable to detailed analysis for the purposes of verification and optimisation. To satisfy these requirements the author has used the Analytic Hierarchy Process (AHP) [1].

The AHP in education

As a lecturer, the author has introduced the AHP into undergraduate and postgraduate student projects in order to train the students in its application. There is another, arguably more important, aspect to this work. The AHP makes the selection process very transparent. This is of great benefit in an educational environment since it reveals in detail a student's thoughts. This in turn reveals the extent to which a student understands the objectives of the engineering exercise being tackled and the relative merits of the alternative solutions. The AHP highlights misconceptions and can be the catalyst for lively debate.

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The Analytic Hierarchy Process (AHP)

The AHP is a selection process that consists of four steps:

1. Decide upon the criteria for selection.
2. Rate the relative importance of these criteria using pair-wise comparisons.
3. Rate each potential choice relative to each other choice on the basis of each selection criterion—this is achieved by performing pair-wise comparisons of the choices.
4. Combine the ratings derived in steps 2 and 3 to obtain an overall relative rating for each potential choice.

Applications of the AHP

The author and his students have applied the AHP to a wide range of 'hard' and 'soft' engineering selection problems. One 'hard' systems application considers the selection of the microprocessor to be used in a data acquisition system (DAS) designed for machine tool condition monitoring [2]. This design project also applies the AHP to the apparently trivial task of selecting the type of connector to be used in connecting the leads from sensors on the machine tool to the DAS. This particular selection process may seem trivial to start with since one might think that the type of connector chosen will have little or no effect on the fundamental performance of the system. However, a cursory inspection of some suppliers' catalogues soon revealed that there are tens or even hundreds of different but apparently suitable connector designs available. Without a systematic approach to this selection exercise it would have been very difficult 'to see the wood from the trees' and to make opportunist gains by taking advantage of a wide choice.

'Methods' as well as artefacts can be selected using the AHP. One application reports the use of the AHP to select a method of transferring data across Europe between computers [3]. Presented in

Table 1. Pair-wise rating of selection criteria

Criterion	Signal usefulness	Ease of maintenance	Ruggedness	Ease of mounting
Signal usefulness	1	3	5	6
Ease of maintenance	1/3	1	3	5
Ruggedness	1/5	1/3	1	4
Ease of mounting	1/6	1/5	1/4	1
Column sum	1.70	4.53	9.25	16.00

Table 2. Normalised pair-wise rating of selection criteria

Criterion	Signal usefulness	Ease of maintenance	Ruggedness	Ease of mounting	Row average
Signal usefulness	0.588	0.662	0.541	0.375	0.541
Ease of maintenance	0.196	0.221	0.324	0.313	0.263
Ruggedness	0.118	0.074	0.108	0.250	0.137
Ease of mounting	0.098	0.044	0.027	0.063	0.058
Column sum	1.000	1.000	1.000	1.000	1.000

Table 3. Pair-wise rating of alternative CM methods with respect to signal usefulness

CM method	Pump outlet pressure	Motor current	Vibration	Acoustic emission
Pump outlet pressure	1	4	2	5
Motor current	1/4	1	1/2	3
Vibration	1/2	2	1	3
Acoustic emission	1/5	1/3	1/3	1
Column span	1.95	7.33	3.83	12

detail here is the application of the AHP by a student [4] to the selection of a condition monitoring method for the hydraulic pump that operates various sub-systems in a Wadkin V4-6 vertical milling machine.

SELECTION OF A CONDITION MONITORING METHOD FOR A HYDRAULIC PUMP

Four condition monitoring methods were assessed in the laboratory—pump outlet pressure, vibration, pump motor current and acoustic emission. Four selection criteria were considered to be relevant to this particular application: signal usefulness in terms of condition monitoring; ease of maintenance of the associated hardware; ruggedness of the associated hardware with respect to harsh industrial environments; ease of mounting of sensors in view of the fact that this is a retrofit operation. A 'useful' signal is one that is sensitive to faults whilst being insensitive to noise and changing ambient conditions, such as pump temperature, unless a simple method of compensation exists.

Having defined the selection criteria, the next step in the AHP is the pair-wise comparison of the importance of the criteria. This is done by assigning a weight between 1 (equal importance) and 9 (absolutely more important) to the more important criterion, and the reciprocal of this value is then assigned to the other criterion in the pair. The results of this operation are presented in Table 1 which shows that, for example, signal usefulness is much more important than ease of mounting. The weightings in Table 1 are then normalised, by dividing each entry in a column by the sum of all the entries in that column, so that they add up to one. Following normalisation, the weights are averaged across the rows to give an average weight for each criterion as shown in Table 2.

The next step is the pair-wise comparison of the CM methods to quantify how well they satisfy each of the criteria. For each pairing within each criterion, the better method is awarded a rating on a scale between 1 (equally good) and 9 (absolutely better), whilst the other method in the pairing is awarded a rating equal to the reciprocal of this value. The results for the 'signal usefulness' criterion are given in Table 3. Each entry in this matrix records how well the method corresponding to its row meets the 'signal usefulness' criterion when compared to the method corresponding its column. For example, the pump outlet pressure is found to be a far more useful CM signal than acoustic emission. The ratings in these comparison matrices are normalised as before and averaged across the rows to give an average normalised rating by criterion for each CM method, as illustrated in Table 4 for 'signal usefulness'. Table 5 summarises the average normalised ratings with respect to each of the selection criteria.

The final step in the AHP is to combine the average normalised CM method ratings (Table 5) with the average normalised criterion weights

Table 4. Normalised pair-wise rating of alternatives with respect to signal usefulness

CM method	Pump outlet pressure	Motor current	Vibration	Acoustic emission	Row average
Pump outlet pressure	0.513	0.545	0.522	0.417	0.499
Motor current	0.128	0.136	0.130	0.250	0.161
Vibration	0.256	0.273	0.261	0.250	0.260
Acoustic emission	0.103	0.045	0.087	0.083	0.080
Column sum	1.000	1.000	1.000	1.000	1.000

Table 5. Average normalised ratings of CM methods with respect to each criterion

	Criterion			
CM method	Signal usefulness	Ease of maintenance	Ruggedness	Ease of moutning
Pump outlet pressure	0.499	0.137	0.074	0.170
Motor current	0.161	0.067	0.284	0.069
Vibration	0.260	0.515	0.471	0.455
Acoustic emission	0.080	0.281	0.171	0.306

Table 6. Overall CM method ratings

CM Method	a_j
Pump outlet pressure	0.326
Motor current	0.148
Vibration	0.367
Acoustic emission	0.158

(Table 2), to produce an overall rating for each CM method, i.e. the extent to which the methods satisfy the criteria is weighted according to the relative importance of the criteria. This is done as follows:

$$a_j = \sum_i (w_i k_{ij}) \quad (1)$$

where:

a_j = overall relative rating for CM method j
w_i = average normalised weight for criterion i
k_{ij} = average normalised rating for CM method j with respect to criterion i.

Table 6 gives the results of this final step. These results show clearly that vibration analysis and pump outlet pressure are the preferred CM methods.

The final column of Table 2 reflects the student's view that the most important signal selection criterion is 'usefulness'. The weight given to this criterion is such that it effectively eliminates condition monitoring methods that are rated lowly under this criterion. This is intuitively correct since it is pointless acquiring a 'useless' signal. The student also gives a high weighting to ease of maintenance. This verifies his appreciation of the economics of industry. Further discussion with the student on this point, prompted by the AHP results, revealed that he wanted to seek solutions that would enable on-line maintenance and thereby avoid increased downtime. The student is well aware that the last thing that production engineers want is increased downtime negating the original benefit of CM. Table 2 also verifies that the student is aware that his particular target monitoring environment is very harsh, as described in his report.

Table 3 reveals how the student interprets his experimental results to reach the conclusion that pump outlet pressure is the most useful signal. His experiments show that the pump outlet pressure is sensitive to the fault conditions to be detected whilst being insensitive to the noise that is present. Conversely, acoustic emission is found in his experiments to be the least useful signal. In contrast, in Table 5 the acoustic emission sensor is highly rated under the categories of 'ease of maintenance' and 'ease of mounting', as it is attached to the outside of the pump.

SELECTION OF ELECTRIC SHOCK PROTECTION METHOD

The AHP has been applied to rating the protection methods available for electric shock protection in a power station environment—thus demonstrating an application within the field of electrical engineering [5]. Five current paths through the human body are considered, each being defined in terms of the points of contact with the body. In assessing which are the most important paths, i.e. which should be weighted most heavily in the assessment of the protection methods, two factors need to be considered—likelihood of occurrence and severity of the resultant shock.

The relative likelihood of each current path is assessed by pair-wise comparisons, using the rating system explained above, with the results given in Table 7. This table shows that, for example, a hand-to-foot shock is assessed as being far more likely than a foot-to-foot shock. This is justified by the student on the grounds that, 'a general worker in a power station or a member

Table 7. Pair-wise rating of likelihood of occurrence of shock paths

Path	Hand-foot	Foot-foot	Hand-hand	Chest-hand	Hand-seat
Hand-foot	1	8	3	7	5
Foot-foot	1/8	1	1/7	1/3	1/4
Hand-hand	1/3	7	1	6	6
Chest-hand	1/7	3	1/6	1	1/2
Hand-seat	1/5	4	1/6	2	1
Total	1.80	23.00	4.48	16.33	12.75

Table 8. Pair-wise rating of severity of shock

Path	Hand-foot	Foot-foot	Hand-hand	Chest-hand	Hand-seat
Hand-foot	1	4	1/4	1/7	1/4
Foot-foot	1/4	1	1/9	1/9	1/9
Hand-hand	4	9	1	1/2	1
Chest-hand	7	9	2	1	2
Hand-seat	4	9	1	1/2	1
Total	16.25	32.00	4.36	2.25	4.36

Table 9. Normalised pair-wise rating of likelihood of occurrence of shock paths

Path	Average normalised likelihood rating	Average normalised severity rating	Product of likelihood and severity ratings	Normalised product (overall rating)
Hand-foot	0.48	0.07	0.03	0.21
Foot-foot	0.04	0.03	0.00	0.01
Hand-hand	0.31	0.24	0.07	0.45
Chest-hand	0.07	0.41	0.03	0.17
Hand-seat	0.10	0.24	0.03	0.15
Total	1	1	0.16	1

Table 10. Pair-wise comparison of protection methods with respect to hand-hand path

Protection method	Footware	Gloves	Ground resistance
Footware	1	1/9	1
Gloves	9	1	9
Ground resistance	1	1/9	1
Total	11.00	1.22	11.00

of the public is far more likely to touch a live unprotected terminal, than the extreme case where a fault has occurred in the power station and a step voltage is made across the ground'. A hand-to-foot shock is far more likely than a chest-to-hand shock because, 'an awkward position would have to be assumed to touch a live terminal with the chest'.

The relative severity of a shock along each current path is assessed by a more analytical approach. Simple body resistance circuits are established to model each current path. Then, using standard data [6], a tolerable voltage is established for each path—a low tolerable voltage indicating a path with a more severe shock effect. The voltages are then compared to establish the relative severity ratings in Table 8.

The results in Tables 7 and 8 are normalised, as before, and the products of the corresponding row averages yield the overall shock path ratings in Table 9. This product means that paths that are more likely and with more severe effect will have a high rating whilst those that are least likely and least severe will have a low rating. For example, the hand-to-hand path has the highest overall rating as it is both highly likely and severe. Therefore, in the rating of the protection methods the ones which are particularly pertinent to preventing this type of shock will be more highly rated. The foot-to-foot path is rated most lowly since the student believes that the likelihood of this situation occurring is relatively low and the severity associated with it is also relatively low.

Three protection methods are now considered. The pair-wise ratings of their effectiveness with respect to the hand-to-hand path are given in Table 10. Similar tables are established for each current path. The average normalised pair-wise ratings of each of the protection methods with respect to each current path are given in Table 11. The overall rating is calculated in Table 12 using equation (1) as before but with:

$a_j =$ (overall relative rating for protection method)$_j$

$w_i =$ (average normalised weight for current path)$_i$

$k_{ij} =$ (average normalised rating for protection method)$_j$ with respect to current path j.

Table 11. Average normalised ratings of protection methods with respect to shock paths

	Shock path				
Protection method	Hand-foot	Foot-foot	Hand-hand	Chest-hand	Hand-seat
Footware	0.33	0.58	0.09	0.09	0.05
Gloves	0.52	0.05	0.82	0.82	0.58
Ground resistance	0.14	0.37	0.09	0.09	0.37

Table 12. Overall rating of protection methods

Protection method	Rating	Rating by alternative student
Footware	0.14	0.14
Gloves	0.71	0.77
Ground resistance	0.15	0.10

Table 13. Selection criteria for data acquisition system keyboard

Selection Criterion	Average Weight
Mounting	0.230
Cost	0.218
Size	0.182
Ruggedness	0.153
Availability/supplier	0.084
Computer interface	0.055
User interface	0.054
Ease of typing	0.025

The results show clearly that, of the methods considered, gloves are the most effective form of shock protection. It must be stressed that the purpose of this exercise is educational. In performing it, the student has had to think carefully about the severity of shock and the effectiveness of protection methods. The purpose of this exercise has not been to formulate a safety policy since clearly all of the protection methods considered are essential.

When another student carried out the same exercise independently the results in the last column of Table 12 were produced [7]. Clearly, there is a high degree of agreement in the overall findings. However, more detailed analysis of the other tables produced along the way revealed some differences that were a stimulus for enthusiastic and constructive debate between the students.

SELECTION OF A KEYBOARD

Nicholson [2] considers the selection of the keyboard to be used with an industrial data acquisition system. The results of the pair-wise comparison of the selection criteria are given in Table 13. These show that the first four or five criteria are by far the most important. Consequently, the last three or four criteria can be ignored to make the exercise simpler and less 'noisy'.

SENSITIVITY ANALYSIS

It is essential to subject to sensitivity analysis any decision making processes that are dependent upon qualitative assessments. For example, when the ruggedness and ease of mounting criteria are compared in the condition monitoring example, clearly ruggedness is more important than ease of mounting. However, on a scale between 1 and 9, it is not precisely clear how much more important it is. A weight of 4 is used to quantify the degree of importance, although scores of 3 or 5 could be justifiably assigned instead. We can associate linguistic terms such as 'slightly more important' or 'very much more important' with the quantified weights. Some authors have produced linguistic definitions for the different scores—for example see [8] and [9]. However, these definitions do not produce unique weights since linguistic terms are 'fuzzy'.

The important issue here is addressing the question, 'How sensitive is the overall decision to small changes in the individual weights assigned during the pair-wise comparison process?' This question can be answered by varying slightly the values of the weights and observing the effects on the decision. This process is made simple if the pair-wise comparison matrices are held in a computer. The author has found spreadsheets particularly suitable for implementing the AHP and carrying out sensitivity analysis.

The sensitivity analysis identifies the pair-wise comparison weights that the overall decision is most sensitive too. These weights are the ones that must be assigned with the greatest accuracy and the AHP results should be qualified by referring to these high sensitivities.

For the condition monitoring example presented above, 'pump outlet pressure' and 'vibration' clearly come out on top. However, the difference in their ratings is marginal when compared with each other, i.e. there is not a clear winner. 'Signal usefulness' and 'ease of maintenance' are the most heavily weighted criteria, so that the overall decision is particularly sensitive to the pair-wise ratings within these criteria. Table 5 shows that 'pump outlet pressure' gets a very good rating for 'signal usefulness' but is poor in respect of 'ease of maintenance'. On the other hand 'vibration' is very good in terms of 'ease of maintenance' but only fairly good in terms of 'signal usefulness'. This means that the final decision will be particularly sensitive to the precise weights assigned to these two heavily weighted criteria. Had the two competing methods performed equally well in respect of these criteria, then the weights assigned to these criteria would not be critical to the final decision.

CONCLUSION

The AHP makes the selection process very transparent. This is of great benefit in an education and training environment since it reveals in detail a student's thoughts. This in turn reveals the extent to which students understand the objectives of an engineering exercise. It also reveals their understanding of the alternative solutions since these must be understood if their relative merits are to be assessed correctly.

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