ABSTRACT: Use of engineering judgement in design and production of quality product is inevitable. Thus, design optimization is important in development of efficient engineering products. Failure to identify important design criteria and estimate their associated significance in design and development of an engineering system can result to design, manufacturing, assembly and operating errors. Therefore, vital design criteria of an engineering product need to be identified and their various level of importance (i.e. weights) revealed using powerful engineering tool. To address this challenge, an Analytical Hierarchy Process (AHP) methodology was employed. The technique was adopted in weight estimation of the wheelchair design criteria such as manufacturing cost (MC), availability of material (AM), reliability (R), nature of environment to be used (NEU), efficiency (E) and anthropometry (A). Experts judgement were employed in the pairwise comparison of the criteria to facilitate the revealing of the criterion with higher weight and the one with lower weight using the mechanism of the AHP technique. A criterion with higher weight is more important than the one with lower weight and vice versa. The illustrative case study revealed that the AHP technique is a viable tool for weight estimation of the wheelchair design criteria.

Keywords: Wheelchair, Design criteria, AHP, Weights

INTRODUCTION

Majority of the wheelchairs designed and assembled do not find optimality in terms of use by the intended users. This may be linked with the nature of the built up environment, the anthropometric information of the paraplegics, the economics of wheelchair development and the social/societal aspect. Therefore, it becomes imperative that a mobility aid that can operate in safety and comfort be used by persons with lower limb deformity otherwise referred to as paraplegics (Ashiedu and Igboanugo, 2013). Therefore, improvement and development of wheelchair design that fits man’s attribute instead of fitting man to machines is a necessity. This cannot be achieved without considering various criteria associated with wheelchair design and their relative weights. The main aim of this research is investigation of relative weights of wheelchair design criteria using an Analytical Hierarchy Process (AHP) technique. Experts have utilised the decision making problem solving capability of AHP technique as a stand-alone method or in combination with other techniques. Evidences of these successes have been reported in relevant literature (Hambali et al. 2009; Mentes and Helvacioglu, 2012; Chan and Kumar, 2007; Yuen et al. 2012; Arslan, 2009; Song et al. 2004; Lirn et al. 2003 and 2004; Guy et al. 2006;
Chang et al. (2008). According to Hambali et al. (2009)’s work, AHP technique is applied in the design concept selection of automotive composite bumper beam during the conceptual design stage. In the work, eight design concepts of automotive composite bumper beam are considered and the most effective one is determined using AHP methodology. In another study, the AHP method has been adopted for dealing with complex decision making problems (Sun, 2010). The aim of the research is to explore the performance evaluation model using an AHP technique in combination with other algorithm. Sun (2010) develop an evaluation model to help the industrial practitioners for the performance evaluation of manufacturing capability, supply chain capability, innovation capability, financial capability, human resource capability and service quality capability of companies. It is reported in the author’s work that the model provided platform for decision analysts to better understand the complete evaluation process and provide a more accurate, effective, and systematic decision support tool. An AHP technique has been applied in quantitative evaluation of precautions on chemical tanker operations (Arslan, 2009). In the work, the author used AHP technique in ranking of the priorities of precautions that are taken by chemical tankers before, during, and after cargo operations. This facilitated the identification of an appropriate management tool that can be adopted to increase the safety level of the chemical tankers at a terminal. The strength of AHP technique has been proved in analysis of the structure of the mooring system selection problem. The technique is used to subdue spread mooring system selection problem by determining the weights of the attributes (Mentes and Helvacioglu, 2012). An AHP technique has been utilized to synthesize the local priorities into the global priority, in order to facilitate the ranking of the causes of the failure in Braglia (2000). Braglia (2000) identified four different factors such as occurrence, severity, detection and expected cost as decision attributes and causes of failure as decision alternatives. In the work, selection of causes of failure is the decision goal. Park et al. (2015); Slavens et al. (2015a); Slavens et al. (2015b); Schnorenberg et al. (2015) have contributed in wheelchair design but there is a gap in the use of AHP model in ranking of wheelchair design criteria from relevant literature. In this research, the AHP model is utilised in weight estimation of wheelchair design criteria to facilitate their ranking, thereby revealing their important level.

METHODOLOGY OF WEIGHT ESTIMATION OF WHEELCHAIR DESIGN CRITERIA

The design of wheelchair is governed by some variables including the manufacturing cost (MC), availability of materials (AM), reliability (R), efficiency (E), nature of environment to be used (NEU) and anthropometry (A) (Ashiedu, 2012). These variables/criteria are significant in the design of wheelchair. These criteria facilitate optimal operations of wheelchair, if the criteria are properly analysed. Additionally, they can contribute in the design of a centricity mobility aid that can eliminate most of the constraints observed in the use of wheelchairs. The information flow in Figure 1 starts from overview of wheelchair design. The next step is identification of criteria that can facilitate best wheelchair design, followed by review of the criteria in order to ensure all relevant criteria have been identified. Once all the criteria have been identified, then weight estimation can follow using the AHP methodology. Otherwise, the identified criteria is re-examined before weight estimation exercise of the criteria. The next step is to review the weights and check if the weight is reasonable using mechanism of the AHP.
overview of wheelchair design

Have all the relevant criteria been identified?

Yes

No

Estimate the weights of the criteria using the AHP methodology

Review the weights of the criteria

Are the weights of the criteria reasonable?

No

Prioritise the criteria in order of importance using their ranks

Print the criteria in order of priority

Start

Overview of wheelchair design

Identify criteria that can facilitate best wheelchair design

Review of the identified criteria

End

Figure 1: A flowchart of weight estimation of wheelchair design criteria using the AHP technique

Analytical Hierarchy Process (AHP)
Saaty introduced AHP technique in 1977 as a multi-criteria decision making tool (Saaty, 1977). Since then, it has been employed in addressing multiple criteria decision problems as evidenced in the works of Saaty (1980); Chan and Kumar (2007); Yuen et al. (2012); Pam (2010); Arslan (2009), Lavasani et al. (2011), Pillay and Wang (2003); Song and Yeo (2004); Lirn et al. (2003, 2004); Guy and Urli (2006); Chang et al. (2008); Mentes and Helvacioglu (2012). It addresses multi-criteria decision problems by setting their priorities. According to Lavasani et al. (2011),
AHP is a methodical approach that implies structuring criteria of multiple options into a system hierarchy, including relative values of all criteria, comparing alternatives for each particular criterion and defining average importance of alternatives. An AHP technique can be used to establish the relative weights of wheelchair design criteria, thus, revealing their importance. In the AHP method, design criteria are usually compared in a pairwise manner using the assessment grades of the criteria described in Table 1. In situation where assessors are more than one, Equation 1, can be used to combine the pairwise comparison exercises.

\[
\text{Average Numerical Value Rating} = \frac{\sum_{i=1}^{n} a_i}{n} \quad (1)
\]

where \(a_i\) is each value estimated by experts for the same criterion and \(n\) is the total number of experts involved in the exercise.

A pairwise comparison \(n\)-by-\(n\) matrix \(D\) is defined to reveal the relative weights of any criteria. The pairwise comparison is usually conducted by arranging \(n\) criteria in row and column of \(n \times n\) matrix \(D\), as evidenced in Equation 2. The \(n\)-by-\(n\) matrix \(D\) is used to represent the quantified judgements on pairs of design criteria \(A_i\) and \(A_j\).

\[
D = \begin{bmatrix}
1 & a_{12} & \ldots & a_{1L} \\
\frac{1}{a_{12}} & 1 & \ldots & \frac{1}{a_{2L}} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{1}{a_{1L}} & \frac{1}{a_{2L}} & \ldots & 1
\end{bmatrix} \quad (2)
\]

Two entry rules are used to define the entries \(a_{ij} (i, j = 1, 2, \ldots, L)\) in Equation 1. The entry rules are described as follows (Riahi et al. 2012):

Rule 1. If \(a_{ij} = \alpha\), then \(a_{ji} = \frac{1}{\alpha}\), \(\alpha \neq 0\).

Rule 2. If \(a_{ij}\) is judged to be of equal relative importance as \(a_{ji}\), then \(a_{ij} = a_{ji} = 1\).

In the AHP method, to calculate the relative weights of the criteria, \(A_i\) and \(A_j\), and \(i, j = 1, 2, 3, \ldots, n\), Equation 3 needs to be introduced and described. The relative weights of the criteria indicate the priority of each criterion in the pairwise comparison matrix in terms of its overall contribution to the decision making process (Pam, 2010).

\[
W_k = \frac{1}{n} \sum_{j=1}^{n} \left( \frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \right) \quad (3)
\]

\((k = 1, 2, 3, \ldots, n)\)

Equation 2 is described as follows (Pam, 2010):

i. \(a_{ij}\) represents the entry of row \(i\) and column \(j\) in a comparison matrix of order \(n\).

ii. Summation of the entries \(a_{ij} (i, j = 1, 2, \ldots, L)\) in each column \(j\), of the pairwise comparison matrix.

iii. Division of each entry of the matrix by the sum of all the entries in the corresponding column \(j\).

iv. Establishment of the arithmetic mean of the entries in each row \(i\).

\(W_k\) values associated with the criteria \(A_i\) and \(A_j\) are reasonable if the Consistency Ratio (CR) is less than or equal to 0.10 (Saaty, 1980). However, this value is arbitrary and has not been proved mathematically (Karahalios et al. 2011). This is the reason that Saaty suggested that CR value could be near 0.2 when any attempt to reduce this value will not necessarily improve the judgement (Dadkhah and Zahedi, 1993; Wedley, 1993). Additionally, in real world it is often very difficult to achieve this value mainly due to the disagreement of experts (Karahalios et al. 2011). The CR is defined as follows:

\[
CR = \frac{CI}{RI} \quad (4)
\]
Table 1: Comparison Scale for Assessment Grades of the Criteria

<table>
<thead>
<tr>
<th>Intensity of importance</th>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
<td>It means that the level of importance of two criteria are equal in wheelchair design optimization</td>
</tr>
<tr>
<td>2</td>
<td>Weak (i.e. between equal importance and moderate importance)</td>
<td>It means that the level of importance of two criteria are between equal importance and moderate importance in wheelchair design optimization</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
<td>It means that a criterion is slightly important over another criterion in wheelchair design optimization.</td>
</tr>
<tr>
<td>4</td>
<td>Moderate plus (i.e. between moderate importance and strong importance)</td>
<td>It means that a criterion is between moderate importance and strong importance over another criterion in wheelchair design optimization.</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
<td>It means that a criterion is strongly favour/importance over another criterion in wheelchair design optimization.</td>
</tr>
<tr>
<td>6</td>
<td>Strong plus (i.e. between strong importance and very strong importance)</td>
<td>It means that a criterion is between strong importance and very strong importance over another criterion in wheelchair design optimization.</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
<td>It means that a criterion is very strongly important over another criterion in wheelchair design optimization.</td>
</tr>
<tr>
<td>8</td>
<td>Very highly strong (i.e. between strong importance and very strong importance)</td>
<td>It means that a criterion is between strong importance and very strong importance over another criterion in wheelchair design optimization.</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
<td>It means that a criterion is extreme importance over another criterion in wheelchair design optimization.</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values</td>
<td>Intermediate values</td>
</tr>
<tr>
<td>1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9</td>
<td>Reciprocals</td>
<td>It means dominance of the second criterion as compared with the first one in wheelchair design optimization.</td>
</tr>
</tbody>
</table>

Table 2: Value of Average Random Index (RI) versus Matrix Order (Saaty, 1980)

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0</td>
<td>0</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>
Table 2 is used to illustrate the values of RI and Equation 5 is used to estimate the CI value. In Equation 5, \( n \) is the matrix order and \( \lambda_{\text{max}} \) is the maximum weight value of the \( n \)-by-\( n \) comparison matrix \( D \). Equation 5 is used to estimate \( \lambda_{\text{max}} \) value.

**DECISION MAKING AND RANKING**

Decision making and ranking is made on criteria with the aim of revealing which criterion is more important than the other. The information provided from the weight estimation exercise using AHP methodology is used for effective ranking of the criteria. The criteria are compared and ranked using their weight values for identification of their order of importance.

**ILLUSTRATIVE CASE STUDY**

In this study, an AHP technique is applied in investigation of weights of wheelchair design criteria. The mechanism of AHP technique is used to facilitate the prioritization of the wheelchair design criteria. The wheelchair design criteria are identified as MC, AM, R, NEU, E and A as evidenced in Figure 2. The step by step procedures of the AHP model is systematically applied in the weight estimation exercise of the wheelchair design criteria.

**Estimation of Weights of Wheelchair Design Criteria**

Most engineering products fail due to wrong decision making during the selection of the design criteria at the early design stage of the product. To overcome this challenge in wheelchair design, three experts with relevant experience in the subject under investigation are engaged to estimate the numerical ratings of the wheelchair design criteria, which will facilitate their weight estimations. They discussed as focused individual participate in the numerical rating of each wheelchair design criterion. The three experts rate each criterion and take the average of their numerical ratings as the actual one. An AHP technique is employed for the weight estimation of the wheelchair design criteria. An AHP hierarchical structure for weight estimations of the wheelchair design criteria has been developed in Figure 2. The weight estimation exercise on the criteria such as MC, AM, R, NEU, E and A is carried out using available data provided by three experts as illustrated in Table 2. Equations 1- 6 and Tables 1, 2 and 3 are used to facilitate the weights estimation of the wheelchair design criteria. Table 3 is used to carry out pairwise comparison of the wheelchair design criteria, using information in Table 1. The aggregation of numerical value rating in Table 3 is conducted using Equation 1.

For instance, in Table 3, the pairwise comparison of MC and AM, by Experts #1, #2 and #3 are estimated in Columns 4, 5 and 6 as numerical value ratings of 7, 7 and 6 respectively. Such numerical value ratings are defined as strong plus, strong plus and very strong importance respectively as evidenced in Table 1. The aggregation of numerical value ratings of 7, 7 and 6 is 6.67 as shown in Table 3. In a similar way, other aggregations of numerical value ratings in Table 3 are revealed. The pairwise comparison carried out in Table 3 is simplified and represented in Table 4. Table 4 stands as matrix form \( D \). Matrix form \( D \) is developed using Equation 2, so as to facilitate the estimation of \( w_{MC}, w_{AM}, w_{R}, w_{NEU}, w_{E} \) and \( w_{A} \) values.
Wheelchair Design

Manufacturing Cost (MC)
Availability of Material (AM)
Reliability (R)
Efficiency (E)
Anthropometry (A)
Nature of Environment to be used (NEU)

Figure 2: An AHP hierarchical structure for wheelchair design criteria

Table 3: Pairwise comparison of the wheelchair design criteria by experts #1 - #3

<table>
<thead>
<tr>
<th>Pairwise Comparison</th>
<th>Important Criterion</th>
<th>Expert #1 Numerical Value Rating</th>
<th>Expert #2 Numerical Value Rating</th>
<th>Expert #3 Numerical Value Rating</th>
<th>Aggregation of Numerical Value Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>AM</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>6.67</td>
</tr>
<tr>
<td>MC</td>
<td>R</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7.67</td>
</tr>
<tr>
<td>MC</td>
<td>NEU</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>7.33</td>
</tr>
<tr>
<td>MC</td>
<td>E</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>MC</td>
<td>A</td>
<td>8</td>
<td>7</td>
<td>8</td>
<td>7.67</td>
</tr>
<tr>
<td>AM</td>
<td>R</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5.33</td>
</tr>
<tr>
<td>AM</td>
<td>NEU</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>5.67</td>
</tr>
<tr>
<td>AM</td>
<td>E</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6.33</td>
</tr>
<tr>
<td>AM</td>
<td>A</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7.67</td>
</tr>
<tr>
<td>R</td>
<td>NEU</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5.67</td>
</tr>
<tr>
<td>R</td>
<td>E</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>5.33</td>
</tr>
<tr>
<td>R</td>
<td>A</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>7.33</td>
</tr>
<tr>
<td>NEU</td>
<td>E</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5.33</td>
</tr>
<tr>
<td>NEU</td>
<td>A</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>7.33</td>
</tr>
<tr>
<td>E</td>
<td>A</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

respectively. Equations 2 and 3, can be used to reveal the $w_{MC}, w_{AM}, w_{R}, w_{NEU}, w_{E}$ and $w_A$ values. Therefore, $w_{MC}$ is mathematically calculated as follows:

$$w_{MC} = \frac{1 + \frac{6.67}{6(9.23)} + \frac{7.67}{32.67} + \frac{7.33}{21.69} + \frac{7}{26.84} + \frac{0.1304}{16.53} + 1.66}{6} = 0.241$$

In a similar way, $w_{AM}, w_{R}, w_{NEU}, w_{E}$ and $w_A$ are calculated as 0.15, 0.088, 0.055, 0.131 and 0.46 respectively. The values of $w_{MC}, w_{AM}, w_{R}, w_{NEU}, w_{E}$ and $w_A$ are acceptable if CR value is less or equal to 0.1. Adopting Equations 4 - 6, information in Table 2 and pairwise comparison analysis of MC, AM,
R, NEU, E and A in matrix form D, the CR value can be found. The CR value can be mathematically calculated as follows:

$$CR = \frac{CI}{RI}$$

where

$$CI = \frac{\lambda_{max} - n}{n-1} = \frac{\lambda_{max} - 6}{6-1} = \frac{\lambda_{max} - 6}{5}$$

RI value is 1.24 because the number (n) of criteria is 6. 6 has a corresponding RI number of 1.24 in Table 2.

$$\lambda_{max}$$ value has been revealed as 7.251, therefore, CI value is 0.25. Since the values of $$\lambda_{max}$$ and CI have been known, CR value can be found as 0.2. Since the CR value is 0.2, the $$w_{MC}, w_{AM}, w_{R}, w_{NEU}, w_{E}$$ and $$w_{A}$$ values are reasonable and can be used to rank them.

**Decision Making and Ranking of Wheelchair Design Criteria**

Since the weights of the MC, AM, R, NEU, E and A have been revealed in Sub-section 5.1, their levels of importance can be identified via ranking. A criterion with highest weight estimate will be chosen as the most important and vice versa. Table 5 can be used to make such a decision. Criterion A has been identified as the most important because of its weight value and rank of 1 as evidenced in Table 5. Therefore, ranks of MC, AM, E, R and NEU can be described as 2, 3, 4, 5 and 6 as shown in Table 5. The implication of the result is that attention should be given to the entire criteria since there are weight values assigned to them. However, slightly more attention should be given to the criterion with more weight values than the one with less weight value during the selection of manufacturing options in wheelchair production.
Table 5: Rank of Wheelchair Design Criteria

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Weight $w$</th>
<th>Rank of Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>$w_{MC} = 0.241$</td>
<td>2</td>
</tr>
<tr>
<td>AM</td>
<td>$w_{AM} = 0.15$</td>
<td>3</td>
</tr>
<tr>
<td>R</td>
<td>$w_{R} = 0.088$</td>
<td>5</td>
</tr>
<tr>
<td>NEU</td>
<td>$w_{NEU} = 0.055$</td>
<td>6</td>
</tr>
<tr>
<td>E</td>
<td>$w_{E} = 0.131$</td>
<td>4</td>
</tr>
<tr>
<td>A</td>
<td>$w_{A} = 0.46$</td>
<td>1</td>
</tr>
</tbody>
</table>

CONCLUSION

An AHP methodology has been applied in this research. The weights of the criteria of wheelchair design have been revealed using the AHP technique. The wheelchair design criteria are the manufacturing cost (MC), availability of materials (AM), reliability (R), efficiency (E), nature of environment to be used (NEU) and anthropometry (A). The criteria are compared with one another using pairwise comparison. The comparison exercise is demonstrated for facilitation of estimation of the criteria’s weights. Nine linguistic terms that can be used for the comparison exercise are identified. Four out of the nine linguistic terms are utilised in the comparison exercise. The four linguistic terms are strong importance, strong plus, very strong importance and very highly strong with numerical rating values of 5, 6, 7 and 8 respectively. The numerical rating values obtained served as a reference/base for pairwise comparison of the criteria. The resultant numerical value rating, after pairwise comparison of criteria are developed by aggregation of each numerical value rating by experts #1 - #3. This information is used in estimation of the weights of MC, AM, R, NEU, E and A denoted as $w_{MC}$, $w_{AM}$, $w_{R}$, $w_{NEU}$, $w_{E}$ and $w_{A}$ respectively. It has been revealed that $w_{A} > w_{MC} > w_{AM} > w_{E} > w_{R} > w_{NEU}$ and are ranked as 1, 2, 3, 4, 5 and 6 respectively, and the ranking is in order of importance. Therefore, $w_{A}$ is more important than others.

REFERENCES


