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Selection of Cotton Fabrics for Optimal Comfort Properties Using Multi-Criteria Decision Making

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ABSTRACT

This paper presents a multi-criteria decision making (MCDM) approach to evaluate the thermal comfort index of fabrics by considering four decision criteria of fabric parameters such as cover, thickness, areal density (GSM) and porosity. The weight or relative importance of each criterion is decided by Analytic Hierarchy Process (AHP). The technique for order preference by similarity to ideal solution (TOPSIS) method of MCDM has been used to rank different types of cotton fabrics in terms of their thermal comfort level. The ranking of fabrics by this method yields a reasonable degree of agreement with the ranking based on thermal resistance value.

Keywords: Fabrics; MCDM; Thermal comfort, Thermal resistance, TOPSIS

1. Introduction

Clothing is needed to protect the human body against hostile climate condition. It assists in the thermo regulatory of the body by maintaining the thermal balance between skin and the atmosphere (Li Y., 2001). Clothing comfort may be termed as a pleasant state arising out of physiological, psychological and physical harmony between a human being and the environment (Das and Alagirusamy, 2010). The thermal comfort is related to fabric's ability to maintain skin temperature and allow transfer of perspiration produced from the body (Das *et al*. 2007). Raj *et al.* (2009) estimated the total thermo-physiological comfort based on the fabric parameter. Alay *et al*. (2012) established that thermal resistance increases with the fabric thickness. Certainly the heat transfer coefficient of the fabric, especially the thermal resistance and perspiration transfer through the fabric have a strong influence on the thermo-physiological comfort of fabric. The fabric criteria such as cover, porosity, areal density and thickness have a direct bearing to the clothing comfort. Hence, multi-criteria decision making (MCDM) seems to a feasible and potent method for selection of fabrics on the basis of comfort behavior.

There are many MCDM methods available namely, Weighted Sum Model (WSM) (Fishburn, 1967), Weighted Product Method (WPM) (Miller and Starr, 1969), Analytic Hierarchy Process (AHP) (Saaty, 1980), Multiplicative AHP (Lootsma, 1993), Revised AHP (Belton and Gear, 1983), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981), Elimination and Choice Translating Reality (ELECTRE) (Roy, 1991) etc. There have been numerous applications of MCDM techniques in industrial decision-making problems. Yurdakul and Tansel (2004) used AHP approach for the credit evaluation in a textile manufacturing firm. Kaya *et al.* (2007) evaluated manufacturing performance criteria like quality, cost, flexibility and speed for a textile company using AHP. Ghosh *et al.* (2012) applied ELECTRE for the selection of raw material in textile industry. Majumdar *et al.* (2011) used AHP for body armor selection. Majumdar *et al.* (2005) compared various MCDM methods such as AHP, multiplicative AHP and TOPSIS for cotton selection problem and observed that TOPSIS yields the best result. Limited information is available with reference to the selection of fabrics based on the comfort properties. In this study, an attempt has been made to rank the cotton fabrics in terms of their comfort levels using the TOPSIS method of MCDM based on four decision criteria namely fabric cover, porosity, areal density and thickness.

Table 1. Decision Matrix for a MCDM Problem

Criteria		C_1	C_2	..	C_j	..	C_n
Weights		w_1	w_2	..	w_j	..	w_n
Alternatives	A_1	x_{11}	x_{12}	..	x_{1j}	..	x_{1n}
	A_2	x_{21}	x_{22}	..	x_{2j}	..	x_{2n}
	:	:	:	..	:	..	:
	A_i	x_{i1}	x_{i2}	..	x_{ij}	..	x_{in}
	:	:	:	..	:	..	:
	A_m	x_{m1}	x_{m2}	..	:	..	x_{mn}

2. MCDM Methods

An MCDM method deals with the selection of optimal alternatives according to their preferential rank under the presence of a finite number of decision criteria. An MCDM problem is commonly expressed in the form of a matrix known as the decision matrix (Table 1). A decision matrix is a ($m \times n$) matrix in which element x_{ij} indicates the performance of alternative A_i when it is evaluated in terms of decision criterion C_j where $i = 1, 2, 3, ..., m$, and $j = 1, 2, 3, ..., n$. Numerical weight (w_j) is attached to each criterion based on its relative importance such that

$$\sum_{j=1}^{n} w_j = 1 \qquad (1)$$

An Over-view of AHP-TOPSIS Methods

TOPSIS is one of the popular methods of MCDM developed by Hwang and Yoon (1981). It is used when a set of alternatives (say garments) has to be ranked in terms of a set of decision criteria (for example, comfort parameters). The basic philosophy of TOPSIS is that the selected alternative should have the shortest distance (in a geometrical sense) from the ideal solution and longest distance from the worst solution. The positive ideal solution supposedly has the best performance scores in all the decision criteria. On the other hand, negative ideal solution has worst performance score on all the decision criteria. The ranking of an alternative is determined based on its geometric distance from the positive ideal solution and negative ideal solution.

In this work the relative weights for different criteria are calculated based on the AHP and the alternatives are ranked using the TOPSIS method. The organization of the amalgamated AHP-TOPSIS method is illustrated by the following steps:

Step 1: Formation of decision hierarchy

In this step the relevant objective or goal, decision criteria and alternatives of the problem are identified. In this hierarchical structure the overall objective or goal of the problem is positioned at the top of the hierarchy and the decision alternatives are placed at bottom levels, the decision criteria's are placed in between top and bottom.

Step 2: Formation of decision matrix

This step produces decision matrix D of criteria and alternative based on information available regarding the problem. If the number of alternatives is m and no of criteria is n, then decision matrix having an order of $m \times n$ is represent as follows:

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (2)$$

where x_{ij} denotes the performance measure of the i-th alternative in terms of the j-th criterion.

Step 3: Construct the Normalized Decision Matrix

In this step the decision matrix is converted to a normalized decision matrix R. An element r_{ij} of the normalized decision matrix is calculated as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (3)$$

and

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (4)$$

Step 4: Formation of pair wise comparison matrix for criteria

In this step the relative importance of different criteria with respect to the objective of the problem is determined using the AHP as proposed by Saaty (1980). Using a scale of relative importance a pair-wise comparison matrix P is constructed and the judgments are entered according to the Saaty's scale as given in Table 2. The entry c_{uv} of matrix P denotes the comparative importance of u^{th} criterion with respect to v^{th} criterion. In the matrix, $c_{vu} = 1/c_{uv}$ and $c_{uv} = 1$ when $u = v$. For p number of criteria, P becomes a $p \times p$ square matrix as shown below:

$$P = \begin{bmatrix} 1 & c_{12} & \ldots & c_{1p} \\ c_{21} & 1 & \ldots & c_{2p} \\ \ldots & \ldots & 1 & \ldots \\ c_{p1} & c_{p2} & \ldots & 1 \end{bmatrix} \quad (5)$$

In order to determine the relative weight of the u^{th} criterion, the normalized geometric mean of the u^{th} row of matrix P is calculated. This is represented as follows:

$$GM_u = \left\{ \prod_{v=1}^{p} c_{uv} \right\}^{\frac{1}{p}} \quad (6)$$

and

$$\text{Relative weight} = \frac{GM_u}{\sum_{u=1}^{p} GM_u} \quad (7)$$

where GM_u is the geometric mean of u^{th} row of matrix P.

To check the consistency in pair-wise comparison judgment, consistency index (CI) and consistency ratio (CR) are calculated by following Equations:

$$CI = \frac{\lambda_{max} - p}{p - 1} \quad (8)$$

and

$$CR = \frac{CI}{RCI} \quad (9)$$

where λ_{max} is the principal eigen value of the matrix P and RCI is the random consistency index whose value is obtained from Table 3. If $CR \leq 0.1$, the judgment is considered to be consistent and therefore acceptable, otherwise the decision maker has to reconsider the entries of matrix P.

Step 5: construct the weighted normalized matrix

The weighted normalized matrix is obtained by multiplying each column of the normalized decision matrix R with the associated criteria weight corresponding to that column. Hence an element v_{ij} of the normalized matrix V is representing as follows:

$$V = R*W \quad (10)$$

where

$$W = \begin{bmatrix} w_1 & 0 & 0 & 0 \ldots & 0 \\ 0 & w_2 & 0 & 0 \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & \ldots & w_n \end{bmatrix} \qquad \sum w_i = 1$$

and

$$v_{ij} = w_j \cdot r_{ij}$$

Step 6: Determine the Ideal and the Negative –Ideal Solutions

The ideal, denoted as A^*, and the negative-ideal, denoted as A^-, alternatives (solutions) are defined as follows:

$$A^* = \left\{ \left(\max_i v_{ij} \middle| j \in J \right), \left(\min_i v_{ij} \middle| j \in J' \right), i = 1,2,3,\ldots,m \right\}$$

$$= \left\{ v_1^*, v_2^*, \ldots\ldots, v_n^* \right\} \quad (11)$$

$$A^- = \left\{ \left(\min_i v_{ij} \middle| j \in J \right), \left(\max_i v_{ij} \middle| j \in J' \right), i = 1,2,3,\ldots,m \right\}$$

$$= \left\{ v_1^-, v_2^-, \ldots\ldots, v_n^- \right\} \quad (12)$$

where J = { j =1, 2, 3,…, n and j is associated with benefit criteria} and J' = {j =1, 2, 3,…, n and j is associated with cost criteria}. For the benefit criteria, the decision maker wants to have the maximum value among the alternatives. Therefore, A^* indicates the ideal solution. Similarly, A^- indicates the negative ideal solution.

Step 7: Calculation of Separation Measure

The n-dimensional Euclidean distance method is next applied to measure the separation distance of each alternative from the ideal solution. Thus, for the distance from the ideal solution we have:

$$S_{i^*} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{j^*})^2} \quad \text{for } i = 1, 2, 3., m \quad (13)$$

where S_{i^*} is the distance of each alternative from the ideal solution. Similarly, for the distance from the negative-ideal solution we have:

$$S_{i^-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{j^-})^2}, \text{ for } i = 1, 2, ., m \quad (14)$$

where S_{i-} is the distance of each alternative from the negative-ideal solution.

Step 8: Calculation of Relative Closeness to the Ideal Solution

In this step the relative closeness (C_{i^*}) value of each alternative with respect to the ideal solution is defined as following Equation:

$$C_{i^*} = \frac{S_i^-}{S_i^* + S_i^-} \quad (15)$$

where $1 \geq C_{i^*} \geq 0$, and i = 1, 2, 3… , m.

Step 9: Rank the Preference Order

All the alternatives are now arrange in a descending order according to the value of C_{i^*}. Therefore, the best alternative is the one that has the shortest distance to the ideal solution. The previous definition can also be used to demonstrate that any alternative which has the shortest distance from the ideal solution is also guaranteed to have the longest distance from the negative-ideal solution.

3. Material and Methods

Thirteen types of cotton fabrics of different weave structures are considered in this study. The values of different fabric parameters such as warp and weft counts, threads density, thickness and fabric areal density (GSM) are given in Table 4. Fabric GSM was measured using a standard GSM cutter. Warp and weft thread densities were measured using a pick glass. The warp and weft counts were determined using a Beesely yarn balance. The fabric cover (f_c) was determined using the following equation (Peirce, 1937)

$$f_c = n_1 d_1 + n_2 d_2 - n_1 n_2 d_1 d_2 \qquad (16)$$

where the subscripts 1 and 2 refer to parameters in warp and weft directions respectively, n = threads/inch, d = yarn diameter in inch which was estimated from the following equation (Peirce, 1937)

$$d = \frac{1}{28\sqrt{Ne}} \qquad (17)$$

where Ne is the yarn English count. The fabric porosity was estimated based on the following equation

$$\text{Fabric porosity} = \left(1 - \frac{G}{\rho h}\right) \qquad (18)$$

where G = fabric GSM (g/m^2), ρ = fiber density (g/m^3) and h = thickness (m). The fibre density for cotton was assumed to be 1.5×10^6 g/m^3.

The pair-wise comparison matrix which is formed using the four decision criteria of fabric such as cover, thickness, GSM and porosity is depicted in Table 5. The obtained values of weights for cover, thickness, GSM and porosity were found to be 0.22, 0.32, 0.19 and 0.27 respectively. The consistency of judgment was checked while determining the weights of the criteria by estimating CR and the value of which was founded much lower than 0.1, hence the judgment was considered to be consistent and acceptable.

The fabric thermal resistance was measured using an ALAMBETA tester where the fabric sample are placed between two plates and the measurement is carried out in a non-convective mode of heat transfer. All the fabrics were made of cotton so fiber conductivity remains constant. The values of the fabric thermal resistance are given in Table 6.

4. Results and Discussion

The relative closeness value (C_{i*}) as given in Equation 15 was used to estimate the thermal comfort index of fabrics by TOPSIS method. The relative closeness values for all the 13 fabrics are shown in Table 6. These fabrics were ranked according to their thermal resistance values as well as the TOPSIS thermal comfort indices. The ranking of fabrics as obtained by these two methods are also given in Table 6. It is observed that the highest TOPSIS comfort index is 0.9417 (fabric Sl. No. 3) and lowest comfort index in the same methods is calculated as 0.1029 (fabric Sl. No. 5). The highest value of thermal resistance is measured to be 0.0133 K.m^2/W (fabric Sl. No. 3) for the same fabric as indicated by TOPSIS method but the lowest value of the thermal resistance is obtained as 0.0047 K.m^2/W (fabric Sl. No. 10) for a different fabric than that of TOPSIS method. The rank correlation coefficient (R_s) is determined between these two methods of thermal comfort ranking of fabrics using the following equation:

$$R_s = 1 - \frac{6\sum d_a^2}{m(m^2 - 1)} \qquad (19)$$

where d_a is the absolute difference between two ranking and m is the total number of alternatives. The rank correlation coefficient is obtained as 0.775, which indicates that the TOPSIS ranking is consistent as thermal resistance ranking. Here number of alternatives is 13 which are greater than 10, so statistical significance level calculates using the following equation:

$$t_{0} = R_s \left[\frac{m-2}{1-{R_s}^2}\right]^{1/2} \qquad (20)$$

where (m-2) is the degree of freedom. For m = 13 and R_s= 0.775, the calculated value of t_0 is 4.0673 which is greater than the tabled value of t at 1% level. The null hypothesis of no association is therefore rejected. This suggests that the two methods of ranking are indeed associated. This suggests that the multi-criteria decision making method is a useful technique for the selection of fabrics on the basis of thermal resistance property from some selected fabric physical parameters. The proposed method incorporates fabric thickness, areal density, cover and porosity in a single parameter entitled 'TOPSIS thermal comfort index' and it shows good correlation with the thermal resistance of the fabric. Hence, this method can be used as a preliminary step to appraise the consumer preference of fabrics from the angle of thermal comfort. As an example, for a given fabric thickness, if the porosity is higher, then the thermal resistance is expected to be more and thus the consumer preference for that fabric in hot and sultry condition will be lower.

Table 2. The Fundamental Relational Scale for Pair Wise Comparisons Proposed by Saaty (1980)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity
7	Very strong importance	An activity is very strongly favored and its dominance is demonstrated
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judgment	When compromise is needed
Reciprocals		If activity *p* has one of the above numbers assigned to it when compared with activity *q*, then *p* has the reciprocal value when compared with *p*

Table 3. RCI Value for Different Numbers of Attributes (*N*)

N	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Table 4. Properties of Different Fabrics

Fabric Sl. No.	Weave	Warp Count (Ne)	Weft Count (Ne)	Ends / inch	Picks / inch	Fractional Cover	Thickness (mm)	Fabric GSM (g/m^2)	Porosity
1	3/1 twill	41	36	150	106	0.940	0.44	151	0.77
2	3/1 twill	38	27	150	98	0.957	0.32	169	0.65
3	3/1 twill	6	6	65	41	0.979	0.95	534	0.63
4	Plain	39	39	144	57	0.881	0.37	173	0.69
5	Plain	38	38	142	81	0.906	0.28	151	0.64
6	Plain	39	38	142	96	0.917	0.23	144	0.58
7	Plain	37	19	138	69	0.918	0.31	161	0.65
8	Plain	37	20	142	67	0.923	0.29	166	0.62
9	2/1 twill	9	13	73	47	0.930	0.42	292	0.54
10	3/1 twill	20	20	112	59	0.944	0.32	210	0.56
11	2/2 twill	20	19	122	57	0.986	0.46	215	0.69
12	2/2 twill	20	20	122	53	0.985	0.49	211	0.71
13	4 end satin	20	20	122	63	0.987	0.47	212	0.70

Table 5. Pair-Wise Comparison Matrix of Criteria

Criteria	Cover Factor	Thickness	GSM	Porosity	GM	Normalized GM
Cover Factor	1	0.67	1	1	0.905	0.221
Thickness	1.5	1	2	1	1.316	0.322
GSM	1	0.5	1	0.67	0.761	0.186
Porosity	1	1	1.5	1	1.107	0.271

Table 6. Thermal Resistance and TOPSIS Thermal Comfort Index of Fabrics with Their Corresponding Rank

Fabric Sl. No.	Thermal resistance ($K.m^2/W$)	Thermal resistance rank	TOPSIS thermal comfort index	TOPSIS thermal rank
1	0.0097	2	0.2388	6
2	0.0061	9	0.1377	9
3	0.0133	1	0.9417	1
4	0.0075	7	0.1757	8
5	0.006	10	0.1029	13
6	0.0049	12	0.1165	12
7	0.0064	8	0.1243	10
8	0.0059	11	0.1234	11
9	0.0077	6	0.3233	2
10	0.0047	13	0.1892	7
11	0.0079	5	0.2912	5
12	0.0091	3	0.3183	3
13	0.0085	4	0.299	4

5. Conclusions

TOPSIS method of MCDM has been applied to determine the thermal comfort index of fabrics. Four fabric parameters such as cover, thickness, GSM and porosity are considered as the decision criteria and their weights (relative importance) are evaluated by AHP method. The ranking of fabrics on account of comfort quality obtained by the TOPSIS method shows a good agreement with the ranking based on thermal resistance value. The method of fabric selection on the basis of comfort quality by TOPSIS score could substitute the need of measuring the fabric thermal resistance. Moreover, the proposed method is flexible and mathematically potent, so it can also be extended to determine the quality of fabrics with respect to moisture, tactile or physiological comfort.

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