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A non-compensatory compromised solution for material selection of bipolar plates for polymer electrolyte membrane fuel cell (PEMFC) using ELECTRE IV

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Abstract

A non-compensatory compromised approach in decision analysis is described within the context of the material selection of the bipolar plate of a polymer electrolyte fuel cell. ELECTRE IV, using embedded outranking relations, has been applied to determine the best compromised possible candidate material, considering all the performance indices including the cost criterion. This study also investigates the effect of replacing components of the selection parameters (i.e. design parameters) with performance indices to solve the same problem. The individual effect of the components of the performance indices on the ranking change in each possible candidate material is studied. It was shown that the ELECTRE IV lists candidate materials from best to worst, taking into account all the material selection criteria. The obtained results show good agreement with available reported results.

Keywords: ELECTRE IV; Non-compensatory solution; Polymer electrolyte membrane fuel cell; Material selection; Bipolar plate

1. Introduction

One of the major reasons for the interest in developing polymer electrolyte fuel cells has been the increasing concern about the environmental consequences of fossil fuel, particularly in transport applications. Polymer electrolyte fuel cells convert chemical energy directly into electrical energy so that only water is produced as waste, thus enabling a reduction in the use of fossil fuels and their resulting poisonous emissions into the environment [1].

An important component of the polymer electrolyte fuel cell stack is the bipolar plate. In a fuel cell stack, the bipolar plate has a multifunctional character, which separates the individual fuel cells; this enables to conduct electrical current from cell to cell, to feed the fuel and air to a gas diffusion layer-electrodes assembly and to remove the heat and reaction products [2]. Conventionally, the bipolar plate is made from graphite: its fair electronic conductivity and high chemical stability allow it to survive the fuel cell environment. However, the use of graphite is limited by the problems of its high cost and low compressive strength, as well as its difficulty machining to form the flow channels [1–9]. Hence, many efforts have been made to find the appropriate material selection for bipolar plates. The metallic materials include Aluminum, Ni–Cr alloys, Titanium, ferritic and austenitic stainless steels and they are potential candidates for bipolar plates. Prospective metallic materials for bipolar plates have been reported [1–27].

In a decisional process, the selection of choices for bipolar plates of PEM fuel cells derives from complex hierarchical comparisons among possible candidate materials which are often based on conflictual selection criteria. A large number of selection criteria, ranging from mechanical, thermal and electrical properties, to corrosion resistance and cost, all play a relevant role in orienting decision making. This shortcoming can be dealt with by adopting a multi-criteria approach with the selection of the most suitable materials among a set of possible materials.

The multiple criteria decision making (MCDM) models have two classifications: multiple objective decision making (MODM) and multiple attribute decision making. MODM have decision variable values which are determined in a continuous

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or integer domain with either an infinitive or a large number of choices, the best of which should satisfy the decision maker's constraints and preference priorities. MADM on the other hand are generally discrete, have a limited number of prespecified alternatives. They require both intra and inter attributes comparisons and involve explicit tradeoffs which are appropriate for the problem explained. We present here the MADM-ELECTRE IV method, which has a high potential to solve material selection problem of bipolar plate for polymer electrolyte fuel cell.

The aims of using the multiple criteria decision making (MCDM) [29] models in material selection procedure are:

- to help the material designer be consistent with fixed material selection criteria;
- to use a representative material database and a transparent assessment procedure;
- to help with the completion of the selection process, focusing on increasing its efficiency.

The detailed operations of the MCDM models, as well as some information concerning the material selection models with the concept of MCDM models, can be found in Refs. [28–31]. The aim of this paper is to use the ELECTRE IV [32–36] model, among MCDM methods, for bipolar plate materials selection for polymer electrolyte fuel cell applications.

2. Methodology

The ELECTRE IV consists of classification procedures which result in a ranking of all possible candidate materials in relation to each other. The method is designed to rank alternatives without using the relative criteria importance coefficients and it is equipped with embedded outranking relations framework [34].

This procedure offers the most satisfactory overall resolution to conflicts between the possible candidate materials which exist at the level of individual selection criteria. The method presents an incomparability relation which is useful when the material designer is not able to compare two candidate materials. On contrary, the method makes the procedures sensitive when a set of candidate materials very close to each other perform in an almost identical manner with all others [36].

To make the pair-wise comparison of candidate materials, the following notations are defined:

- $m_{\mathrm{p}}(M_k, M_i)$ is the number of performance indices for which candidate material M_i is strictly preferred to candidate material M_k;
- $m_{\mathrm{q}}(M_k, M_i)$ is the number of performance indices for which candidate material M_i is preferred to candidate material M_k;
- $m_{\mathrm{in}}(M_k, M_i)$ is the number of performance indices for which candidate materials M_i and M_k are considered indifferent, although candidate material M_i has a better performance than candidate material M_k;
- $m_{\mathrm{o}}(M_i, M_k) = m_{\mathrm{o}}(M_k, M_i)$ is the number of performance indices for which candidate material M_i and candidate material M_k perform identically.

If m is the total number of criteria, it is clear that:

$$m = m_{\mathrm{p}}(M_k, M_i) + m_{\mathrm{q}}(M_k, M_i) + m_{\mathrm{in}}(M_k, M_i) + m_{\mathrm{o}}(M_k, M_i) + m_{\mathrm{in}}(M_k, M_i) + m_{\mathrm{p}}(M_k, M_i) + m_{\mathrm{q}}(M_k, M_i) \quad (1)$$

The four levels of domination are represented in the outranking relation as follows:

- quasi-domination S_{q}: M_i outranks M_k with quasi-domination if

$$M_i S_{\mathrm{q}} M_k \Leftrightarrow \begin{cases} u_{\mathrm{p}}(M_k, M_i) + u_{\mathrm{q}}(M_k, M_i) = 0 \\ u_{\mathrm{in}}(M_k, M_i) \le 1 + u_{\mathrm{in}}(M_k, M_i) \\ \quad + u_{\mathrm{p}}(M_k, M_i) + u_{\mathrm{q}}(M_k, M_i) \end{cases} \quad (2)$$

- canonical domination S_{c}: M_i outranks M_k with canonical domination if

$$M_i S_{\mathrm{c}} M_k \Leftrightarrow \begin{cases} u_{\mathrm{p}}(M_k, M_i) = 0 \\ u_{\mathrm{p}}(M_k, M_i) \le u_{\mathrm{q}}(M_k, M_i) \\ u_{\mathrm{q}}(M_k, M_i) + u_{\mathrm{in}}(M_k, M_i) \\ \quad \le 1 + u_{\mathrm{in}}(M_k, M_i) \\ \qquad + u_{\mathrm{p}}(M_k, M_i) + u_{\mathrm{q}}(M_k, M_i) \end{cases} \quad (3)$$

- pseudo-domination S_{p}: M_i outranks M_k with pseudo-domination if

$$M_i S_{\mathrm{p}} M_k \Leftrightarrow \begin{cases} u_{\mathrm{p}}(M_k, M_i) = 0 \\ u_{\mathrm{q}}(M_k, M_i) \le u_{\mathrm{p}}(M_k, M_i) + u_{\mathrm{q}}(M_k, M_i) \end{cases} \quad (4)$$

- veto-domination S_{v}: M_i outranks M_k with veto-domination if

$$M_i S_{\mathrm{v}} M_k \Leftrightarrow \begin{cases} u_{\mathrm{p}}(M_k, M_i) = 0 \quad \text{or} \\ u_{\mathrm{q}}(M_k, M_i) = 1 \\ \text{not } M_k P_{v_j} M_i, \ \forall j \quad \text{and} \\ u_{\mathrm{q}}(M_k, M_i) \ge \dfrac{m}{2} \end{cases} \quad (5)$$

By representing the constant discrimination threshold $s(\lambda)$, the material designer is able to distinguish if one outranking relation is more credible than another, such that

- within the first step of classification, the strongest domination relations between those established are taken into consideration;
- within the second step of classification procedure, it is the two strongest domination relations that intercede in the procedure of ranking the remaining candidate materials, etc.

The final ranks of possible candidate materials are thus derived from an exploiting procedure. This procedure contains ascending and descending distillations and from these come either partial or complete final pre-orders [36]. Whether the final result is a partial pre-order (not containing a relative ranking of all of the possible candidate materials), rather than a complete pre-order, depends on the level of consistency between the rankings from the two orders. Briefly, the exploitation procedure in ELECTRE IV starts by deriving from the fuzzy relation

Table 1
List of candidate materials for bipolar plates

Material number	Material name
1	316 Austenitic stainless steel
2	310 Austenitic stainless steel
3	317L Austenitic stainless steel
4	316L Austenitic stainless steel
5	Aluminium (gold plated)
6	AISI 446 ferritic stainless steel
7	AISI 436 ferritic stainless steel
8	AISI 444 ferritic stainless steel
9	AISI434 ferritic stainless steel
10	304 Austenitic stainless steel
11	Titanium (coated with nitride)
12	A560 (50Cr–Ni)

two complete pre-orders [37]. A final partial pre-order Z is then built by the intersection of the two complete pre-orders, Z_1 and Z_2. These pre-orders are obtained according to two variants of the same principle, both acting in an antagonistic way on the floating actions. The partial pre-order Z_1 is defined as a partition on the set into q ordered classes, $\bar{B}_1, \ldots, \bar{B}_h, \ldots, \bar{B}_\mathrm{q}$, where $\bar{B}_1$ is the head-class in Z_1. Each class $\bar{B}_h$ is composed of ex-aequo elements according to Z_1. The complete pre-order Z_2 is determined in a similar manner, using ordered classes, $\bar{B}'_1, \ldots, \bar{B}'_2 \quad \bar{B}'_h, \ldots, \bar{B}'_u$ with $\bar{B}'_u$ being the head-class. Each one of these classes is obtained as a final distilled of a distillation procedure. The detailed designed to compute Z_1 starts (first distillation) by defining an initial set $D_0 = A$ (first distillation). This leads to the first final distilled $\bar{B}_1$. After finding $\bar{B}_h$, in the distillation $h+1$, the procedure sets $D_0 = A \backslash (\bar{B}_1 \cup \ldots \bar{B}_h)$. According to Z_1, the actions in class $\bar{B}_h$ are, preferred to those of class $\bar{B}_{h+1}$ i.e., descending (top-down). The procedure leading to Z_2 is quite identical, except that now the actions in $\bar{B}_{h+1}$ are preferred to those in class $\bar{B}_h$; ascending (bottom-up) distillation. A complete pre-order is finally suggested taking into account the partial pre-orders (i.e. by intersecting Z_1 and Z_2) and some additional consideration [37]. The detailed operations of the ELECTRE IV methods and its exploitation procedure can be found in Refs. [29–37].

3. Modeling and simulation

An analytical model is developed by authors in Ref. [27] to predict the performance of bipolar plates for polymer electrolyte fuel cell (Table 1). The obtained performance indices in that model are taken into account when producing the decision matrix in the given problem. For modeling a given problem, at the initial stage, one should select all the material properties related to the given functional requirements. Also, minimum constraints on the materials under question should be applied to screen a number of candidate materials from all the materials available in a database. One can use the Cambridge Engineering Selector (CES) software and database for finding the proper candidate materials and related properties, which are developed by Ashby and Cambridge University. The produced decision matrix is presented in Tables 2 and 3. For modeling the given problem,

Table 2
Performance decision matrix for material selection of bipolar plate for PEFC

Performance index number	Design concept	Material number (performance index)	1	2	3	4	5	6	7	8	9	10	11	12
1	Maximize stiffness-minimize weight	$E^{1/3}/\rho$	0.729	0.840	0.867	0.768	2.474	0.822	0.891	0.821	0.950	1.018	1.824	0.952
2	Maximize strength-minimize weight	$\sigma_\mathrm{f}^{1/2}/\rho$	2.812	2.781	3.214	3.714	5.814	3.240	3.141	3.10	3.351	3.735	5.792	3.342
3	Minimize thermal distortion	$\sigma_\mathrm{f}/E\alpha$	0.147	0.094	0.133	0.111	0.036	0.246	0.2	0.198	0.159	0.092	0.142	0.200
4	Minimize thermal shock and distortion	σ/κ	19.02	29.31	24.10	24.43	158.8	13.12	15.70	15.63	20.97	40.26	40.67	16.64
5	Maximize heat flux	$\kappa/\mu^{1/2}$	270.9	251	244.4	269.6	629.4	295.4	305.8	292.0	267.3	232.0	203.9	237.3
6	Minimize hydrogen embrittlement	K_t^2/E	253.5	44.15	174	322.0	4.224	76.60	28.95	51.49	42.52	12.42	4.385	50.56
7	Maximize electronic conductivity	Resistivity (μΩ cm)	71	80	74	69	3.9	65	55	57	62	77	60.3	40
8	Minimize cost	Cost (CAN$/Kg)	5.089	10.83	7.142	5.184	50	4.954	5.69	5.53	5.76	5.99	34.56	10.37
9	Minimize corrosion rate	Corrosion rate (in./yr)	0.081	0.081	0.23	0.081	2	0.105	0.105	0.105	0.105	0.081	0.061	0.005
10	Minimize cost-maximize environmental impact	Recycle fraction	0.7	0.7	0.7	0.7	0.9	0.75	0.75	0.75	0.75	0.7	0.65	0.3
11	Minimize separation of the anode and cathode components	Hydrogen permeability	5.1	5.4	5.3	2.2	160	0.69	0.69	0.69	0.69	5.4	0.32	4.2

Table 3
The threshold values of each attribute for material selection of the bipolar plate

Performance index	Thresholds		
	Indifference threshold	Preference-threshold	Veto-threshold
$E^{1/3}/\rho$	0.5	1	1.5
$\sigma_{\mathrm{f}}^{1/2}/\rho$	0.1	0.2	0.5
$\sigma_{\mathrm{f}}/E\alpha$	0.2	0.25	0.75
σ/κ	0.02	0.05	0.15
$\kappa/\mu^{1/2}$	0.08	0.75	2
K_{t}^{2}/E	5	20	50
Resistivity	10	15	25
Price	3	5	10
Corrosion rate	0.01	0.02	0.05
Recycle fraction	0	0.05	0.1
Hydrogen permeability	0.1	0.5	2

one uses LAMSADE computer code, which implements ELECTRE methods. It runs on Windows 3.1, 95, 98, 2000, Millennium and XP. This software was developed by Bernard Roy et al. at the University of Paris Dauphine.

An analytical solution is considered for examining and evaluating the criteria and their related performance indexes in the studied case. This analytical solution has been covered recently in the authors' papers accepted for publication in the Journal of Power sources [26] and in the Journal of the Electrochemical Society [27]. This is based on the following considerations on the hydrogen/oxygen fuel cell.

For PEMFC, hydrogen is oxidized at the anode (according to the following equation) and protons enter the electrolyte and are transported to the cathode:

$$\mathrm{H}^2 \rightarrow \ 2\mathrm{H}^+ + 2\mathrm{e}^- \tag{6}$$

At the cathode, the supplied oxygen reacts according to:

$$\mathrm{O}_2 + 4\mathrm{H}^+ + 4\mathrm{e}^- \rightarrow \ 2\mathrm{H}_2\mathrm{O} \tag{7}$$

These electrochemical reactions are characterized by the thermodynamic equilibrium potential described by the Nernst equation:

$$E(j) = E^0 + \frac{RT}{2F}\ln\left(\frac{P_{\mathrm{H}_2}^2 P_{\mathrm{O}_2}}{P_{\mathrm{H}_2\mathrm{O}}^2}\right) \tag{8}$$

Electrical energy comes from a PEMFC only when a current is drawn, but the actual cell potential $\Delta E(j)$ is decreased from its ideal potential because of irreversible losses:

$$\Delta E(j) = E_{\mathrm{c}}(j) - E_{\mathrm{a}}(j) = E(j) - (|\eta_{\mathrm{a}}(j)| + |\eta_{\mathrm{c}}(j)| + R_{\mathrm{e}}(j)) \tag{9}$$

The bipolar plates are used as current collectors and also to connect the cells in series for a stack which provides us a system with a certain power. The measure of power per unit mass for a fuel cell stack, including n similar cells, is called specific power:

$$P = \frac{n[E(j) - (|\eta_{\mathrm{a}}(j)| + |\eta_{\mathrm{c}}(j)| + R_{\mathrm{e}}(j))]J(j)}{M} \tag{10}$$

where M is the total mass of the fuel cell stack. The total mass of the other parts of PEMFC – including membranes, cathodes and anodes – compared to the mass of the bipolar plates in a specified fuel cell stack is negligible, and replacing the mass of bipolar plates m instead of total mass M in the Eq. (10) can be considered as a good approximation. As a result, a light and highly conductive bipolar plate, which satisfies the mechanical, thermal, corrosive and electrochemical conditions of a PEFC, should be a suitable selection for increasing the specific power density of the stack. A light bipolar plate with specified thickness t, length a and width b, should meet the constraint on its stiffness, S, meaning that it should not deflect under a static load F during the operation time of the fuel cell. This constraint requires that the stiffness of the bipolar plate be high enough to tolerate the maximum possible deflection of an applied load. To determine the stiffness, the bipolar plate is modeled as a simply supported plate subject to a uniform load applied over the entire in-plane area of the bipolar plate:

$$S = \frac{F}{y_{\mathrm{m}}} \geq \chi\frac{Et^3}{b^4} \tag{11}$$

χ can be obtained from the following relation:

$$\chi = -0.00505\left[\left(\frac{a}{b}\right)^5\right] + 0.0068\left[\left(\frac{a}{b}\right)^4\right] - 0.0306\left[\left(\frac{a}{b}\right)^3\right] + 0.0371\left[\left(\frac{a}{b}\right)^2\right] + 0.0835\left[\left(\frac{a}{b}\right)\right] - 0.0519 \tag{12}$$

Decreasing the geometry parameters of the bipolar plate reduces the mass of the fuel cell stack, but it is noted that the stiffness constraint should be met. Introducing the Eqs. (11) and (12) into mass relation ($m = \rho V$) leads to the following relation:

$$m \geq \left(\frac{\rho}{E^{1/3}}\right)\left(\frac{Sb^7}{\chi}\right)^{1/3} a \tag{13}$$

Obviously, the best material for a light, stiff bipolar plate is that with large values of $E^{1/3}/\rho$ index.

In the strength-limited design, the objective function is still to minimize the mass but the constraint is now that of strength. Therefore, the bipolar plate has to be designed in such a way that it will not fail under a given load. This means that it should stand up to the maximum bending stress of a uniform load applied over the entire area of plate. The maximum stress in a simply supported plate due to a uniform load is defined as:

$$\sigma_{\mathrm{F}} \geq \beta\frac{Fb^2}{t^2} \tag{14}$$

where β follows:

$$\beta = -0.00907\left[\left(\frac{a}{b}\right)^5\right] + 0.0097\left[\left(\frac{a}{b}\right)^4\right] - 0.0137\left[\left(\frac{a}{b}\right)^3\right] + (-0.1883)\left[\left(\frac{a}{b}\right)^2\right] + 0.8678\left[\left(\frac{a}{b}\right)\right] - 0.3874 \tag{15}$$

Again, introducing the Eqs. (14) and (15) into mass relation ($m = \rho V$) will result in the following equation:

$$m \geq \left(\frac{\rho}{\sigma_{\mathrm{F}}^{1/2}}\right)(F\beta)^{1/2}ab^2 \tag{16}$$

The mass is minimized by selecting materials with the large values of the index $\sigma_{\mathrm{F}}^{1/2}/\rho$.

When the fuel cell starts operating, the temperature of the bipolar plate suddenly changes by ΔT, thermal strains $\varepsilon_{\mathrm{t}}=1/2(E\alpha(T_{\mathrm{i}}-T_{0}))$ happen and the temperature gradient through the thickness of the plate will be linear. The maximum thermal stress in the given bipolar plate is defined as:

$$\sigma_{\mathrm{t}} = \frac{1}{2}E\alpha\left[T_{\mathrm{i}} + T_{\mathrm{o}} - 2T_{\mathrm{o}} + \frac{1-\nu}{3-\nu}(T_{\mathrm{i}} - T_{\mathrm{o}})\right] \tag{17}$$

If this stress exceeds the tensile stress of the bipolar plate, a fracture results. The safe temperature interval ΔT is therefore maximized by choosing a material with a large value of $\alpha_{\mathrm{t}}/E\alpha$. Also, the plate distortion due to temperature changes is proportional to the thermal strain gradient and is defined by using Fourier's Law in the steady-state condition:

$$\frac{\mathrm{d}\varepsilon_{\mathrm{t}}}{\mathrm{d}x} = \frac{\alpha\,\mathrm{d}T}{\mathrm{d}x} = \left(\frac{\alpha}{\kappa}\right)Q \tag{18}$$

For a given geometry and heat flow, the distortion is reduced by selecting material with large values of the index (α/κ). The heat content of the bipolar plate per unit area, when heated through a temperature interval of ΔT, gives the objective function:

$$Q = \frac{\sqrt{2\xi}\,\Delta T\kappa}{\mu^{1/2}} \tag{19}$$

The heat capacity of the bipolar plate is minimized by choosing material with a high value of $\kappa/\mu^{1/2}$.

When the hydrogen embrittlement happens in the bipolar plate, it defects elastically until it fractures. The elastic energy per unit stored in the bipolar plate is the integral over the volume of:

$$U = \int_0^{\sigma_F = \frac{CK_{\mathrm{t}}}{\sqrt{\pi a_f}}} \sigma\,\mathrm{d}\varepsilon = \frac{C^2}{2\pi a_{\mathrm{f}}}\left(\frac{K_{\mathrm{t}}^2}{E}\right) \tag{20}$$

For a given initial flaw size, energy is maximized by choosing materials with large values of K_{t}^2/E.

The high resistance to corrosion in high acid environments is another essential requirement for a bipolar plate; one can consider the amount of corrosion in sulphuric acid (lower is desirable) as the corrosion resistance performance index.

Since high electrical conductivity is desirable in order to enhance the specific power density of the stack according to the Eq. (10), one can make the amount of electrical resistivity of the bipolar plate (lower is desirable) the electrical criterion.

Cost criteria are divided into two main parts; (1) the first one is proportional to the density of the bipolar plate according to Eqs. (6) and (7); (2) the price of the base material, which is specified by the fraction recycled and the price of the material (higher and lower values are desirable for both, respectively). The fraction recycled is a measure of the proportion of a bipolar plate in use in products which can economically be recycled. The other criterion is the gas compatibility of the bipolar plate, which is proportional to hydrogen permeability. A small number for this index denotes desirability for separation of the anode and cathode components.

In order to check the sensitivity of the results to the inclusion of indices, one solved the same decision problem considering the material properties (design parameters) as individual criteria.

Based on the above consideration, we will make the comparison of candidate materials and present the two indices of concordance and global concordance. By determining these values, we will show that the material designer will be able to evaluate the degree of concordance between such comparisons and the adapted system of weights and thresholds.

The concordance index is defined as follows:

$$c_j(M_i, M_k) = \frac{g(M_i) + p_j - g(M_k)}{p_j - q_j} \Leftrightarrow q_j \prec g(M_i) - g(M_k) \leq p_j \tag{21}$$

$$c_j(M_i, M_k) = 0 \Leftrightarrow g(M_i) - g(M_k) \leq q_j \tag{22}$$

$$c_j(M_i, M_k) = 1 \Leftrightarrow p_j \leq g(M_i) - g(M_k) \tag{23}$$

$c_j(M_i, M_k)$ shows the degree of concordance with the assertion that M_i outranks (is at least as good as) M_k. The concordance index decreases linearly from its maximum value when $g_j(M_k)$ passes the indifference threshold and it reaches its minimal value when $g_j(M_k)$ reaches its preference threshold.

4. Results and discussion

Table 4 and Figs. 1 and 2 summarize the results of distillation procedures and final ranking of the candidate materials obtained using the performance indices as attributes of the decision matrix.

One cannot extract the same results from Table 2 (i.e. decision matrix) due to the conflicting tradeoffs between selection criteria. The final ranks of candidate materials in Figs. 1 and 2 are derived by a distillation procedure in Table 4 whose outcome contains two orders: descendant and ascending distillation results. The candidate materials which have the highest rank in both orders fulfill the objectives that the material designer has fixed and are suitable and reliable for use.

For more information, the credibility ranking matrices are presented in Appendices 1 and 2. When one considers the performance indices in the decision matrix, not including the criterion of cost (price of material and recycle fraction), material 4 [1–14,18] is the best choice and materials 1 [1–14,18], 6 [24,25], 11 [9] and 12 [1,19] are considered the second choices (see Fig. 1). By adding the cost criterion to other performance indices, the rank of materials 11 and 12 goes down and materials 1, 4 and 6 keep their ranks in comparison to the first case. For mass production of the PEFCs, the cost criterion plays an essential role and, as seen, materials 4, 1 and 6 have high performances in both cases. They are therefore the most appropriate

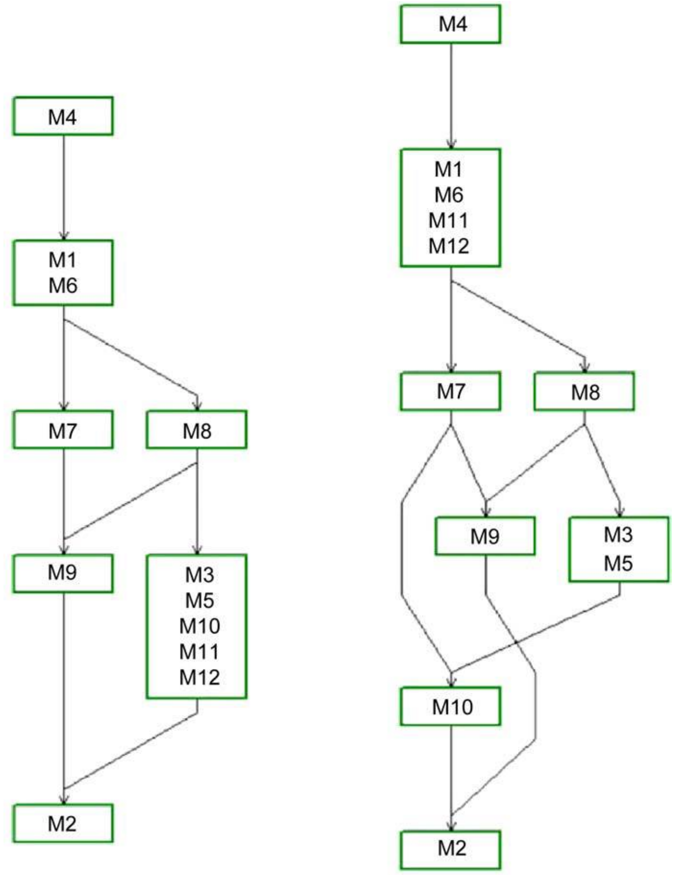
Table 4
Results of distillation procedures

Material number	Results of distillation procedure							
	Performance without the criterion of cost		Performance with the criterion of cost		Design parameter without the criterion of cost		Design parameter with the criterion of cost	
	Descending distillation ranking	Ascending distillation ranking	Descending distillation ranking	Ascending distillation ranking	Descending distillation ranking	Ascending distillation ranking	Descending distillation ranking	Ascending distillation ranking
1	2	1	2		4	1	3	1
2	4	5	4	4	4	3	3	2
3	4	1	4	1	4	1	3	1
4	1	1	1	1	4	1	3	1
5	4	1	4	1	4	1	3	1
6	2	1	2	1	4	1	3	1
7	2	2	2	2	4	1	3	1
8	3	1	3	1	3	2	2	3
9	3	4	3	3	2	1	1	1
10	4	3	4	1	4	1	3	1
11	2	1	4	1	4	1	3	1
12	2	1	4	1	1	1	3	1

selections that present the highest performances among the set of possible candidate materials.

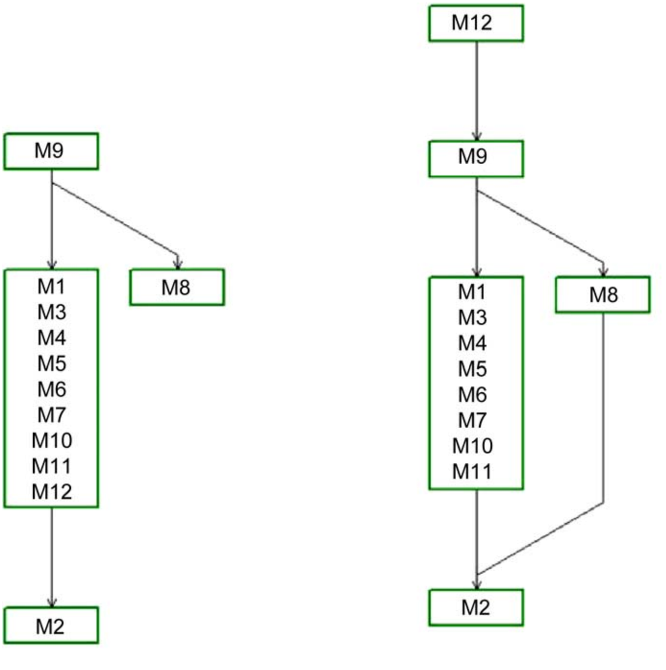
In order to evaluate the individual effect of design parameters (components of the performance indices) as attributes in the decision matrix, compared to the ranking change in each candidate material, the solution is repeated without – and with – considering the criterion of cost. For comparison purposes, the results of the two new cases are shown in Table 4, Fig. 2 and Appendices 3 and 4. The new results show that the ranking of candidate materials changes significantly in comparison to the case where the performance indices are considered as attributes in the decision matrix. Materials 12 and 9 keep their ranks as first choices without – and with – the criterion of cost, respectively, so they are reliable to select as the appropriate materials.

Finally, it is worth noting that material 2 shows a rank that is significantly worse than other alternatives. The reason is clear: all criteria values for material 8 dominate those for material 2 regarding the defined threshold values. Accordingly, one may



(b) with the criterion of cost (a) without the criterion of cost

Fig. 1. Ranks of candidate materials with considering the performance indices: (a) without the criterion of cost and (b) with the criterion of cost.



(b) With the criterion of cost (a) Without the criterion of cost

Fig. 2. Ranks of candidate materials with considering the design parameters: (a) without the criterion of cost and (b) with the criterion of cost.

decide to repeat the solution by eliminating this material – which clearly is the worst material solution and has no power to compete with other alternatives – in order to add to the accuracy of the final decision, particularly when the method is linked to a material database.

Compromise decision-making: From Table 4 and Figs. 1 and 2, one should notice that the ELECTRE IV for both cases – performance and design parameter – prefers the Austenitic and ferritic stainless materials. Given the high rank for the criterion of cost in different candidate materials in Table 4, it is presumed that the designers' expectations and conflicts are critical in making a final decision. Therefore, the decision space is constrained such that the criterion of cost does not exceed the threshold rank of 6. As a result, material 12 (which has a high price and the lowest recycle fraction) is dismissed and the decision is reduced to finding a compromised solution between materials 4, 6 and 9 [24,25], which have cost ranks better than the threshold. Recalling Figs. 1 and 2, the ranking curve for the case – without considering the criterion of cost – indicates that material 4 has the best rank among the three candidate materials which have the highest performance. On the other hand, considering the decision matrix in Table 2, it becomes clear that materials 9 and 6 are interchangeable (their material properties are fairly close: both ferritic stainless steels). As a result, material 6 (i.e., AISI 446) is preferred over material 4 since it brings a lower price and higher recycle fraction. This encourages us to select material 4 as the best choice and shows that, in an approach which involves replacing the material 4 already in use with a newer material, material 6 is therefore the most appropriate. This confirms the obtained results about the applicability of material 6 in Refs. [24,25] compared to material 4. In addition, the materials which are selected as the best choices by the ELECTRE IV are in agreement with the reported results [1–26] which contain information about the applicability of these materials for the bipolar plate in PEFC.

5. Concluding remarks

A multi-criteria approach for the material selection of the bipolar plate for PEFC is presented. The fundamental problem in the material selection of the bipolar plate with multifunctional character is the trade-off and conflict between criteria. Separate optimization of criteria is impossible, thus the problem is inherently multi-objectives. For this shortcoming, a non-compensatory solution using embedded outranking relations based on the ELECTRE IV method has been applied for material selection of the bipolar plate in polymer electrolyte fuel cell. The decision matrix is introduced for selecting the appropriate materials for the bipolar plate, based on the possible metallic candidate material and the performance indices as the attributes. This is done both with and without the criterion of cost, which plays an essential role for mass production of bipolar plates. The individual effect of the components of the performance indices on the ranking change in each possible candidate material is studied. The ELECTRE IV lists candidate materials from best to worst, taking into account all the material selection criteria. These results show good agreement with available reported results.

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Appendix A. Nomenclature

M_i	candidate material
S_q	quasi-domination
S_c	canonical domination
S_p	pseudo-domination
S_v	veto-domination
E	elastic modulus of bipolar plate
ρ	density of bipolar plate
σ_f	tensile strength of bipolar plate
α	expansion coefficient of bipolar plate
κ	thermal conductivity of bipolar plate
μ	thermal diffusivity
K_t	the fracture toughness of bipolar plate

Appendix B

Ranking and credibility matrixes for performance analysis without the criterion of cost.

Material ID number	1	2	3	4	5	6	7	8	9	10	11	12
1	1	0.8	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0
4	0	1	0	1	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0
6	0	0.2	0	0	0	1	0	0	0.8	0	0	0
7	0	0	0	0	0	0	1	0	0.8	0	0	0
8	0	0.2	0	0	0	0	0.6	1	0	0	0	0
9	0	0.2	0	0	0	0	0	0	1	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0
11	0	0	0	0	0	0	0	0	0	0.8	1	0
12	0	0.8	0	0	0	0	0	0	0	0.2	0	1

Material ID number	4	1	6	11	12	7	8	3	5	9	10	2
4	I	P	P	P	P	I	P	P	P	P	P	P
1	P^-	I	I	I	I	P	P	P	P	P	P	P
6	P^-	I	I	I	I	P	P	P	P	P	P	P
11	P^-	I	I	I	I	P	P	P	P	P	P	P
12	P^-	I	I	I	I	P	P	P	P	P	P	P
7	P^-	P^-	P^-	P^-	P^-	I	R	R	R	P	P	P
8	P^-	P^-	P^-	P^-	P^-	R	I	P	P	P	P	P
3	P^-	P^-	P^-	P^-	P^-	R	P^-	I	I	R	P	P
5	P^-	P^-	P^-	P^-	P^-	R	P^-	I	I	R	P	P
9	P^-	P^-	P^-	P^-	P^-	P^-	P^-	R	R	I	R	P
10	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	R	I	P
2	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	I

I: indifference; P: strong preference; P^-: weak preference; R: incomparable.

Appendix C

Ranking and credibility matrixes for performance analysis with the criterion of cost.

Material ID number	1	2	3	4	5	6	7	8	9	10	11	12
1	1	0.8	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0
4	0	1	0	1	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0
6	0	0.2	0	0	0	1	0	0	0.8	0	0	0
7	0	0	0	0	0	0	1	0	0.8	0	0	0
8	0	0.2	0	0	0	0	0.6	1	0	0	0	0
9	0	0.2	0	0	0	0	0	0	1	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0
12	0	0.8	0	0	0	0	0	0	0	0	0	1

Material ID number	4	1	6	7	8	3	5	9	10	11	12	2
4	I	P	P	P	P	I	P	P	P	P	P	P
1	P^-	I	I	P	P	P	P	P	P	P	P	P
6	P^-	I	I	P	P	P	P	P	P	P	P	P
7	P^-	P^-	P^-	I	R	R	R	P	R	R	R	P
8	P^-	P^-	P^-	R	I	P	P	P	P	P	P	P
3	P^-	P^-	P^-	R	P^-	I	I	R	I	I	I	P
5	P^-	P^-	P^-	R	P^-	I	I	R	I	I	I	P
9	P^-	P^-	P^-	P^-	P^-	R	R	I	R	R	R	P
10	P^-	P^-	P^-	R	P^-	I	I	R	I	I	I	P
11	P^-	P^-	P^-	R	P^-	I	I	R	I	I	I	P
12	P^-	P^-	P^-	R	P^-	I	I	R	I	I	I	P
2	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	I

I: indifference; P: strong preference; P^-: weak preference; R: incomparable.

Appendix D

Ranking and credibility matrixes of decision matrix with the design parameter without the criterion of cost.

Material ID number	1	2	3	4	5	6	7	8	9	10	11	12
1	1	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0
4	0	1	0	1	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0
8	0	0.2	0	0	0	0	0	1	0	0	0	0
9	0	0.2	0	0	0	0	0	0.8	1	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0
12	0	1	0	0	0	0	0	0	0	0	0	1

Material ID number	12	9	1	3	4	5	6	7	8	10	11	2
12	I	P	P	P	P	I	P	P	P	P	P	P
9	P^-	I	P	P	P	P	P	P	P	P	P	P
1	P^-	P^-	I	I	I	I	I	I	R	I	I	P
3	P^-	P^-	I	I	I	I	I	I	R	I	I	P
4	P^-	P^-	I	I	I	I	I	I	R	I	I	P
5	P^-	P^-	I	I	I	I	I	I	R	I	I	P
6	P^-	P^-	I	I	I	I	I	I	R	I	I	P
7	P^-	P^-	I	I	I	I	I	I	R	I	I	P
8	P^-	P^-	R	R	R	R	R	R	I	R	R	P
10	P^-	P^-	I	I	I	I	I	I	R	I	I	P
11	P^-	P^-	I	I	I	I	I	I	R	I	I	P
2	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	P^-	I

I: indifference; P: strong preference; P^-: weak preference; R: incomparable.

Appendix E

Ranking and credibility matrixes of decision matrix with the design parameter with the criterion of cost.

Material ID number	1	2	3	4	5	6	7	8	9	10	11	12
1	1	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0
4	0	1	0	1	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0
8	0	0.2	0	0	0	0	0	1	0	0	0	0
9	0	0.2	0	0	0	0	0	0.6	1	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0
12	0	1	0	0	0	0	0	0	0	0	0	1

Material ID number	9	1	3	4	5	6	7	8	10	11	12	2
9	I	P	P	P^-	P	P	P	P	P	P	P	P
1	P^-	I	I	I	I	I	I	R	I	I	I	P
3	P^-	I	I	I	I	I	I	R	I	I	I	P
4	P^-	I	I	I	I	I	I	R	I	I	I	P
5	P^-	I	I	I	I	I	I	R	I	I	I	P
6	P^-	I	I	I	I	I	I	R	I	I	I	P
7	P^-	I	I	I	I	I	I	R	I	I	I	P
8	P^-	R	R	R	R	R	R	R	R	R	R	R
10	P^-	I	I	I	I	I	I	R	I	I	I	P
11	P^-	I	I	I	I	I	I	R	I	I	I	P
12	P^-	I	I	I	I	I	I	R	I	I	I	P
2	P^-	P^-	P^-	P^-	P^-	P^-	P^-	R	P^-	P^-	P^-	I

I: indifference; P: strong preference; P^-: weak preference; R: incomparable.

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