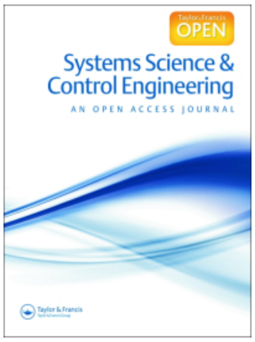

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Decision science: a multi-criteria decision framework for enhancing an electoral voting system

Raphael Kwaku Botchway [a], Abdul Bashiru Jibril [b,c], Zuzana Komínková Oplatková [a], Roman Jasek [a] and Michael Adu Kwarteng [b]

[a]Faculty of Applied Informatics, Tomas Bata University in Zlin, Zlin, Czech Republic; [b]Faculty of Management and Economics, Tomas Bata University in Zlin, Zlin, Czech Republic; [c]Rabat Business School, International University of Rabat, Technopolis Rabat-Shore Rocade Rabat-Salé, Morocco

ABSTRACT
The deployment of effective and efficient information and communication technologies (ICTs) remains a major priority for the smooth running of electoral management systems worldwide. To guarantee the integrity of the electoral voting process and ensure the reliability of the electoral results, selecting the correct vendor with the requisite expertise is a key success factor that cannot be ignored. This paper proposes a framework for selecting a vendor to offer support and implementation services using the Voting Solutions for All People (VSAP) programme as a case study. Our proposed framework uses a hybrid multi-criteria decision-making (MCDM) methodology comprising the analytical hierarchy process (AHP) and technique for order of preference by similarity to ideal solution (TOPSIS). Consistency tests and sensitivity analysis are carried out to check the quality of the expert's inputs and the robustness of our approach respectively. Our work offers a better understanding of the role a hybrid AHP-TOPSIS method plays in selecting a suitable vendor to play an effective role in enhancing the voter system's credibility in a democratic process. Again, the study extends the application of MCDM methods to areas such as supplier selection for electoral voting systems.

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MCDM; AHP; TOPSIS; elections; procurement; ICT; vendor

Introduction

In every representative democracy, the presence of a credible electoral/voting management system guarantees the right of all eligible citizens to exercise their franchise in a free and fair manner to reinforce political accountability. Democracy, defined from the perspective of the Oxford English Dictionary, 'is a system of government by the whole population or all the eligible members of a state, typically through elected representatives' (Oxford, n.d.). This implies that a functioning democracy requires people to be elected which is achieved through voting. Democracy reinforces choice, participation, political accountability, transparency, and the rule of law. Voting as we know is the foundation for any successful democracy hence must be accessible and secure for all eligible voters since the right to vote and participate in the governance of one's country is considered the cornerstone of democracy. Interestingly, this fundamental right is recognized and enshrined in 'Article 21 of the Universal Declaration of Human Rights adopted unanimously by the United Nations General Assembly in 1948' (Assembly, 1948). However, without an exhaustive, credible, and reliable electoral roll, the right to vote cannot be achieved.

Over the years, there have been some continuous efforts to enhance the structures, operational systems, and procedures used to conduct elections in Los Angeles County, California, United States of America (U.S.A.) in a manner that guarantees transparency, authenticity, and accessibility. Despite the deployment and usage of information and communications technologies (ICTs) to primarily promote transparency and accessibility in the voting system processes, a lot more work still needs to be done to resolve the challenges presented by this outdated system that serves a sophisticated and growing electorate. A 2017 report launched by the Brennan Centre for Justice (Norden & Vandewalker, 2017) mentioned voter machines as one of the critical elements of the election system infrastructure of the United States (U.S.) that needed to be secured from hackers to avoid casting doubts on the integrity of vote tallies. While we cannot provide any form of evidence to substantiate the claim that the voting gadgets of the US have been compromised or not by foreign entities, the question as to

CONTACT Raphael Kwaku Botchway botchway@utb.cz, ralph.botchway@gmail.com
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whether the voting machines can be hacked remains unanswered (Brian, 2016; Laurie, 2016; NPR Staff, 2016). The experiences of countries like Ukraine and South Africa (SA) from cyberattacks require the US to take urgent steps to eliminate the vulnerabilities inherent in its voting system to prevent any form of hacker exploitation in the future (Norden & Vandewalker, 2017). It is public knowledge that the Ukrainian presidential elections in 2014 was targeted by cyber attackers, who deleted a sizeable number of files to render the voting system unusable days before the election (Mark, 2014). The election proceeded as planned only after officials restored the system from backups. Again, in South Africa's first ever democratic historic elections organized in 1994, a cybercriminal attempted rigging the elections by altering the total votes tallied (John, 2010). After investigations, it was observed that the hacker logged into a remote computer of the election management system and manipulated the votes tallied for some parties participating in the elections (Martin, 2010).

While it is obvious that an outdated twentieth-century election system is highly vulnerable to a twenty-first-century threat, it is commendable that the Brennan Centre for Justice (Norden & Vandewalker, 2017) report of 2017 mentioned voting machines as a key element of the US election infrastructure that needed to be secured. To safeguard the integrity of the electoral process and ensure the reliability of the electoral results, selecting the correct vendor (herein referred to as supplier) with the requisite expertise is a key factor that cannot be ignored. Our work considers the selection of a vendor to supply a ballot marking device (BMD) for the 'voter solutions for all people' (VSAP) programme in Los Angeles County (County of Los Angeles, 2017).

It is worth noting that suppliers are active players in the supply chain life cycle. According to (Gülen, 2007), purchased materials and services constitute 80% of total production costs in most high technology industries. Essentially, there exist two (2) classes of supplier/vendor selection that are prominent in supply/vendor selection literature. They are single-sourcing and multi-sourcing. For a single-source vendor selection, the firm/buyers' needs are entirely satisfied by one supplier with the buyer having to make only one decision. However, this is different when it comes to the multi-sourcing approach which happens to be the most common. The multi-sourcing approach is used when multiple suppliers are selected because of the inability of a single supply to satisfy the firm/buyer's orders. Consequently, firms must select the best suppliers as well as allocate quantities that each selected firm must supply to create and maintain a consistent competitive environment (Alyanak & Armaneri, 2009). Unlike single sourcing, multi-sourcing offers certainty in terms of timely product delivery and flexibility of product orders due to the aggregate variety of orders placed by the firm (Ghodsypour & O'Brien, 1998; Jolai et al., 2011).

In this sense, multicriteria decision-making methods (MCDM) stand out as the preferred approach that supports the decision analysis process by measuring the general criteria to select the alternative that best suits the scenario (Oey et al., 2018).

Although several studies (Bayode et al., 2020; Behzadian et al., 2012; Biderci & Canbaz, 2019; Sharma & Sehrawat, 2020) have been realized in the field of MCDM literature, it can be noticed that the application of hybrid decision-making techniques like AHP-TOPSIS within the context of electoral material procurement has not attracted the required attention.

Since the usage of the BMD constitutes a key component of the voter system design under the VSAP project, selecting the right vendor with the requisite expertise remains a priority as far as the success of the project is concerned.

Specifically, the study seeks to propose a novel MCDM framework for analysing criteria that influences decision-making and evaluation when selecting the most suitable BMD vendor using a hybrid multi-criteria decision (AHP-TOPSIS) model. Additionally, our hybrid AHP-TOPSIS tool will help to optimize the vendor selection process in electoral management organizations and, at the same time contribute significantly to BMD vendor selection literature considering the limited cases and examples in this area of knowledge.

To this end, we affirm to the best of our knowledge that no study in MCDM literature has applied a hybrid AHP-TOPSIS model for the selection of a BMD vendor in the electoral material procurement process. In sum, the main contributions of our research are outlined as follows:

- broaden the MCDM literature and pioneer the consideration of supplier/vendor selection problems in the voter systems procurement process.
- to assist election material procurement officers to make relevant decisions
- extend the frontiers and applications of hybrid MCDM methods in enhancing the evaluation of electoral service providers in the electoral material procurement process.
- MCDM methods contribution to voter system design in a democracy

The remainder of the paper is structured as follows: firstly, we provide an elaborate review or background of related literature and introduce the vendor selection methods. We proceed further by giving an overview of the methodology deployed, followed by a numerical illustration (case study) after which sensitivity analysis is performed. The results obtained are then discussed together with the study implications. Lastly, we present the concluding remarks.

Background

Supplier/vendor selection methods

Earlier works by Ho et al. (2010) reviewed MCDM related literary works for supplier/vendor selection and evaluation. Several other researchers over the last few years have also incorporated various independent or hybrid MCDM approaches (Bayode et al., 2020; Behzadian et al., 2012; Biderci & Canbaz, 2019; Deng et al., 2014; Sharma & Sehrawat, 2020; Zhang & Su, 2019). According to (Chen, 2011; Ha & Krishnan, 2008) combining more than one technique for vendor selection enhances the quality of the models used. Examples of Independent or single MCDM approaches used in earlier studies include AHP (Marufuzzaman et al., 2009), analytical network process (ANP) (Chou, 2018), data envelopment analysis (DEA) Toloo & Mensah, 2019, interpretive structural modeling (ISM) (Govindan et al., 2012), DEMATEL (Qarnain et al., 2020) and Fuzzy TOPSIS (Afful-Dadzie et al., 2015; Kwok & Lau, 2019). Some hybrid MCDM techniques identified by (Ho et al., 2010) in their research work for solving supply selection problems include AHP and linear programming (LP) (Ghodsypour & O'Brien, 1998). DEMATEL-TOPSIS (Sangaiah et al., 2015), DEMATEL-TOPSIS-ELECTRE (Sangaiah et al., 2017), AHP-PROMETHEE (Sari et al., 2020), AHP-QFD-VIKOR (Piengang et al., 2019) are other hybrid approaches used by different researchers in their respective works. However, there are a few studies where hybrid AHP-TOPSIS models are applied in different domains for decision-making (Bathrinath et al., 2020; Hasan et al., 2019; Konstantinos et al., 2019; Rajak & Shaw, 2019). The summary of related literary references is presented in Table 1.

Voting systems for all people (VSAP)

Los Angeles County is undoubtedly the most densely populated county in the US with a voter population of more than 5.4 million people on its electoral roll (Kim, 2020). While the accuracy and integrity of the

Table 1. Summary of related literary works.

Author	Theme	Approach
Afful-Dadzie et al. (2015)	Selecting start-up businesses in a public venture capital with intuitionistic fuzzy TOPSIS.	IF-TOPSIS
Bathrinath et al. (2020)	Risk analysis in textile industries using AHP-TOPSIS.	AHP-TOPSIS
Bayode et al. (2020)	Integration of geophysically derived parameters in characterization of foundation integrity zones: An AHP approach.	AHP
Behzadian et al. (2012)	A state-of the-art survey of TOPSIS applications	TOPSIS
Biderci and Canbaz (2019)	Ergonomic Room Selection with Intuitive Fuzzy TOPSIS Method	IF-TOPSIS
Chou (2018)	Application of ANP to the selection of shipping registry: The case of Taiwanese maritime industry.	ANP
Deng et al. (2014)	Supplier selection using AHP methodology extended by D numbers.	AHP
Ghodsypour and O'Brien (1998)	A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming	AHP-LP
Govindan et al. (2012)	Analysis of third party reverse logistics provider using interpretive structural modeling.	ISM
Hasan et al. (2019)	Selection of Scholarship Acceptance Using AHP and TOPSIS Methods.	AHP-TOPSIS
Konstantinos et al. (2019)	A Decision Support System methodology for selecting wind farm installation locations using AHP and TOPSIS: Case study in Eastern Macedonia and Thrace region, Greece.	AHP-TOPSIS
Kwok and Lau (2019)	Hotel selection using a modified TOPSIS-based decision support algorithm.	TOPSIS
Marufuzzaman et al. (2009)	Supplier selection and evaluation method using Analytical Hierarchy Process (AHP): a case study on an apparel manufacturing organization	AHP
Piengang et al. (2019)	An APS software selection methodology integrating experts and decisions-maker's opinions on selection criteria: A case study.	AHP-QFD-VIKOR
Qarnain et al. (2020)	Analyzing factors necessitating conservation of energy in residential buildings of Indian subcontinent: A DEMATEL approach	DEMATEL
Rajak and Shaw (2019).	Evaluation and selection of mobile health (mHealth) applications using AHP and fuzzy TOPSIS.	AHP-TOPSIS
Sangaiah et al. (2017)	An integrated fuzzy DEMATEL, TOPSIS, and ELECTRE approach for evaluating knowledge transfer effectiveness with reference to GSD project outcome.	Fuzzy DEMATEL-TOPSIS-ELECTRE
Sangaiah et al. (2015)	A combined fuzzy DEMATEL and fuzzy TOPSIS approach for evaluating GSD project outcome factors.	DEMATEL-fuzzy TOPSIS
Sari et al. (2020)	Using AHP and PROMETHEE multi-criteria decision making methods to define suitable apiary locations	AHP-PROMETHEE
Sharma and Sehrawat (2020)	Quantifying SWOT analysis for cloud adoption using FAHP-DEMATEL approach: evidence from the manufacturing sector.	FAHP-DEMATEL
Toloo and Mensah (2019)	Robust optimization with nonnegative decision variables: a DEA approach	DEA
Zhang and Su (2019)	A combined fuzzy DEMATEL and TOPSIS approach for estimating participants in knowledge-intensive crowdsourcing.	DEMATEL-TOPSIS

Source: From literature.

Figure 1. Ballot marking device prototype (Source: County of Los Angeles, 2017).

existing voting system's service to the electorate during elections is not in doubt, their inability to provide the needed technological latitude required to sustain an ever-increasing diverse voter population as a result of its obsolete technology and system design challenges calls for immediate action. As such, this provides the county with a fine opportunity to redefine the voting experience in accordance with the voter requirements, aspirations, and capabilities that offers ease of access, safety, and confidentiality aided by state-of-the-art technologies. To achieve this objective, the County's Registrar-recorder/County clerk seeks to resolve the numerous voting system drawbacks through the VSAP initiative launched in September 2009. Considering the diversity, intricacy, and population dynamics of the county, the VSAP will offer greater and better opportunities to voters in the county to participate in the voting process by providing adequate voting alternatives in a manner that is favourable, safe, and reliable. It is worth mentioning that the VSAP project attracted a tall list of people comprising scholars, inventors, usability and security professionals, technology and heads of academic institutions as well as an array of community-based interest groups, civil society organizations, and opinion leaders who served as advisors because the County believes that public input and ownership of the new system will be an important guardian to the democratic process (Dean, 2019). A major component of the VSAP system is the ballot marking device (BMD) shown in Figure 1. As the anticipated successor of the county's soon to be decommissioned InkaVote system, the BMD comes fitted with specialized multimedia capabilities and features available in thirteen different languages providing handicapped voters an opportunity to personalize their voting experience when exercising their franchise. In terms of auditing, legibility, and safety, the ballot sheets generated by the BMDs surpass the electoral regime standards set by the federal government. During the manufacturing and certification phase of the project, the L. A County selects a vendor (BMD vendor) to manufacture and supply the BMD device which is a major component of the VSAP system (Dean, 2019).

Methods

Figure 2 depicts our model framework which comprises knowledge acquisition, implementation, and analysis. The knowledge acquisition phase entails a brief review of related scholarly works, establishing the research objective after which we identify the relevant criteria and alternatives required in consultation with the domain experts. To ensure that our methodology can be easily deployed and reproducible, we implemented our framework using Microsoft Excel (MS Excel) which is a popular and commonly used software (e.g. for engineering applications).

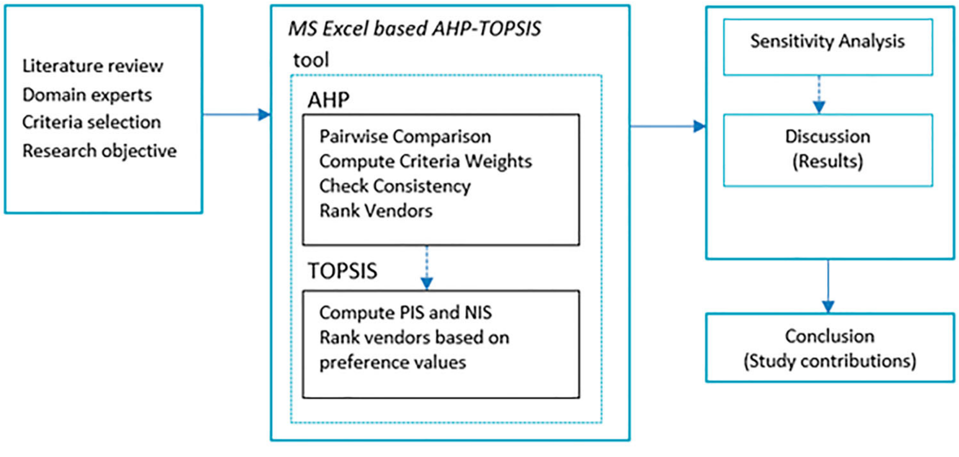

Figure 2. Conceptual framework of study.

Lastly, we perform sensitivity analysis to check the robustness of our approach, discuss the results and present our study implications.

BMD vendor selection criteria

Since the 1960s, various researchers have focussed their studies on establishing credible criteria for the supplier/vendor selection task. A historical look at the literature on criteria for supplier selection revealed that cost was the most essential criterion considered during the latter part of the 1970s and at the beginning of the 1980s. Subsequently, cycle time (CT) and customer responsiveness (CR) became the focus during the early 1990s until the attention shifted to flexibility in the late 1990s (Huang & Keskar, 2007). However, some authors in recent times consider environmental factors as a key issue that must not be ignored when shortlisting vendor selection criteria. Weber in his work (Weber & Current, 1993; Weber et al., 1991) his work identified price (P), delivery (D), quality (Q), facilities and capacity (FC), geographic location (GL), and technology capability (TC) as the most important criteria. According to Ho et al. (2010), the most popular criteria is quality (Q), followed by delivery (D), price/cost (P/C), manufacturing capability (MC), service (S), management (M), and technology (T).

For our work, we identified and shortlisted the following criteria after reviewing the related literature and interaction with industry experts. These are quality of product (QP), cost (C), relationship quality (RQ), manufacturing capacity (MC), product warranty (PW), on-time-delivery (OTD), and brand reputation (BR) (see Figure 3).

Analytical hierarchy process (AHP)

AHP which was developed by Saaty (Saaty, 1987), has been used extensively to solve numerous complex decision-making problems due to its simplicity and flexibility (Borade et al., 2013; Kannan & Vinay, 2008). It helps decision-makers develop a solution that best fits the objective and comprehension of the given task. It offers a rational and comprehensive framework for organizing a decision problem, representing and measuring its components, and then relating those components to the general objectives the evaluation of other optional solutions. As a first step, the decision matrix is broken down into a hierarchy of simplified easy to understand mini-problems where every mini-problem is analysed individually.

The goal, evaluating criteria and alternatives/options constitute the hierarchy. Afterwards, we conduct a pairwise comparison of the criteria and alternatives/options. The second step is the comparison of the alternatives and the criteria. After the problem decomposition and hierarchy construction, the prioritization process starts to determine the relative significance of the criteria at every level. The pairwise judgment begins from the second level and ends at the last level (i.e. alternatives). At every level, there is a pairwise comparison of criteria based on their levels of influence in accordance with the criteria specified at the higher level (Albayrak & Erensal, 2004).

The multiple pairwise comparisons in AHP based on a standardized comparison scale of nine levels called the Saaty scale (Saaty, 1987, 1990) are defined in Table 2.

Step-by-step implementation of the AHP is shown using the equations below.

We consider an $n \times n$ real matrix B, represented by equation (1) that depicts the pairwise comparison matrix where each criterion is compared against every other criterion (see Table 3), with n defining the number of criteria.

$$B = [b_{ij}] = \begin{bmatrix} 1 & b_{12} & \cdots & b_{1j} \\ 1/b_{12} & 1 & \cdots & b_{2j} \\ \vdots & \cdots & 1 & \vdots \\ 1/b_{1j} & 1/b_{2j} & \cdots & 1 \end{bmatrix} \text{.........} \quad (1)$$

b_{ij} = an entry in matrix B that defines the relevance of the *ith* criterion with respect to the *jth* criterion. In other words, b_{ij} represents a pairwise comparison of the *ith* criterion in the *jth* column. Whenever $b_{ij} > 1$, then the *ith* criterion is considered more relevant than the *jth* criterion, however, the *jth* criterion is considered more relevant compared to the *ith* criterion if the condition $b_{ji} > 1$ holds. Based on the reciprocity axiom (Forman & Gass, 2001), $b_{ij} = 1$ for $i = j$ and $b_{ij} = \frac{1}{b_{ji}}$ for $i < j$. It must be noted that the values stored in the pairwise comparison matrix are subsequently aggregated to form a vector of relative weights for each criterion used in the matrix.

Next, we use equation (2) to determine the expression for matrix normalization.

$$w = \sum_{j=1}^{j=n} b_{ij} = [w_1, \ldots, w_n] \text{.......} \quad (2)$$

Table 2. Saaty scale (Saaty, 1987).

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favour one over the other
5	Much more important	Experience and judgment strongly favour one over the other
7	Very much important	Experience and judgment very strongly favour one over the other
9	Extremely more important	The evidence favouring one over the other is of the highest possible affirmation
2,4,6,8	Intermediate scores	

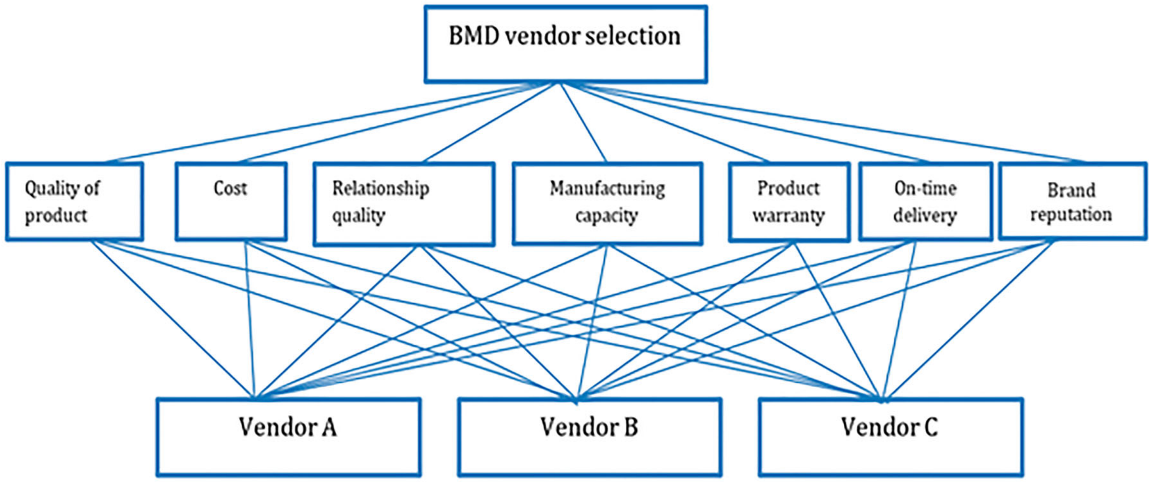

Figure 3. AHP hierarchy for BMD vendor selection.

Table 3. An aggregation of the pairwise criteria comparison matrix.

Criteria	QP	C	RQ	MC	PW	OTD	BR
QP	1	1	2	5	3	4	3
C	1	1	3	4	2	3	2
RQ	1/2	1/3	1	3	1	1/2	1
MC	1/5	1/4	1/3	1	1/3	1/4	1/2
PW	1/3	1/2	1	3	1	1/2	1
OTD	1/4	1/3	2	4	2	1	3
BR	1/3	1/2	1	2	1	1/3	1
Total	3 5/8	4	10 1/3	22	10 1/3	9 3/5	11 1/2

QP, Quality of product; C, cost; RQ, relationship quality; MC, manufacturing capacity; PW, product warranty; OTD, on-time-delivery; BR, brand reputation.
Source: Authors' processing from MS Excel.

Once we finish the pairwise comparison matrices process, we proceed to the matrix normalization phase aided by the resulting mathematical expression given by equation (2). Equation (3) accomplishes this task.

$$\frac{B}{w} = \sum_{j=n}^{j=1} b_{ij} \times \frac{1}{w} = \begin{bmatrix} 1 & b_{12} & \cdots & b_{1j} \\ 1/b_{12} & 1 & \cdots & b_{2j} \\ \vdots & \vdots & 1 & \vdots \\ 1/b_{1j} & 1/b_{2j} & \cdots & 1 \end{bmatrix} \times \left[\frac{1}{w_1} \ldots\ldots \frac{1}{w_n} \right] \ldots\ldots \quad (3)$$

We now compute the normalized principal eigenvector with the help of Equation (4).

$$W_j = \frac{1}{m} \sum_{j=n}^{j=1} \frac{b_{1j}}{w_j} \ldots\ldots \quad (4)$$

It must be noted that the eigenvector which is consistent with the largest eigenvalue (λ_{max}) of the pairwise comparison matrix B (see equation (1)), given by equation (5) determines the relative weights.

$$B_w = \lambda_{max} w \ldots\ldots \quad (5)$$

Equation (6) computes the overall weights of the vendors (sum of the matrix multiplication of vectors d_{ik} and e_{kj})

$$W_{ij} = \sum_{k=1}^{n} d_{ik} \times e_{kj} \ldots\ldots \quad (6)$$

Technique for order of preference by similarity to ideal solution (TOPSIS)

The TOPSIS method is formulated on a concept that suggests that our preferred alternative must have the smallest geometric distance from the positive ideal solution and the highest geometric distance from the negative ideal solution. TOPSIS applies the weights found in the AHP model in identifying the best and worst possible ratings of the set of alternates.

By aggregating and offsetting, the method juxtaposes a set of alternatives or options by grouping weights for each criterion, normalizing each criterion's results and computing the geometric distance or separation measure between each alternative and the ideal alternative or option, also called the best result in each criterion.

The rank of the ideal solution must be equal to 1 while that of the worst alternative must be closer to 0 according to (Huang et al., 2011; Jadidi et al., 2010). In similarity to other MCDM techniques, selecting the criteria and alternatives constitutes the first step when using TOPSIS. The second step involves the allocation of weights to the criteria by the decision-makers. We finally construct our decision matrix after the alternatives are assigned scores for every criterion. Mathematically, the TOPSIS method is implemented using the equations outlined in the steps below. As a start, we apply Equation (9) to create our decision matrix ($\mathcal{D}M$).

$$\mathcal{D}M = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \ldots\ldots\ldots\ldots \quad (7)$$

We then proceed to build the normalized decision matrix ($n\mathcal{D}M$) with help of equation (8).

$$n\mathcal{D}M = t_{ij} \ldots\ldots\ldots\ldots \quad (8)$$

where t_{ij} is defined by the expression $\frac{y_{ij}}{\sqrt{\sum_{i=1}^{m} y_{ij}^2}}$.

Equation (9) produces the weighted version of the $n\mathcal{D}M$ defined by S below.

$$S = s_{ij} \ldots\ldots\ldots\ldots \quad (9)$$

where

$$s_{ij} = w_j \cdot t_{ij} \ldots\ldots\ldots \quad (10)$$

Equation (11) computes the positive ideal solution denoted by (S_j^+), while equation (12) gives the negative ideal solution represented (S_j^-).

$$S_j^+ = \max_i(S_{ij}) \ldots\ldots\ldots \quad (11)$$

$$S_j^- = \min_i(S_{ij}) \ldots\ldots\ldots \quad (12)$$

The geometric distance (separation measure) of each alternative or option from the positive and negative ideal solutions is determined using equations (13) and (14).

$$V_i^* = \sqrt{\sum_{j=1}^{n} (S_j^+ - S_{ij})^2}, \forall_i \in [1\ldots m] \ldots\ldots\ldots \quad (13)$$

$$V_i' = \sqrt{\sum_{j=1}^{n} (S_j^- - S_{ij})^2}, \forall_i \in [1\ldots m] \ldots\ldots\ldots \quad (14)$$

Equation (15) computes the relative closeness (RC_i).

$$RC_i = \frac{V_i^*}{V_i^* + V_i'}, \forall i \in [1\ldots\ldots m], 0 \leq RC_i \leq 1 \ldots\ldots\ldots\ldots \quad (15)$$

Lastly, the alternatives are ranked to produce a preference order based on their RC_i values which is an indicator of their performance. They are usually arranged in descending order where the most preferred or best alternative corresponds to the alternative with the highest RC_i value. This step provides an opportunity to compare the relative performances of the alternatives.

Numerical case study

In this section, we discuss the BMD vendor selection for the VSAP. Three potential vendors A, B and C were shortlisted for evaluation after preliminary screening. An extensive review of the relevant literature coupled with interactions with electoral material procurement experts informed our decision to use the shortlisted criteria. Figure 3 describes the hierarchy of BMD vendor selection. In this study, we used seven (7) criteria for our evaluation (see Table 3).

It must be noted that the inputs were provided in a pairwise form by electoral material procurement experts and subsequently aggregated by computing their mean scores. Lastly, we adopt the methodology described in the background section to allocate the relevant weights and proceed to rank our alternatives.

Stage 1: allocate criteria weights based on the Saaty scale (Saaty, 1987)

Table 3 depicts the criteria comparison matrix using the Saaty scale (Saaty, 1987) values as a reference. The normalized matrix and allocation of criteria weights is achieved using equations (3) and (4) after equation (2) has determined the expression for matrix normalization. Table 4 depicts the normalized matrix and weights allocated to the criteria. It is obviously clear from the results shown in Table 4 that the quality of product criterion is the best among the shortlisted criteria used for the study.

Stage 2: allocate respective weights to every vendor per each criterion

The Saaty scale (Saaty, 1987) is used as a basis to compare the vendors for every criterion in the study. Table 5 shows

Table 4. Results of the criteria matrix weights after normalization.

Criteria	QP	C	RQ	MC	PW	OTD	BR	Mean
QP	0.2765	0.2553	0.1935	0.2273	0.2903	0.4174	0.2609	0.27446020
C	0.2765	0.2553	0.2903	0.1818	0.1935	0.3130	0.1739	0.24063750
RQ	0.1382	0.0851	0.0968	0.1364	0.0968	0.0522	0.0870	0.09891396
MC	0.0553	0.0638	0.0323	0.0455	0.0323	0.0261	0.0435	0.04266646
PW	0.0922	0.1277	0.0968	0.1364	0.0968	0.0522	0.0870	0.09840970
OTD	0.0691	0.0851	0.1935	0.1818	0.1935	0.1043	0.2609	0.15548045
BR	0.0922	0.1277	0.0968	0.0909	0.0968	0.0348	0.0870	0.08943173

QP, Quality of product; C, cost; RQ, relationship quality; MC, manufacturing capacity; PW, product warranty; OTD, on-time-delivery; BR, brand reputation.
Source: Authors' processing from MS Excel.

Table 5. Aggregate criterion per alternatives pairwise comparison matrix.

QP	Vend A	Vend. B	Vend. C	C	Vend. A	Vend. B	Vend. C
Vend. A	1	1/9	1/4	Vend. A	1	9	8
Vend. B	9	1	2	Vend. B	1/9	1	1
Vend. C	4	1/2	1	Vend. C	1/8	1	1
Total	14.00	1.61	3.25	Total	1.24	11.00	10.00
RQ	Vend. A	Vend. B	Vend. C	MC	Vend. A	Vend. B	Vend. C
Vend. A	1	2	7	Vend. A	1	1/3	1/7
Vend. B	1/2	1	4	Vend. B	3	1	1/3
Vend. C	1/7	1/4	1	Vend. C	7	3	1
Total	1.64	3.25	12.00	Total	11.00	4.33	1.48
PW	Vend. A	Vend. B	Vend. C	OTD	Vend. A	Vend. B	Vend. C
Vend. A	1	1/2	1/7	Vend. A	1	2	1/2
Vend. B	2	1	1/4	Vend. B	1/2	1	1/4
Vend. C	7	4	1	Vend. C	2	4	1
Total	10.00	5.50	1.39	Total	3.50	7.00	1.75
BR	Vend. A	Vend. B	Vend. C				
Vend. A	1	1/3	2				
Vend. B	3	1	9				
Vend. C	1/2	1/9	1				
Total	4.50	1.44	12.00				

Source: Authors' processing from MS Excel.

the aggregate criterion per alternatives pairwise comparison matrix. Next, we repeat the operations involving equations (2)–(4) in stage 1 to produce Table 6.

Stage 3: compute the vendor rankings with AHP

Equation (9) produces the weighted version of the $n\mathcal{D}M$. The AHP-based ranking of vendors is achieved using equation (6) with the best value highlighted with colour yellow. Alternatively, aggregating the individual rows of the weighted *nDM*(see Table 7) also produces the same AHP-based ranking of vendors results. Equations (11) and (12) computes S_j^+ and S_j^- respectively.

Stage 4: determine the vendor rankings with TOPSIS

Equations (13) and (14) computes the geometric distance (separation measure) from the S_j^+ as well as the geometric distance from the S_j^- respectively (see Tables 7–9).

Equation (15) computes the RC_i to the ideal solution. The RC_i of the alternatives used in the study is presented in Table 10. The results from Table 10 indicate that vendor A is the best or highly preferred alternative since its RC_i value of 0.50596269 is the biggest. The next best alternative is Vendor B with Vendor C occupying the last spot (Tables 11 and 12).

Consistency test (CT)

To ensure the validity of our AHP, we conduct consistency tests to satisfy ourselves that inputs received from the electoral material procurement experts are consistent.

The consistency index (*CI*) which describes the output quality of the AHP is given by:

$$CI = \frac{(\lambda_{\max} - n)}{(n - 1)} \ldots\ldots\ldots\ldots \tag{16}$$

Lastly, the consistency ratio (*CR*), a parameter that determines whether our evaluations are consistent and

Table 6. Normalized version of Table 4.

QP	Vend A	Vend. B	Vend. C	Mean	C	Vend A	Vend. B	Vend. C	Mean
Vend. A	0.071429	0.068966	0.076923	0.072439	Vend. A	0.808989	0.818182	0.80	0.809057
Vend. B	0.642857	0.620690	0.615385	0.626310	Vend. B	0.089888	0.090909	0.10	0.093599
Vend. C	0.285714	0.310345	0.307692	0.301250	Vend. C	0.101124	0.090909	0.10	0.097344
RQ	Vend A	Vend. B	Vend. C	Mean	MC	Vend A	Vend. B	Vend. C	Mean
Vend. A	0.608696	0.615385	0.583333	0.602471	Vend. A	0.090909	0.076923	0.096774	0.088202
Vend. B	0.304348	0.307692	0.333333	0.315124	Vend. B	0.272727	0.230769	0.225806	0.243101
Vend. C	0.086957	0.076923	0.083333	0.082404	Vend. C	0.636364	0.692308	0.677419	0.668697
PW	Vend A	Vend. B	Vend. C	Mean	OTD	Vend A	Vend. B	Vend. C	Mean
Vend. A	0.10	0.090909	0.102564	0.097824	Vend. A	0.285714	0.285714	0.285714	0.285714
Vend. B	0.20	0.181818	0.179487	0.187102	Vend. B	0.142857	0.142857	0.142857	0.142857
Vend. C	0.70	0.727273	0.717949	0.715074	Vend. C	0.571429	0.571429	0.571429	0.571429
BR	Vend A	Vend. B	Vend. C	Mean					
Vend. A	0.222222	0.230769	0.166667	0.206553					
Vend. B	0.666667	0.692308	0.750000	0.702991					
Vend. C	0.111111	0.076923	0.083333	0.090456					

Source: Authors' processing from MS Excel.

Table 7. Weighted version of the $n\mathcal{D}M$.

	Criteria							
Alternatives	QP	C	RQ	MC	PW	OTD	BR	AHP Score
Vend. A	0.01988164	0.19468942	0.05959281	0.00376327	0.00962687	0.04442299	0.01847237	**0.35044936**
Vend. B	0.17189730	0.02252341	0.03117021	0.01037226	0.01841263	0.02221149	0.06286974	0.33945704
Vend. C	0.08268127	0.02342467	0.00815094	0.02853093	0.07037020	0.08884597	0.00808962	0.31009360
Max	0.17189730	0.19468942	0.05959281	0.02853093	0.07037020	0.08884597	0.06286974	
Min	0.01988164	0.02252341	0.00815094	0.00376327	0.00962687	0.02221149	0.00808962	

QP, Quality of product; C, cost; RQ, relationship quality; MC, manufacturing capacity; PW, product warranty; OTD, on-time-delivery; BR, brand reputation.
Source: Authors' processing from MS Excel.

Table 8. Geometric distance (separation measure) from the positive ideal solution (S_j^+).

	Criteria							
Alternatives	QP	C	RQ	MC	PW	OTD	BR	V_i^*
Vend. A	0.02310876	0	0	0.00061344	0.00368975	0.00197340	0.00197113	**0.17707761**
Vend. B	0	0.02964114	0.00080784	0	0.00269959	0.00444015	0	**0.19472663**
Vend. C	0.00795950	0.02933161	0.00264627	0	0	0	0.00300086	**0.20721545**

QP, Quality of product; C, cost; RQ, relationship quality; MC, manufacturing capacity; PW, product warranty; OTD, on-time-delivery; BR, brand reputation.
Source: Authors' processing from MS Excel.

Table 9. Geometric distance (separation measure) from the negative ideal solution (S_j^-).

	Criteria							
Alternatives	QP	C	RQ	MC	PW	OTD	BR	V_i'
Vend. A	0	0.02964114	0.00264627	0	0	0.00049335	0	**0.181352018**
Vend. B	0.02310876	0	0.00052989	0.00004368	0.00007719	0	0.00300086	**0.163585994**
Vend. C	0.00394379	0	0	0.00061344	0.00368975	0.00444015	0	**0.112640795**

QP, Quality of product; C, cost; RQ, relationship quality; MC, manufacturing capacity; PW, product warranty; OTD, on-time-delivery; BR, brand reputation.
Source: Authors' processing from MS Excel.

Table 10. RC_i values for the respective alternatives.

Alternatives	$\sum(V_i^*, V_i')$	RC_i
Vend. A	0.35842962	**0.50596269**
Vend. B	0.35831263	**0.45654544**
Vend. C	0.31985624	**0.35216069**

Source: Authors' processing from MS Excel.

Table 11. AHP-based ranking of vendors.

Alternative	Preference (P_j)	Rank
Vend. A	0.35044936	1*
Vend. B	0.33945704	2
Vend. C	0.31009360	3

Source: Authors' processing from MS Excel.

Table 12. TOPSIS-based ranking of vendors.

Alternative	Preference (P_j)	Rank
Vend. A	0.505962693	1*
Vend. B	0.456545437	2
Vend. C	0.352160687	3

Source: Authors' processing from MS Excel

acceptable, is computed by dividing the *CI* by the random index (*RI*) using equation (17).

$$CR = \frac{CI}{RI}\ldots\ldots\ldots\ldots \quad (17)$$

CR has an accepted upper limit value of 0.1. If the final $CR > 0.1$, then the evaluation exercise must be repeated to enhance consistency. The consistency metric can be used to evaluate the consistency of decision-makers as well as the consistency of the overall hierarchy (Wang & Yang, 2007). Tables 13 and 14 shows the *RI* and CT summary results respectively.

Table 13. Random Index (RI) (Saaty, 1980).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 14. CT summary.

Comparison matrix	Consistency (%)
Main criteria	5.445543527
QP	0.195394072
C	0.268489493
RQ	0.239692425
MC	0.929733966
PW	0.284437784
OTD	0
BR	2.619772735

QP, Quality of product; C, cost; RQ, relationship quality; MC, manufacturing capacity; PW, product warranty; OTD, on-time-delivery; BR, brand reputation.
Source: Authors' processing from MS Excel.

Sensitivity analysis (SA)

It is a standard practice to subject models proposed by researchers to various analyses such as sensitivity analysis to test its stability (Pianosi et al., 2016; Saltelli et al., 2000). SA measures the influence of exogenous (input/independent) variables on endogenous (output/dependent) variables and vice versa on the model parameters. It is a useful technique for examining the influence of economic and technical parameters on the parameters of a model (Salciccioli et al., 2016). The algorithm below details the steps applied in our study to perform sensitivity analysis (see Triantaphyllou & Sánchez, 1997; cited in Kaur, 2014).

Table 15. Decision matrix (adapted from Kaur, 2014).

	Criteria					
Altern.	C_1 $\mathcal{W}_{11}$	C_2 $\mathcal{W}_{22}$	$\dots$	...	...	$C_{\mathcal{Q}}$ $\mathcal{W}_{\mathcal{Q}}$
B_1	b_{11}	b_{12}	$\dots$	...	...	$b_{1\mathcal{Q}}$
B_2	b_{21}	b_{22}	$\dots$	...	...	$b_{2\mathcal{Q}}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$B_{\mathcal{P}}$	$b_{\mathcal{P}1}$	$b_{\mathcal{P}2}$	$\dots$	...	...	$b_{\mathcal{P}\mathcal{Q}}$

Table 16. Steps involved in implementing sensitivity analysis algorithm **(**Kaur, 2014).

Step	Remark	Equation
1	Compute δ_{kij}	$\delta_{kij} = \frac{(P_j - P_i)}{(b_{jk} - b_{ik})}$
2	Compute δ'_{kij}	$\delta'_{kij} = \frac{(P_j - P_i)}{(b_{jk} - b_{ik})} \times \frac{100}{\mathcal{W}_k}$
3	Select the C_k that matches the minimum $\lvert\delta'_{kij}\rvert$ score and compute D'_k (i.e. degree of C_k)	$D'_k = \min_{1 \le i < j \le p} \{\lvert\delta'_{kij}\rvert\}$, $\forall q \ge k \ge 1$
4	Compute the sensitivity coefficient (i.e. $sens(C_k)$)	$sens(C_k) = \frac{1}{D'_k}$, $\forall q \ge k \ge 1$

From literature in our paper (Manuscript ID: TSSC1954106).

Algorithm (Kaur, 2014)

Given alternatives B_i, $\forall_i \in [1 \dots \mathcal{P}]$ and criteria C_j, $\forall_j \in [1 \dots \mathcal{Q}]$, we define a decision problem consisting of $\mathcal{P}$ alternatives and $\mathcal{Q}$ criteria (see Table 14) define. If all the criteria weights $\mathcal{W}_j$ are given, then it is expected that

$$\sum_{j=1}^{n} w_j = 1 \tag{18}$$

The entry b_{ij}, $\forall_i \in [1 \dots \mathcal{P}]$, $\forall_j \in [1 \dots \mathcal{Q}]$ defines the pairwise comparison in the *ith* row and the *jth* column. b_{ij} also denotes the relevance of alternative B_i relative to criterion C_j (Table 15).

Definition

(i) Represent the smallest change in weight $\mathcal{W}_k$ and criterion C_k by δ_{kij}, $1 \le i < j \le \mathcal{P}; 1 \le k \le \mathcal{Q}$, where it is possible to reverse the rank of alternatives B_i and B_j (see equation in step 1 from Table 16)

(ii) We assign δ'_{kij} to represent the changes in comparative terms (see equation in step 2 from Table 16).

Numerical case study for sensitivity analysis (SA)

The decision matrix ($\mathcal{DM}$) under consideration is the weighted (standardized) $\mathcal{DM}$ which is renamed as Table 17 based on Table 15. We use the equations outlined in steps 1 and 2 from Table 15 to compute all possible values of δ_{kij} and δ'_{kij} presented in Tables 18 and 19 respectively. Finally, we calculate the sensitivity coefficient for each criterion shown in Table 20 using the equation in step 4 (see Table 16) after executing step 3.

Discussion and implications

This study aimed at addressing the problem of selecting a vendor to supply BMDs to help realize the VSAP system objectives in Los Angeles County, California, U.S.A. using a hybrid AHP-TOPSIS technique. To achieve this, we began by identifying and shortlisting the relevant criteria (7) after reviewing literary works by several authors and engaging electoral material procurement experts via interviews. Afterwards, we received inputs in pairwise comparison format from the procurement experts and then computed their mean values. We adopted the approach described in the segment after the background section to allocate criteria weights and proceed to conduct the ranking of the alternatives. Results of the AHP process shown in Table 11 indicates that vendor *A* is the most preferred vendor with vendors *B* and *C* occupying the second and last spot respectively. Interestingly, our TOPSIS results in Table 12 also rank vendor *A* as the best vendor followed by vendor *B* and lastly vendor *C*. Based on these observations, it is clear that vendor *A* should be selected from the other vendors. The consistency ratio was less than 10% (see Table 14). Finally, we conducted a sensitivity analysis to determine the most essential criterion for selecting each vendor. The results of sensitivity analysis (see Table 20) points to the fact that the most sensitive and effective criterion in descending order of prominence based on their respective $sens(C_k)$ values are quality of product (QP), cost (C), brand reputation (BR), on-time-delivery (OTD), relationship quality (RQ), product warranty (PW) and manufacturing capacity (MC) (see Jain et al., 2018; Nuengphasuk & Samanchuen, 2019).

The managerial implication of the developed AHP-TOPSIS model is that it can provide support to practitioners and decision makers in making strategic, tactical and

Table 17. Weighted (standardized) $\mathcal{DM}$ (presented in the form of Table 14).

Vendors	QP 0.27446020	C 0.24063750	RQ 0.09891396	MC 0.04266646	PW 0.09840970	OTD 0.15548045	BR 0.08943173
Vend. A	0.01988164	0.19468942	0.05959281	0.00376327	0.00962687	0.04442299	0.01847237
Vend. B	0.17189730	0.02252341	0.03117021	0.01037226	0.01841263	0.02221149	0.06286974
Vend. C	0.08268127	0.02342467	0.00815094	0.02853093	0.07037020	0.08884597	0.00808962

Source: Authors' processing from MS Excel.

Table 18. Results of δ_{kij}.

Pair of Vendors	Criteria						
	QP	C	RQ	MC	PW	OTD	BR
A–B	−0.072310478	0.063847241	0.386745938	−1.663239223	−1.251152223	0.494893569	−0.2475895
A–C	−0.642611497	0.235633794	0.784492484	−1.629373463	−0.664365307	−0.908443278	3.88681127
B–C	0.329127368	−32.58028297	1.275602292	−1.617047762	−0.565142619	−0.440664329	0.53602364

Source: Authors' processing from MS Excel.

Table 19. Results of δ'_{kij}.

Pair of Vendors	Criteria						
	QP	C	RQ	MC	PW	OTD	BR
A–B	−26.34643471	26.53253983	390.9922875	−3898.235833	−1271.370775	318.2995466	−276.84754
A–C	−234.1364953	97.92064502	793.1059672	−3818.862574	−675.1014148	−584.2813514	4346.12128
B–C	119.9180669	−13539.1544	1289.608008	−3789.974073	−574.2752934	−283.4210521	599.366318

Source: Authors' processing from MS Excel.

operational decisions by bringing out robust and reliable results. This framework can be used by managers of different industries in different applications such as maintenance strategy selection, material handling equipment selection and many other decision-making processes. However, the decision-making processes involved in this framework will depend on experts' preferences and the individuals involved in the decision-making process. Firms need to understand the criteria used in selecting good vendors. Managers need to think strategically and concentrate on a vendor criterion set that evaluates vendors across several spheres that includes quality of product because a clearly defined and suitable criterion set will go a long way to improve the performance of vendors to attain customer satisfaction. Again, the ranking of vendors using our approach helps to set a standard of comparison in a reliable manner where both highly rated and lowly ranked vendors are selected and eliminated respectively. From the voter's perspective (especially the physically challenged and visually impaired), a good BMD device supplied by the selected vendor indicates clearly how good technology enhances accessibility and the overall election experience.

Theoretically, the study extends the application of MCDM algorithms by offering deeper insights on the acquisition of effective and efficient electoral voting gadgets through a structured public procurement process. As indicated in the related literature works segment above (see Bayode et al., 2020; Behzadian et al., 2012; Biderci & Canbaz, 2019; Deng et al., 2014; Sharma & Sehrawat, 2020; Zhang & Su, 2019), several disciplines such as business, science and engineering have all used MCDM (multi-criteria decision making) techniques in one way or the other. Although the vendor selection process is one key area where MCDM models have been applied, not much is heard of the application of vendor selection in the area of electoral material procurement for voting purposes.

Table 20. SA for each criterion.

Sensitivity of criterion ($sens(C_k)$)	Value	Rank
$sens(QP)$	0.0379558	1*
$sens(C)$	0.0376896	2
$sens(RQ)$	0.0025576	5
$sens(MC)$	0.0002639	7
$sens(PW)$	0.0017413	6
$sens(OTD)$	0.0035283	4
$sens(BR)$	0.0036121	3

The results in Table 20 indicate that $sens(QP)$ is the highest. As such, we can conclude that the most sensitive and effective criterion in descending order of prominence based on their respective $sens(C_k)$ values are quality of product (QP), cost(C), brand reputation (BR), on-time-delivery(OTD), relationship quality(RQ), product warranty(PW) and manufacturing capacity(MC).
Source: Authors' processing from MS Excel.

This drawback informed our decision to propose a hybrid AHP-TOPSIS methodology for vendor selection using the VSAP initiative in Los Angeles County as our case study. Having said this, contemporary works authored by (Jain et al., 2018; Kamalakannan et al., 2020) corroborates our work which highlights the efficiency of hybrid MCDM techniques such as AHP-TOPSIS in solving vendor selection problems. Again, this research work provides relevant insights for both scholars and professionals in MCDM techniques and electoral material procurement research literature. To check the relevance and robustness of the results, a sensitivity analysis is also performed. Additionally, this study also offers a greater and better comprehension regarding the application of a hybrid AHP-TOPSIS approach in selecting a suitable vendor to play a key and effective role in enhancing the voter system's credibility in the democratic process.

Conclusion

Advances in information technology have triggered the need for election management bodies to take decisions that ensure that elections are organized in a manner that reflects the will of the people. To achieve this, conducting elections using electronic voting gadgets like the BMD has received considerable attention. After all, without free and fair elections, there cannot be a democratic society. For this reason, choosing a good BMD vendor for the VSAP system is very important due to the desire by the County to offer a greater and better opportunity to voters in the County to participate in the electoral process by creating other alternatives for voting where the electorates can exercise their franchise in a favourable, safe, and reliable manner. As part of our research work, we pursued a methodological structure that initially defined the problem, identified the selection and weighting criteria after which we generated and qualified the alternatives against the selected criteria before finally calculating the optimal alternative. Given the unique features provided by the BMD, we believe that this study does not only provide a method that can be utilized at the organizational level but also provides the following benefits namely;

- accessibility: increase in user participation in the voting process (especially visually and physically challenged voters).
- auditing: BMD device generates a voter receipt that guarantees that votes are correctly issued and accounted for.
- precision and reliability: remove errors in the manual count by generating a receipt for each vote cast and providing accurate and prompt publication of results.

Considering the relationships between criteria presented in this work, organizations are provided an opportunity to devise and refine adequate criteria to avoid the risk of selecting sub-optimal solutions.

Our hybrid approach is simple, convenient and an efficient tool to help the decision-makers choose the suitable BMD vendor among the alternative vendors. To assist decision-makers with the implementation of the model, an AHP-TOPSIS tool was developed using MS-Excel. This tool can be applied to other decision-making problems in the election management process such as the procurement of other voting materials like biometric voter registration devices, laptops, etc. However, this study is not without limitations. A major bottleneck encountered during our work is the fewer number of respondents and the selection of vendors based on their ability to meet economic criteria while excluding green vendor selection criteria which creates environmental consciousness among vendors which is an essential part of the global climate change agenda.

It must also be noted that the results obtained are based on the preference values given by the domain experts. It is our considered opinion that in the future, we can explore other MCDM techniques such as Intuitionistic fuzzy AHP, interval Type-2 fuzzy AHP-TOPSIS, etc. to enrich the vendor selection process.

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ORCID

Raphael Kwaku Botchway http://orcid.org/0000-0002-4726-2898
Abdul Bashiru Jibril http://orcid.org/0000-0003-4554-0150
Zuzana Komínková Oplatková http://orcid.org/0000-0001-8050-162X
Roman Jasek http://orcid.org/0000-0002-9831-9372

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