Journal of Medical Systems (2019) 43: 219
https://doi.org/10.1007/s10916-019-1339-9

SYSTEMS-LEVEL QUALITY IMPROVEMENT

Mobile-Based Patient Monitoring Systems: A Prioritisation Framework Using Multi-Criteria Decision-Making Techniques

E. M. Almahdi[1] · A. A. Zaidan[1] · B. B. Zaidan[1] · M. A. Alsalem[1,2] · O. S. Albahri[1] · A. S. Albahri[1,3]

Received: 13 March 2019 / Accepted: 13 May 2019 / Published online: 6 June 2019
© Springer Science+Business Media, LLC, part of Springer Nature 2019

Abstract
This study presents a prioritisation framework for mobile patient monitoring systems (MPMSs) based on multicriteria analysis in architectural components. This framework selects the most appropriate system amongst available MPMSs for the telemedicine environment. Prioritisation of MPMSs is a challenging task due to (a) multiple evaluation criteria, (b) importance of criteria, (c) data variation and (d) unmeasurable values. The secondary data presented as the decision evaluation matrix include six systems (namely, Yale–National Aeronautics and Space Administration (NASA), advanced health and disaster aid network, personalised health monitoring, CMS, MobiHealth and NTU) as alternatives and 13 criteria (namely, supported number of sensors, sensor front-end (SFE) communication, SFE to mobile base unit (MBU) communications, display of biosignals on the MBU, storage of biosignals on the MBU, intra-body area network (BAN) communication problems, extra-BAN communication problems, extra-BAN communication technology, extra-BAN communication protocols, back-end system communication technology, intended geographic area of use, end-to-end security and reported trial problems) based on the architectural components of MPMSs. These criteria are adopted from the most relevant studies and are found to be applicable to this study. The prioritisation framework is developed in three stages. (1) The unmeasurable values of the MPMS evaluation criteria in the adopted decision evaluation matrix based on expert opinion are represented by using the best–worst method (BWM). (2) The importance of the evaluation criteria based on the architectural components of the MPMS is determined by using the BWM. (3) The VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method is utilised to rank the MPMSs according to the determined importance of the evaluation criteria and the adopted decision matrix. For validation, mean ± standard deviation is used to verify the similarity of systematic prioritisations objectively. The following results are obtained. (1) The BWM represents the unmeasurable values of the MPMS evaluation criteria. (2) The BWM is suitable for weighing the evaluation criteria based on the architectural components of the MPMS. (3) VIKOR is suitable for solving the MPMS prioritisation problem. Moreover, the internal and external VIKOR group decision making are approximately the same, with the best MPMS being 'Yale–NASA' and the worst

This article is part of the Topical Collection on *Systems-Level Quality Improvement*

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10916-019-1339-9) contains supplementary material, which is available to authorized users.

✉ A. A. Zaidan
aws.alaa@gmail.com; aws.alaa@fskik.upsi.edu.my

E. M. Almahdi
esam.motasher@gmail.com

B. B. Zaidan
bilalbahaa@fskik.upsi.edu.my

M. A. Alsalem
mohammed.asum@gmail.com

O. S. Albahri
osamahsh89@gmail.com

A. S. Albahri
ahmed.bahri1978@gmail.com

1 Department of Computing, Universiti Pendidikan Sultan Idris, Tanjong Malim, Perak, Malaysia

2 Department of Management Information System, College of Administration and Economic, University of Mosul, Mosul, Iraq

3 College of Engineering, University of Information Technology and Communications, Baghdad, Iraq

MPMS being 'NTU'. (4) For the objective validation, remarkable differences are observed between the group scores, which indicate the similarity of internal and external prioritisation results.

Keywords Mobile patient monitoring system · Multicriteria decision-making technique · VIKOR · BWM

Introduction

Telemedicine used in healthcare has been growing rapidly because it offers several benefits such as providing health-related information of patients [1–11] and remote healthcare services to patients in distant locations [12–22]. Mobile health (M-health) in the telemedicine refers to 'the use of emerging mobile information and communication technology, especially the Internet with mobile devices, to improve or enable health and healthcare'. M-health system and application are considered the new paradigm for conventional computation for providing high-quality healthcare. M-health can aid citizens to be responsible for their own health and prosperity, reduce expensive visits to hospitals and move towards prevention rather than cure. At present, M-health has attracted considerable attention due to the increasing number of high-performance mobile devices and wireless access technologies [23–25]. M-health is a part of electronic health, which uses mobile devices (such as smart phones and personal digital assistants) and communication technologies (such as wireless and Global Positioning System technologies) to enhance traditional medical services [26]. The M-health pattern guarantees real-time patient monitoring, diagnostic and therapy support, disease tracking, teleconsultation and awareness services.

Mobile patient monitoring is a M-health application, which refers to the continuous or repeated measurement of vital signs of a remotely moving patient through the use of mobile computing, wireless communication and network computing technologies [27]. The qualifications of any mobile patient monitoring system (MPMS) can be improved by using the network resources of all available wireless networks in various multiaccess environments. The benefits of such systems can be utilised through the mobility amongst different radio access networks. Reliable mobility management can be accomplished by assigning application flows to convenient interfaces through the use of intelligent decisions and adaptability based on available network resources [28]. MPMSs are used to provide doctors or healthcare organisations with biosignals from wearable sensors [29]. Recently, mobile devices and wireless sensor technologies have been utilised in developing MPMSs using wireless sensors [30, 31].

The elderly population and patients with chronic diseases especially need MPMSs to provide accurate healthcare services and aid decision makers (caregivers and doctors) in saving lives. However, the selection of MPMSs involves many aspects [32–34]. Many studies have attempted to evaluate and benchmark MPMSs to assist users in selecting suitable MPMS. However, their evaluation and benchmarking have focused on one or several aspects of MPMSs and neglected the rest. [34] proposed a new platform for the healthcare of the elderly and people with disabilities and compared it with other previous systems. [35] presented a new MPMS based on a user-centred design methodology and reviewed its advantages and disadvantages compared with those of seven previous systems. [36] compared MPMSs to identify their similarities and differences by using a set of functional and nonfunctional requirements. [32] introduced a generic architecture-associated terminology and a classificatory framework. [33] described and compared two M-health solutions on the basis of their different aspects. All these efforts in the evaluation and benchmarking of MPMSs were dependent on individual evaluation criteria, Thus, such benchmarking does not completely reflect the quality of these systems; none of these systems simultaneously present an integrated framework for benchmarking based on multiple evaluation criteria.

The MPMS architecture comprise two main parts, that is, the body area network (BAN) and the back-end system (BEsys). The BAN is a network of communication devices that are worn on, around or inside the body and are used to obtain health data and provide M-health services to patients. Moreover, the BAN comprises a mobile base unit (MBU) and other BAN devices, such as actuators and sensors, which are used to collect vital signs of patients for clinical purposes. Sensor front-end (SFE) transmits biosignals from the sensors to the MBU, which acts as a gateway for transmitting biosignals from the BAN to the BESys for processing and analysis. BESys comprises back-end server(s) and supplementary applications for processing biosignals and other data received by servers [27].

Benchmarking MPMSs is a challenging task due to multiple criteria. This task is considered a multicriteria problem and includes the following issues.

(1) Multiple evaluation criteria. Each system should be simultaneously evaluated and benchmarked according to a set of criteria to facilitate the application of an acceptable benchmarking. Considering all the system specifications using all important criteria is difficult because each criterion only measures one specification of the system.
(2) Importance of criteria. The importance of each criterion should be determined on the basis of other criteria; some criteria are more important than others.

(3) Data variation. The existence of various values in each criterion with respect to each MPMS is observed.
(4) Unmeasurable data. Linguistic evaluation criteria are required to be represented to be applicable to the MCDM technique. Meanwhile, unmeasurable evaluation criteria include categorical criteria (such as interval values and ranges), text (including communication technologies), binominal criteria (that is, yes/no) and polynomial criteria (such as colours).

All these issues can be solved by using multicriteria decision-making (MCDM) technique. MCDM can be used to achieve the benchmarking and prioritisation of the MPMSs to enable the users to select the best amongst them. MCDM is defined as an extension of decision theory that covers any decision with multiple objectives [37–42]. A methodology for assessing alternatives on individual, often conflicting criteria, and combining them into one overall appraisal [43–49]. When different criteria are involved in decision problems, MCDM is considered the most popular amongst decision-making methods [50–58]. MCDM can be proposed as the best solution for problems of decision makers [59–63]. The extensive use of MCDM can be due to its superior efficiency, rationality and clarity compared with that of traditional processes to improve the quality of decisions [64]. The objectives of MCDM are to (i) prioritise alternatives in descending order of performance, (ii) classify valid alternatives; and (iii) help data miners choose appropriate alternatives [65–68]. Healthcare decision makers can enhance decision making by systematically obtaining appropriate solutions through many existing MCDM techniques [69, 70]. Several MCDM theories have been identified. MCDM techniques include numerous methods that depend on mathematical approaches and human interaction [71, 72].

To the best of the author's knowledge, no MCDM method has been used for the benchmarking and prioritisation of MPMSs in terms of MPMS selection, thereby presenting a theoretical gap. In several studies, numerous MCDM methods, such as AHP and best–worst method (BWM), have been proposed and used to calculate criterion weights [73–77]. AHP allows the decision makers to structure the decision-making problem into a hierarchy tree and facilitates understanding of the problem. However, this approach possesses high time consumption because of the number of pairwise comparisons and requires mathematical calculations that increase with the number of attributes and alternatives. Moreover, AHP is significantly restrained by the human capacity for information processing; thus, 7 ± 2 is regarded as the ceiling for comparison. However, scoring and prioritisation in AHP depend on the alternatives considered for evaluation, and the removal or addition of alternatives may change the final prioritisation (rank reversal problem). The BWM requires fewer comparisons and saves more time for decision making and producing reliable and consistent results compared with existing pairwise comparison-based methods [78–81]. The BWM also yields more coordinated results and has fewer pairwise comparisons than AHP [82]. The MEW and WPM can eliminate any element to be measured and utilise proportional values instead of actual ones. Nevertheless, these methods do not provide any solution with equal decision matrix (DM) weight. WSM and HAW techniques are easy to use and understand. However, utilising both techniques become difficult with the increase in the number of criteria because the weights of the attributes are arbitrarily assigned. The use of common numerical scaling to obtain the final score is another limitation of these methods. SAW considers all criteria/attribute, intuitively decides and offers simple calculation; however, it does not commonly discover the actual situation, and all criterion values must be positive and maximum. TOPSIS and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) are applied to situations that involve several alternatives and criteria. These methods are also particularly suitable for quantitative or objective data and entail the application of a compromise priority approach to achieve multiple responses [83–85]. TOPSIS determines the shortest distance to the ideal solution and the longest distance from the ideal passive solution; nonetheless, the relative importance of these distances is ignored [84, 86, 87]. By contrast, VIKOR functionally relates to emergent problems. This method is one of the most practical approaches to handle real-world problems. VIKOR can quickly find the best alternative [83]. Thus, it is suitable for situations that involve several alternatives and features. However, VIKOR cannot elicit weights and examine the consistency of judgement [86]. Several studies [82, 87–92] have applied BWM with VIKOR to improve the consistency of weights. The use of BWM with VIKOR has been widely suggested because VIKOR cannot calculate weights and check consistency on its own [80, 81, 90].

Methodology

This section describes and explains the methodology phases of the proposed framework for MPMSs. The methodology comprises four phases. Phase 1 is the identification and preprocessing phase, which finds suitable data for the proposed framework. Phase 2 is the determination phase, which ascertains the importance of the available criteria. Phase 3 is the development phase, which establishes the prioritisation framework for MPMSs. Phase 4 is the validation phase, which verifies the proposed framework. Figure 1 presents the entire proposed framework.

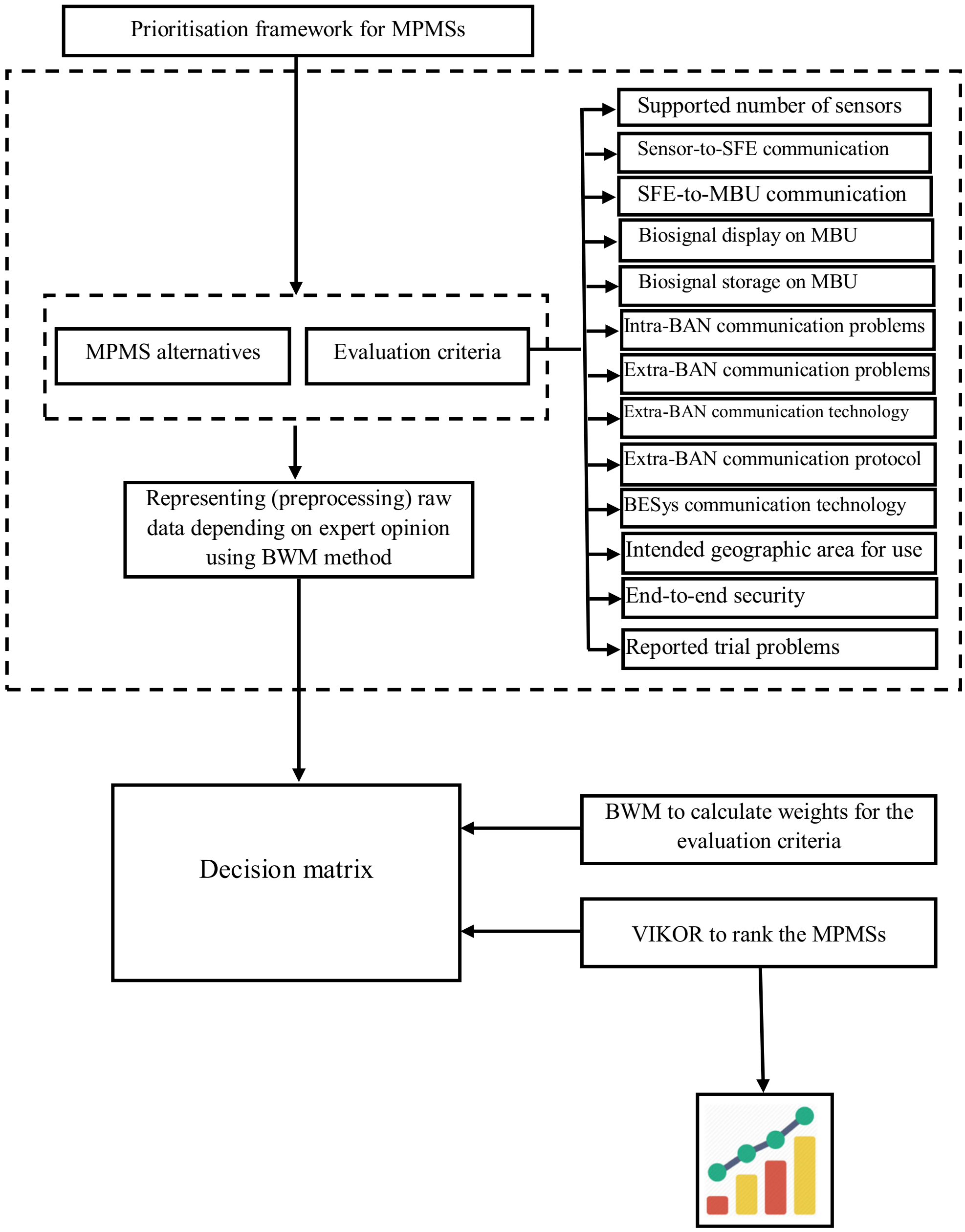

Fig. 1 Framework for prioritisation of MPMSs

Phase 1: Identification and representation phase

In this phase, the data used for testing the proposed framework are identified. The DM consists of two parts, namely, evaluation criteria and alternatives (MPMSs), as shown in Table 1, which was adopted from the most relevant study [32]. This table includes the data that cover the evaluation criteria based on the generic architecture of MPMSs.

As shown in Table 1, the MPMSs are evaluated on the basis of the following criteria. Criterion 1 presents the set of sensors integrated into the BAN (the value is numbers). Criterion 2, which has two values (RF or wired), is the communication used between sensors and the SFE. Criterion 3, which has four values (RF, serial, BT and wired), presents the communication used between the SFE and the MBU. Criterion 4 presents the capability of the MBU to display biosignals (the value is yes or no). Criterion 5 indicates the capability of the MBU to store biosignals (the value is yes or no). Criteria 6 and 7 report the availability of problems in intra-BAN (the value is yes or no) and extra-BAN (the value is yes or No) communications, respectively. Criterion 8, which has six values (3G/GSM, WLAN, RF, multihop ad hoc or WLAN/3G/general packet radio service (GPRS)), shows the extra-BAN communication technology. Criterion 9 decides which of the three values (HTTP, SMAC or TCP/IP) are used for the extra-BAN communication protocol. Criterion 10 presents the BESys

Table 1 Adopted data provided by [7]

Criteria MPMS	1. Supported number of sensors	2. Sensors-to-SFE communication	3. SFE-to-MBU communication	4. Biosignal display on the MBU	5. Biosignal storage on the MBU	6. Intra-Ban communication problems	7. Extra-BAN communication problems	8. Extra-BAN communication technology	9. Extra-BAN communication protocol	10. BESys communication technology	11. Intended geographic area for use	12. End-to-end security	13. Reported trial problems
Yale–NASA	5	RF	RF	No	No	No	No	RF	SMAC	TCP/IP	Outdoor	No	Yes
AID-N	3	Wired	Serial	Yes	No	No	Yes	Multihop ad hoc	SMAC	Web Services	Indoor	No	Yes
PHM	>6	Wired	BT	Yes	Yes	No	No	3G, GSM	TCP/IP	Web Services	Indoor/ Outdoor	No	No
CMS	1	RF	Wired	No	No	No	Yes	Multihop ad hoc	SMAC	IP	Indoor	No	Yes
NTU	2	Wired	Serial	Yes	Yes	No	No	WLAN	TCP/IP	HTTP	Indoor	Yes	No
MH	>10	Wired	BT	Yes	Yes	No	Yes	WLAN, 3G, GPRS	HTTP	Jini	Indoor/ Outdoor	No	Yes

communication technology with five values (web services, Jini, IP, TCP/IP or HTTP). Criterion 11 reports the three values of intended geographic area (indoor, outdoor or outdoor/indoor). Criterion 12 presents the availability of security solutions for the transmission of biosignals (the value is yes or no). Finally, Criterion 13 indicates the availability of technical problems, communication problems and user acceptance during trial version (the value is yes or no).

Some of these criteria need representation to be applicable to MCDMs. Using MCDM theory in the raw data shown in Table 1 is mathematically inapplicable due to the following reasons: (1) inconsistent format (strings and numbers) of the values in the raw data and (2) the use of different communication technologies and protocols. Moreover, the values of the used data must be digitalised for the prioritisation framework.

Data representation

The process of data representation must be designed and applied amongst raw data in the DM. The values in Table 1 must be digitalised for their usage in MCDM analysis techniques and representing the data on the basis of experts' opinion. The experts provide opinions on the values that must be represented using the BWM. Table 2 presents the criteria, which include the values for representation.

Integer values are designated by the data representation to each extracted value. The integer values indicate the state of the values in prioritisation based on the DM. According to Tables 1 and 2, Criteria 1, 4, 5, 6, 7, 12 and 13 do not need experts' opinions; they are represented as two types. The first type includes integer values that can be represented as numbers, such as in Criterion 1. The second type comprises binominal values (yes/no), which can be represented as 1 for yes and 0 for no, such as in Criteria 4, 5, 6, 7, 12 and 13. Criteria with multiple values, such as Criteria 2, 3, 8, 9, 10 and 11, cannot be represented and need experts' opinions based on BWM standards. The experts' role is to provide their opinion on each value relative to others. The BWM converts such opinion into digits.

Experts decide the best and worst values in each criterion. They conduct a pairwise comparison between the best value and the other values to determine the predilection of the best value over all other values and then process the pairwise comparison between the other values and the worst value to determine the preference of all values for the least important value. The designed form in Appendix A-1 is used to designate experts' opinion based on BWM standards. The pairwise steps of the six criterion values that need representing are presented in Table 1.

(1) C2 has two values, namely, RF and wired. The best and worst values are selected, and the preference value is given.

Table 2 Criteria including values for representation

Criteria	Evaluation according to values
Criterion 1	Its values are ready to use.
Criterion 2	Its values need representation based on experts' opinions according to BWM standards.
Criterion 3	Its values need representation based on experts' opinions according to BWM standards.
Criterion 4	Its values do not need experts' opinions.
Criterion 5	Its values do not need experts' opinions.
Criterion 6	Its values do not need experts' opinions.
Criterion 7	Its values do not need experts' opinions.
Criterion 8	Its values need representation based on experts' opinions according to BWM standards.
Criterion 9	Its values need representation based on experts' opinions according to BWM standards.
Criterion 10	Its values need representation based on experts' opinions according to BWM standards.
Criterion 11	Its values need representation based on experts' opinions according to BWM standards.
Criterion 12	Its values do not need experts' opinions.
Criterion 13	Its values do not need experts' opinions.

(2) C3 has four values, namely, RF, serial, BT and wired.
(3) C7 has five values, namely, RF, multihop ad hoc, 3G/GSM, WLAN and WLAN/3G/GPRS.
(4) C8 has three values, namely, SMAC, TCP/IP and HTTP.
(5) C9 has five values, namely, TCP/IP, web services, IP, HTTP and Jini.
(6) C10 has three values, namely, indoor, outdoor and indoor/outdoor.

Each expert scores each value by following the steps of selecting the best and worst amongst the values. They use the 1–9 measurement scale in giving a preference score for a pairwise comparison of the best value with the other values and for the other values in comparison with the worst value. The BWM mathematical model is used to convert those values into digits. Additional description of this mathematical model is provided in the next section.

Phase 2: Determination phase

This phase focuses on determining the importance of the available criteria and calculates the weights of the evaluation criteria in the DM. These weights determine the importance of each criterion and should thus help in the prioritisation. Conducting the prioritisation is difficult if all criteria have the same importance. The importance of each criterion amongst the other criteria must be considered. The BWM is used to calculate the weights of the evaluation criteria due to its reliability and few comparison requirements. This phase comprises three steps. The first step is designing the expert form to collect experts' opinions. The compatibility of this form with the BWM and the comparison amongst criteria are considered. The second step is expert selection, in which the experts' opinion on the identified criteria is collected. The third step involves eliciting the weights for the criteria using the BWM.

The experts' opinion in the field of research must be obtained to gather all the necessary data for a BWM analysis. A form is designed to collect experts' opinion on the criteria according to the BWM standard. The BWM is used to calculate the weights for evaluation criteria. The experts are then selected from several academic experts (four experts; [93–96]. This study depends on the experts' opinion on the criteria to help 1) represent the data from the previous phase and 2) rank the criterion weights. Moreover, the experts are selected from those who have a minimum of five years of experience [97]. The BWM procedure to set the appropriate weights for multiple criteria includes the following five steps [80, 98].

Step 1: Determining a set of decision criteria

Before deciding the best alternative, the criteria set to be used by decision makers must be determined ($C_1, C_2, \ldots, C_n$). Table 3 provides the selected criteria, and their weights are calculated.

Step 2: Determining the best and worst criteria

Depending on the decision, the most desirable or the most important criterion is treated as the best criterion, whereas the least desirable or least important criterion is the worst criterion. The definition of the best and worst criteria depends on the viewpoints of decision makers.

Step 3: Conducting a pairwise comparison between the best criterion and the other criteria

Pairwise comparison is performed between the identified best criterion and other criteria to determine the predilection of the best criterion over all the other criteria, as shown in Fig. 2.

Table 3 Selected criteria

Criterion set	Description
C_1	Supported number of sensors
C_2	Sensor-to-SFE communication
C_3	SFE-to-MBU communication
C_4	Biosignal display on the MBU
C_5	Biosignal storage on the MBU
C_6	Intra-BAN communication problems
C_7	Extra-BAN communication problems
C_8	Extra-BAN communication technology
C_9	Extra-BAN communication protocol
C_{10}	BESys communication technology
C_{11}	Intended geographic area for use
C_{12}	End-to-end security
C_{13}	Reported trial problems

A value from 1 to 9 must be specified by the experts to symbolise the importance of the best criterion over the other criteria. A factor known as 'best-to-others' will result from this procedure.

$$AB = (a_{B1}, a_{B2}, \ldots, a_{Bn}), \quad (1)$$

where a_{Bj} refers to the importance of the best criterion *B* over criteria *j*, and a_{BB} =1.

Step 4: Pairwise comparison between the other criteria and the worst criterion, as shown in Fig. 2.

The preference of all criteria over the least important criterion (the worst criterion) is determined through comparison. Experts identify the importance of all criteria on the basis of the worst criterion; the values from 1 to 9 are used to specify the importance. A factor known as 'others-to-worst' will result from this procedure.

$$A_w = (a_{1w}, a_{2w}, \ldots, a_{nw}), \quad (2)$$

Table 4 Consistency index

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency index	0.0	0.44	1.0	1.63	2.30	3.00	3.73	4.47	5.23

where a_{jw} indicates the preference of criterion j over the worst criterion W, and $a_{ww} = 1$.

Step 5: Calculating optimal weights ($W^*1, W^*2, \ldots, W^*n$)

The perfect weight for a criterion is one in which for each pair of W_B/Wj and Wj/Ww, and $W_B/W_j = a_{BJ}$ and $W_j/W_w = a_{jw}$.

A solution with the maximum absolute differences should be identified to achieve these conditions for all j.

$$\left|\frac{W_B}{W_j} - a_{Bj}\right| and \left|\frac{W_i}{W_w} - a_{Bjw}\right| \quad (3)$$

All values of *j* are minimised. Considering the nonnegativity and sum condition for the weights, the following problem is created:

$$\text{minmax}_j \left\{ \frac{W_B}{W_j} - a_{Bj}|, \left|\frac{W_j}{W_w} - a_{jw}\right| \right\}, \quad (4)$$

such that

$$\sum_j W_j = -1,$$

$$W_j \geq 0, \text{ for all } j.$$

Problem (5) can be substituted into the following problem:
Minimise ξ.
such that

$$\left|\frac{W_B}{W_J} - a_{Bj}\right| \leq \xi, \textit{for all } j, \quad (5)$$

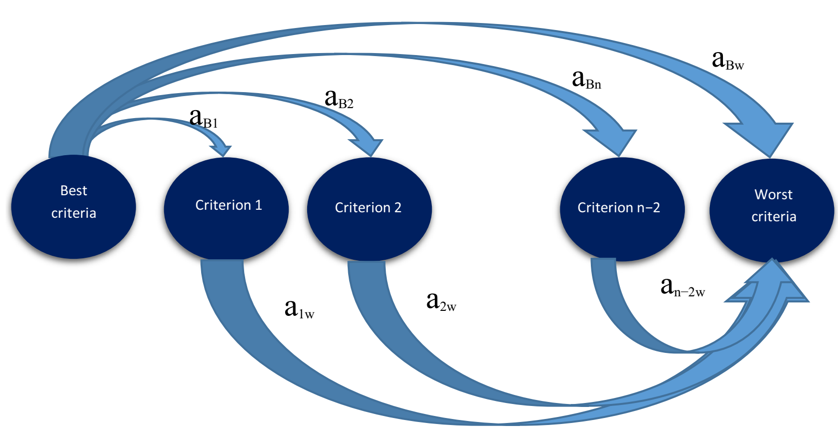

Fig. 2 Reference comparisons in the BWM method

$$\left|\frac{W_j}{W_w} - a_{jw}\right| \le \xi, for\ all\ j, \tag{6}$$
$$\sum_j W_j = -1.$$

The perfect weights $w_1^*: w_2^*; \ldots; w_n^*$ and ξ n are achieved by solving Problem (5).

The value of * reflects the reliability of outcomes and relies on the scope of consistency in the comparisons. The value closest to zero leads to high consistency and reliability. The consistency ratio (CR) using ξ* and the corresponding consistency index are calculated as follows:

$$\text{Consistency Ratio} = \frac{\xi^*}{Consistency\ Index}. \tag{7}$$

As proposed by [80], a high ξ* value yields a consistent factor (Table 4).

Phase 3: Development phase

This phase focuses on developing a new framework for prioritisation of MPMSs on the basis of the determined importance of the evaluation criteria and adopted DM. Therefore, a new framework is developed on the basis of MCDM techniques. The VIKOR method is used to rank the various alternatives (MPMSs) of the weighted DM, as presented in Phase 1. The phase steps are presented below.

Step 1: Defining the highest and lowest values for each criterion

The best f^*i and worst f^-i values of all criterion functions, i = 1, 2, ..., n, are identified. If function i represents a benefit, then

$$f_i^* = \max_j f_{ij}, \quad f_i^- = \min_j f_{ij}. \tag{8}$$

Step 2: Constructing a weighted DM

Weights are calculated in the BWM for all criteria. A set of weights ($w = w_1, w_2, w_3, \cdots, w_j, \cdots, w_n$) by the decision maker is accommodated in the DM. This set of weights is equal to 1. The resulting matrix can also be calculated, as shown as follows:

$$WM = wi*\left(f^*i - fij\right)/\left(f^*i - f^-i\right). \tag{9}$$

The following weighted matrix is produced by the previous process:

$$\begin{bmatrix} w_1\left(f^*1-f11\right)/\left(f^*1-f^-1\right) & w_2\left(f^*2-f12\right)/\left(f^*2-f^-2\right) & \ldots & w_i\left(f^*i-fij\right)/\left(f^*i-f^-i\right) \\ w_1\left(f^*1-f21\right)/\left(f^*1-f^-1\right) & w_2\left(f^*2-f22\right)/\left(f^*2-f^-2\right) & \ldots & w_i\left(f^*i-fij\right)/\left(f^*i-f^-i\right) \\ \vdots & \vdots & \vdots & \vdots \\ w_1\left(f^*1-f31\right)/\left(f^*1-f^-1\right) & w_2\left(f^*2-f32\right)/\left(f^*2-f^-2\right) & \ldots & w_i\left(f^*i-fij\right)/\left(f^*i-f^-i\right) \end{bmatrix}. \tag{10}$$

Step 3: Calculating S_j and R_j in rough numbers

The S_j and R_j values, (j = 1, 2, 3, …, J) and (i = 1, 2, 3, …, n), are calculated as

$$Sj = \sum_{i=1}^n wi*\frac{f^*i-fij}{f^*i-f^-i}, \tag{11}$$

$$Rj = \max_i wi*\frac{f^*i-fij}{f^*i-f^-i}, \tag{12}$$

where wi expresses the weights of the criteria by presenting their relative importance.

Step 4: Calculating Q_i in rough number

The value of Q_j, $j = (1, 2, \cdots, J)$, is calculated as follows:

$$Q_j = \frac{v\left(S_j - S^*\right)}{S^- - S^*} + \frac{(1-v)\left(R_j - R^*\right)}{R^- - R^*}, \tag{13}$$

where

$$S^* = \min_j S_j, S^- = \max_j S_j,$$

$$R^* = \min_j R_j, R^- = \max_j R_j.$$

v is presented as the weight of the strategy of 'the majority of the criteria' (or 'the maximum group utility'); the value of v = 0.5.

Step 5: Performing alternative prioritisation

The set of alternatives can be ranked by sorting the values (S, R and Q) in ascending order. The lowest value indicates optimal performance.

Step 6: Examining the 'acceptable advantage' and 'acceptable stability' in decision making

The alternative $a^{'}$ is proposed as a compromise solution, which is ranked the best by the measure Q (minimum) if the following two conditions are satisfied:

- C1. 'Acceptable advantage';
- $Q(a^{''}) - Q(a^{'}) \geq DQ$,

where $(a^{''})$ is the alternative at the second position in the prioritisation list by Q, $DQ = 1/(J - 1)$, where J is the number of alternatives.

C2. 'Acceptable stability' with the decision-making context: alternative $a^{'}$ should also be the best ranked by S and/or R.

This compromise solution is stable within the decision-making process and can be subjected to 'voting by majority rule' ($v > 0:5$), 'by consensus' ($v \cong 0.5$) or 'with veto' ($v < 0.5$). Herein, v is the decision-making strategy weight of 'the majority of the criteria' (or 'the maximum group utility'). VIKOR can be applied to various environments. This study depends on individual and group contexts in decision making to eliminate the variation, and the GDM is applied depending on two techniques, namely, internal and external aggregation.

Phase 4: Validation phase

This phase focuses on the objective validation of the proposed framework. The results of the proposed prioritisation framework are verified using objective validations. In this study, two statistical methods are used, namely, mean ± standard deviation (SD), to ensure the validity of the MPMS prioritisation based on the proposed prioritisation framework.

Mean is the average result, which can be calculated as follows:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i. \tag{14}$$

The SD for determining the amount of dispersion or variation in the value set is calculated as follows:

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - \overline{x}\right)^2}. \tag{15}$$

On the basis of the prioritisation result determined from the proposed prioritisation framework, the MPMS scoring values are divided into three groups to validate the prioritisation results using the two aforementioned tests. Each group contains an equal number of MPMSs (two MPMSs in each group) according to the MPMS scoring values of the prioritisation results. According to a statistical platform, this process is applied using mean ± SD methods to confirm that the first group has the lowest scoring value when the mean and SD are measured. For result validation, the first group is presumed to have the lowest mean and SD in comparison with that of the other two groups. The mean and SD results of the second group must be higher than or equal to those of the first group. The mean and SD results for the third group should be higher than those of the first and second groups or equal to those of the second group. Accordingly, the results of the methodological arrangement statistically imply that the first group should have the lowest result amongst the groups [99, 100].

Results and discussion

Data representation results

The data used in this study are adopted from the most relevant study by [32], as presented in Table 1; they contain some values that must be represented. The use of decision-making theory for the raw data is mathematically inapplicable based on the aforementioned reasons in Section "Phase 1: Identification and representation phase". Thus, the data representation process is applied to the raw data on the basis of four experts' opinion according to the BWM standard to convert their judgements into weights for each of the six criterion values that need representing, as described in Section "Data representation". The results of the representation process based on Expert 1 are presented in Table 5, and the results of the representation process based on the other three experts are presented in Appendix B (Tables B1–B3).

The best and worst values are identified, a comparison between the best value and the others is performed and a comparison between all values and the worst value is achieved. The linear model of the BWM is solved according to Eqs. (5) and (6) in Section "Phase 2: Determination phase" to obtain the score values, and Eq. (7) is used to calculate the CR of each expert's preferences, as mentioned in Section "Phase 2: Determination phase". The obtained score values provided by the experts are different. Table 6 shows the final results of data representation from the four experts based on arithmetic mean.

Table 6 shows the final DM after representation depending on the opinion of the four experts. This final DM result is used in prioritisation (Table 7).

Table 5 Results of the representation based on BWM standards (First expert)

Expert 1							
C2: Sensor-to-SFE communication							
List of values	Best value	Other values	Scores				Score values
RF	RF	Wired	7				0.875
Wired		–	–				0.125
Consistency: 0.0							
C3: SFE-to-MBU communications							
List of values	Best value	Other values	Scores	Other values	Worst value	Scores	Score values
RF	RF	Serial	7	RF	Serial	7	0.572
Serial		BT	3	BT		5	0.066
BT		Wired	5	Wired		3	0.226
Wired		–	–	–		–	0.136
Consistency: 0.029							
C8: Extra-BAN communication technology							
List of values	Best value	Other values	Scores	Other values	Worst value	Scores	Score values
RF	WLAN, 3G, GPRS	RF	7	Multihop ad-hoc	RF	5	0.051
Multihop ad hoc		Multihop ad hoc	5	3G and GSM		3	0.125
3G and GSM		3G and GSM	3	WLAN		5	0.208
WLAN		WLAN	5	WLAN, 3G and GPRS		7	0.125
WLAN, 3G and GPRS		–	–	–		–	0.491
Consistency: 0.035							
C9: Extra-BAN communication protocol							
List of values	Best value	Other values	Scores	Other values	Worst value	Scores	Score values
SMAC	SMAC	TCP/IP	3	SMAC	HTTP	5	0.644
TCP/IP		HTTP	5	TCP/IP		3	0.244
HTTP		–	–	–		–	0.111
Consistency: 0.039							
C10: BESys communication technology							
List of values	Best value	Other values	Scores	Other values	Worst value	Scores	Score values
TCP/IP	TCP/IP	Web services	3	TCP/IP	HTTP	5	0.433
Web services		IP	3	Web services		3	0.164
IP		HTTP	5	IP		3	0.164
HTTP		Jini	3	Jini		3	0.075
Jini		–	–	–		–	0.164
Consistency: 0.026							
C11: Intended geographic area of use							
List of values	Best value	Other values	Scores	Other values	Worst value	Scores	Score values
Indoor	Indoor/Outdoor	Indoor	5	Outdoor	Indoor	3	0.111
Outdoor		Outdoor	3	Indoor/Outdoor		5	0.244
Indoor/Outdoor		–	–	–		–	0.644
Consistency: 0.039							

Three specific issues must be addressed in the comparison and prioritisation processes using the adopted DM, that is, (1) multiple evaluation criteria, (2) importance of criteria and (3) data variation. Therefore, MCDM is used to handle these issues. The results are presented in the next two sections.

Weight results of the evaluation criteria based on BWM

Weight results are presented and explained in this section. As mentioned in Section "Phase 2: Determination phase", four

Table 6 Final results of represented value based on arithmetic mean

Arithmetic mean	
C2: Sensor-to-SFE communication	
List of values	Score value
RF	0.833
Wired	0.166
C3: SFE-to-MBU communication	
List of values	Score value
RF	0.368
Serial	0.110
BT	0.399
Wired	0.155
C8: Extra-BAN communication technology	
List of values	Score value
RF	0.064
Multihop ad hoc	0.143
3G and GSM	0.146
WLAN	0.176
WLAN, 3G and GPRS	0.418
C9: Extra-BAN communication protocol	
List of values	Score value
SMAC	0.644
TCP/IP	0.214
HTTP	0.140
C10: BESys communication technology	
List of values	Score value
TCP/IP	0.300
Web services	0.297
IP	0.118
HTTP	0.127
Jini	0.155
C11: Intended geographic area of use	
List of values	Score value
Indoor	0.114
Outdoor	0.228
Indoor/Outdoor	0.657

experts were asked to provide their preferences on the evaluation criteria for MPMSs (six systems) via the BWM. The weight results of Expert 1 for the evaluation criteria are presented in Table 8, and the detailed results of the three other three are shown in Appendix C (Tables C1–C3).

Table 8 and Appendix C (Tables C1–C3) show that the results of the weights depend on the four experts based on the BWM. For the evaluation criteria, the following steps are conducted: (1) identifying the best and worst criteria; (2) performing a comparison between the best criteria and the others; (3) comparing all criteria and the worst criterion; and (4) solving the linear model of the BWM according to Eqs. (5)

Table 7 Final DM result

Criteria MPMS	1. Supported number of sensors	2. Sensor-to-SFE communication	3. SFE-to-MBU communication	4. Biosignal display on the MBU	5. Biosignal storage on the MBU	6. Intra-BAN communication problems	7. Extra-BAN communication problems	8. Extra-BAN communication technology	9. Extra-BAN communication protocol	10. BESys communication technology	11. Intended geographic area for use	12. End-to-end security	13. Reported trial problems
Yale–NASA	5	0.833	0.368	0	0	0	0	0.064	0.644	0.300	0.228	0	1
AID-N	3	0.166	0.110	1	0	0	1	0.143	0.644	0.297	0.114	0	1
PHM	6	0.166	0.399	1	1	0	0	0.146	0.214	0.297	0.657	0	0
CMS	1	0.833	0.155	0	0	0	1	0.143	0.644	0.118	0.114	0	1
NTU	2	0.166	0.110	1	1	0	0	0.176	0.214	0.127	0.114	1	0
MH	10	0.166	0.399	1	1	0	1	0.418	0.140	0.155	0.657	0	1

Table 8 Results of BWM for the weight preferences of the evaluation criteria of MPMSs (Expert 1)

Expert 1							
List of criteria	Best criterion	Other Criteria	Scores	Other criteria	Worst criterion	Scores	Weight
C_1	C_1	C_2	1	C_1	C10	9	0.137
C_2		C_3	1	C_2		8	0.126
C_3		C_4	3	C_3		8	0.126
C_4		C_5	3	C_4		8	0.057
C_5		C_6	3	C_5		8	0.057
C_6		C_7	3	C_6		7	0.057
C_7		C_8	5	C_7		7	0.057
C_8		C_9	5	C_8		5	0.034
C_9		C_{10}	9	C_9		5	0.034
C_{10}		C_{11}	1	C_{11}		7	0.011
C_{11}		C_{12}	3	C_{12}		3	0.114
C_{12}		C_{13}	1	C_{13}		8	0.057
C_{13}		–	–	–		–	0.126
Consistency: 0.0065							

and (6) in Section "Phase 2: Determination phase" to obtain the weights. The CR of the preferences of each expert is calculated using Eq. (7), as mentioned in Section "Phase 2: Determination phase". In all the tables, the overall CR for the scores of the four experts shows an acceptable ratio of less than 0.1. Table 9 illustrates the weight results of the four experts.

As shown in Table 9, Expert 1 assigned the maximum weight for C1 with a value of 0.1379 and the minimum weight for C10 with a value of 0.0114. Expert 2 assigned the maximum weight for C3 with a value of 0.2282 and the minimum weight for C13 with a value of 0.0169. Expert 3 assigned the maximum weight for C9 and C10 with a value of 0.1690 and the minimum weight for five criteria, namely, C1, C4, C5, C12 and C13, with a value of 0.0422. Expert 4 assigned the maximum weight for two criteria, namely, C12 and C13) with a value of 0.1637 and the minimum weight for C5 with a value of 0.0249.

The final results are used in the application of the VIKOR method in the next section, as mentioned in Section 2.3.1.

Prioritization results of MPMSs based on VIKOR method

The results of the prioritisation framework for MPMSs according to the weighted DM are presented in this section. As described in Section 2.3.1, two main decision-making contexts are emphasised, that is, individual decision making and group decision making (GDM). GDM includes internal and external aggregations. In the following subsections, the results of the individual and group VIKOR decision-making contexts are presented.

Table 9 BWM weight results of the four experts

Expert 1		Expert 2	
List of criteria	Weights	List of criteria	Weights
C_1	0.137	C_1	0.101
C_2	0.126	C_2	0.060
C_3	0.126	C_3	0.228
C_4	0.057	C_4	0.101
C_5	0.057	C_5	0.060
C_6	0.057	C_6	0.060
C_7	0.057	C_7	0.060
C_8	0.034	C_8	0.043
C_9	0.034	C_9	0.101
C_{10}	0.011	C_{10}	0.060
C_{11}	0.114	C_{11}	0.060
C_{12}	0.057	C_{12}	0.043
C_{13}	0.126	C_{13}	0.016
Consistency: 0.0065		Consistency: 0.0144	
Expert 3		Expert 4	
List of criteria	Weights	List of criteria	Weights
C_1	0.042	C_1	0.058
C_2	0.056	C_2	0.136
C_3	0.056	C_3	0.136
C_4	0.042	C_4	0.013
C_5	0.042	C_5	0.024
C_6	0.084	C_6	0.058
C_7	0.084	C_7	0.058
C_8	0.084	C_8	0.034
C_9	0.169	C_9	0.034
C_{10}	0.169	C_{10}	0.058
C_{11}	0.084	C_{11}	0.058
C_{12}	0.042	C_{12}	0.163
C_{13}	0.042	C_{13}	0.163
Consistency: 0.0518		Consistency: 0.0074	

Table 10 Prioritisation results of the weights according to Expert 1

MPMS	Q	Order
Yale–NASA	0.21349	1
AID-N	0.759235	4
PHM	0.630191	3
CMS	0.835924	5
NTU	0.877946	6
MH	0.377946	2

Prioritization results of individual context for the weights of different *experts* based on the VIKOR method

The weight preferences of the evaluation criteria from the viewpoint of each expert are used in VIKOR to rank the alternatives (MPMSs). In VIKOR, the dependency is on the Q value in prioritisation of the alternatives; a low Q value denotes a good alternative, whereas a high Q value represents a poor alternative, as described in Section 2.3.1. The VIKOR results of prioritisation according to the weights of Expert 1 are shown in Table 10, and those by the other three experts are presented in Appendix D (Tables D1–D3).

Table 10 and Appendix D (Tables D1–D3) show that the lowest Q value in the first rank is 0.133148 for 'Yale–NASA'; thus, the highest MPMS in this rank is 'Yale–NASA'. 'NTU' has the highest Q value of 0.888889, which indicates that this MPMS is the worst in this rank. In the second rank, the lowest Q value is 0.043647 for 'MH'; thus, the highest MPMS in this rank is 'MH'. The highest Q value is 1 for 'NTU', which indicates that this MPMS is the worst. In the third rank, the lowest Q value is 0 for disaster aid network '(AID-N)', which implies that the highest MPMS in this rank is 'AID-N'. The highest Q value is 1 for 'NTU', which implies that this MPMS is the worst. In the fourth rank, the lowest Q value is 0 for 'MH', which indicates that this MPMS is the best in this rank. The highest Q value is 1 for 'NTU', which denotes that this MPMS is the worst in this rank. In conclusion, the prioritisation scores are affected by the differences in the weights provided by experts. Figure 3 shows the variance amongst the VIKOR results.

As shown in Fig. 3, the MPMS rank varies depending on the weights provided by the four experts. According to the weights provided by Expert 1, 'Yale–NASA' is the first index. Meanwhile, the first index based on the weights provided by Experts 2 and 4 is 'MH'. The first index based on the weights provided by Expert 3 is 'AID-N'. The second index according to the weights provided by Expert 1 is 'MH'. The second index based on the weights provided by Expert 2 is 'PHM'. The second index based on the weights provided by Experts 3 and 4 is 'Yale–NASA'. 'PHM' is the third index according to the weights provided by Experts 1 and 3. The third index based on the weights provided by Expert 2 is 'Yale–NASA'. The third index according to the weights provided by Expert 4 is 'CMS'. The fourth index based on the weights of Experts 1 and 4 is 'AID-N' and that for Experts 2 and 3 is 'MS' and 'MH', respectively. The fifth index based on the weights provided by Experts 1 and 4 is 'CMS'. 'AID-N' is the fifth index according to the weights provided by Expert 2. The fifth index according to the weights provided by Expert 4 is 'PHM'. Finally, according to the weights provided by the four experts, 'NTU' is the sixth index. The results of the individual context clearly show variances amongst the prioritisations of the four experts. Thus, a group VIKOR decision-making context is necessary to provide alternative prioritisation that considers the overall decision makers. The results of the group VIKOR decision-making context are illustrated in the following subsection.

Prioritisation results of group context for the weights of different experts based on VIKOR method

In this subsection, two ways are used to apply VIKOR to a group decision environment depending on multiple decision makers, namely internal and external aggregations. As mentioned in Section 2.3.1, internal GDM results are calculated by the arithmetic mean of the final weights of the four experts'

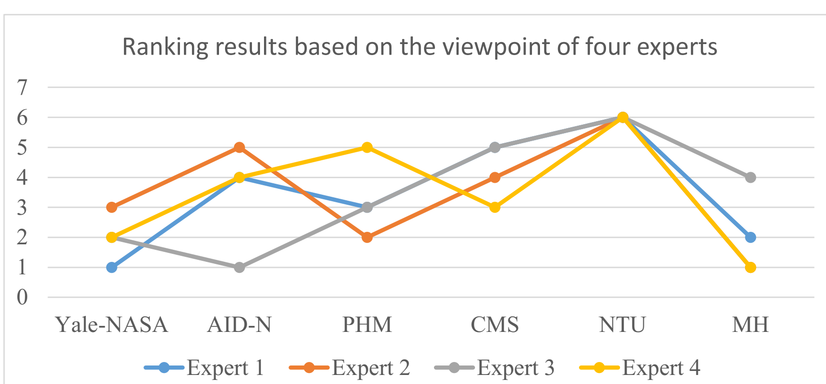

Fig. 3 Prioritization results based on the weights of four experts

preferences to eliminate the variation amongst the four experts. Then, VIKOR is applied on the basis of the final arithmetic mean results. The arithmetic mean of the Q values for the prioritisation results of each expert is used to calculate the external assembly results, and the external group prioritisation depends on the final Q values. Table 11 shows the overall prioritisation results of VIKOR with internal and external GDM for the six MPMSs.

As shown in Table 11, the results of internal and external GDM show that the order of the best/first three MPMSs is Yale–NASA, MH and PHM. The worst/last MPMS based on the results of internal and external GDM is NTU. Other MPMSs have different orders between internal and external GDM. The order of those MPMSs based on internal prioritisation is CMS as the fourth and AID-N as the fifth. On the basis of external prioritisation, AID-N and CMS are fourth and fifth, respectively. Therefore, the best three indices of MPMSs in internal and external GDM are equal, and the worst index MPMS is equal as well. The remaining two MPMSs have different score indices. From this point, the internal and external aggregation decision-making ranks can be considered the final prioritisation results and will be used in validation processes. The next section comprehensively describes the validation results.

Results of validation

This section presents the validation processes of the internal and external GDM ranks. Objective validation processes are used in this study. As mentioned in Section "Phase 4: Validation phase", the validation process for MPMS prioritisation results is obtained by dividing the prioritisation result into three groups of two MPMSs in each group. For each group, the mean ± SD is calculated to ensure that the prioritisation of MPMSs undergo systematic prioritisation. After normalisation and weighting process for the represented raw data of the first, second and third groups of MPMS. The validation results for internal and external GDM are presented in Table 12.

As shown in Table 12, the validation results for internal aggregation GDM indicate that the mean ± SD in the first group is lower than that in the second group in most values, except for C2 in the first group M = 0.048 ± 0.067 and in the second group M = 0.047 ± 0.067; C7 in the first group M = 0.033 ± 0.045 and in the second group M = 0.032 ± 0.045; C9 in the first group M = 0.043 ± 0.060 and in the second group M = 0.036 ± 0.051. The mean ± SD are equal for C4 M = 0.027 ± 0.038, C5 M = 0.023 ± 0.032, C6 M = 0.0 ± 0.0 and C12 M = 0.077 ± 0.0. The mean ± SD for the second group is lower than that in the third group for most criteria, except for C4 in the second group M = 0.027 ± 0.038 and in the third group M = 0.0 ± 0.0; C8 in the second group M = 0.038 ± 0.0 and in the third group M = 0.036 ± 0.002; C10 in the second group M = 0.038 ± 0.052 and in the third group M = 0.036 ± 0.049; and C12 in the second group M = 0.077 ± 0.0 and in the third group M = 0.038 ± 0.054. The mean ± SD are equal for (C5 M = 0.023 ± 0.032, C6 M = 0.0 ± 0.0, C7 M = 0.032 ± 0.045, C9 M = 0.036 ± 0.051 and C13 M = 0.043 ± 0.061).

Regarding the validation results for the external aggregation GDM, the mean ± SD in the first group is lower than that in the second group, except for C4 in the first group M = 0.027 ± 0.038 and in the second group M = 0.0 ± 0.0; C9 in the first group M = 0.042 ± 0.060 and in the second group M = 0.036 ± 0.051; C10 in the first group M = 0.03 ± 0.042 and in the second group M = 0.001 ± 0.0; and C13 in the first group M = 0.0 ± 0.0 and in the second group M = 0.043 ± 0.061. The mean ± SD are equal for C5 M = 0.023 ± 0.032, C6 M = 0.0 ± 0.0, C7 M = 0.032 ± 0.045 and C12 M = 0.077 ± 0.0. The mean ± SD for the second group is lower than that in the third group for most values, except for C2 in the second group M = 0.095 ± 0.0 and in the third group M = 0.047 ± 0.067; C8 in the second group M = 0.038 ± 0.0 and in the third group M = 0.036 ± 0.002; and C12 in the second group M = 0.077 ± 0.0 and in the third group M = 0.038 ± 0.054. The mean ± SD are equal for C5 M = 0.023 ± 0.032, C6 M = 0.0 ± 0.0, C7 M = 0.032 ± 0.045, C9 M = 0.036 ± 0.051 and C13 M = 0.043 ± 0.061. Accordingly, the first group has a lower value than that of the second group, and the second group has a lower value than that of the third group for internal and external GDM. Overall, the ranks of internal and external GDM are valid and systematic.

Table 11 Overall prioritisation results of VIKOR with internal and external GDM

Internal GDM			External GDM		
MPMS	Q	Order	MPMS	Q	Order
Yale–NASA	0.124982	1	Yale–NASA	0.1256775	1
AID-N	0.779007	5	AID-N	0.4837975	4
PHM	0.34741	3	PHM	0.38386	3
CMS	0.642803	4	CMS	0.6510775	5
NTU	1	6	NTU	0.832435	6
MH	0.151255	2	MH	0.239745	2

Conclusion

The number of MPMSs is continuously increasing to provide healthcare services and save the lives of patients. Biosignal transmission can be an important factor in the remote patient monitoring field. Search and review were performed for MPMS selection, focusing on benchmarking

Table 12 Validation results of internal and external GDM ranks

MPMS	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Internal aggregation for GDM													
Yale–NASA	0.047	0.000	0.015	0.054	0.046	0.000	0.065	0.049	0.000	0.000	0.063	0.077	0.000
MH	0.000	0.095	0.000	0.000	0.000	0.000	0.000	0.000	0.085	0.060	0.000	0.077	0.000
Mean	0.024	0.048	0.008	0.027	0.023	0	0.033	0.025	0.043	0.030	0.032	0.077	0.000
Std	0.033234019	0.067175144	0.010606602	0.038183766	0.032526912	0	0.045961941	0.034648232	0.060104076	0.042426407	0.044547727	0	0
Overall mean	0.028												
Overall SD	0.5031493												
PHM	0.038	0.095	0.000	0.000	0.000	0.000	0.065	0.038	0.073	0.001	0.000	0.077	0.087
CMS	0.085	0.000	0.116	0.054	0.046	0.000	0.000	0.038	0.000	0.075	0.080	0.077	0.000
Mean	0.0615	0.0475	0.058	0.027	0.023	0	0.0325	0.038	0.0365	0.038	0.04	0.077	0.0435
Std	0.033234019	0.067175144	0.082024387	0.038183766	0.032526912	0	0.045961941	0	0.051618795	0.052325902	0.056568542	0	0.06152
Overall mean	0.040192												
Overall SD	0.040088												
AID-N	0.066	0.095	0.137	0.000	0.046	0.000	0.000	0.038	0.000	0.001	0.080	0.077	0.000
NTU	0.075	0.095	0.137	0.000	0.000	0.000	0.065	0.034	0.073	0.071	0.080	0.000	0.087
Mean	0.0705	0.095	0.137	0	0.023	0	0.0325	0.036	0.0365	0.036	0.08	0.0385	0.0435
Std	0.006363961	0	0	0	0.032526912	0	0.045961941	0.002828427	0.051618795	0.049497475	0	0.054447	0.06152
Overall mean	0.0483462												
Overall SD	0.0234433												
Validation results for the external aggregation GDM													
Yale–NASA	0.047	0.000	0.015	0.054	0.046	0.000	0.065	0.049	0.000	0.000	0.063	0.077	0.000
MH	0.000	0.095	0.000	0.000	0.000	0.000	0.000	0.000	0.085	0.060	0.000	0.077	0.000
Mean	0.0235	0.0475	0.0075	0.027	0.023	0	0.0325	0.0245	0.0425	0.03	0.0315	0.077	0
Std	0.033234019	0.067175144	0.010606602	0.038183766	0.032526912	0	0.045961941	0.034648232	0.060104076	0.042426407	0.044547727	0	0
Overall mean	0.0281923												
Overall SD	0.0314934												
PHM	0.038	0.095	0.000	0.000	0.000	0.000	0.065	0.038	0.073	0.001	0.000	0.077	0.087
AID-N	0.066	0.095	0.137	0.000	0.046	0.000	0.000	0.038	0.000	0.001	0.080	0.077	0.000
Mean	0.052	0.095	0.0685	0	0.023	0	0.0325	0.038	0.0365	0.001	0.04	0.077	0.0435
Std	0.01979899	0	0.096873629	0	0.032526912	0	0.045961941	0	0.051618795	0	0.056568542	0	0.06152
Overall mean	0.039												
Overall SD	0.0280667												
CMS	0.085	0.000	0.116	0.054	0.046	0.000	0.000	0.038	0.000	0.075	0.080	0.077	0.000
NTU	0.075	0.095	0.137	0.000	0.000	0.000	0.065	0.034	0.073	0.071	0.080	0.000	0.087
Mean	0.08	0.0475	0.1265	0.027	0.023	0	0.0325	0.036	0.0365	0.073	0.08	0.0385	0.0435
Std	0.007071068	0.067175144	0.014849242	0.038183766	0.032526912	0	0.045961941	0.002828427	0.051618795	0.002828427	0	0.054447	0.06152
Overall mean	0.048346												
Overall SD	0.023443												

and prioritisation to determine the research gap, challenges and open issues in the MPMS selection process. A serious gap was found in the reviewed studies, which failed to benchmark a set of MPMSs according to selected criteria in an integrated platform. These studies only partially conducted benchmarking and prioritisation. Such shortcoming causes a challenge in the comparison of numerous MPMSs to determine the best due to the following: varying evaluation criteria, criterion importance, data variation and unmeasurable values. The goal of using MCDM methods is not only to predict the choices of decision makers but also to help humans make informed decisions. This study reviewed the selected evaluation criteria based on the architectural components of MPMSs for benchmarking. This study proposed a prioritisation framework based on MCDM techniques for comparing and prioritising MPMSs to fill the research gap and address the challenges and open issues. The methodology was clarified on the basis of four key phases. The identification and preprocessing, including data representation design and raw data application based on judgements of experts, are involved in Phase 1. Phase 2 determined the importance of the available criteria based on the BWM. The development of a new prioritisation framework for comparison and prioritisation based on the VIKOR method comprised Phase 3. The validation process was Phase 4. The results of the proposed framework are presented and discussed in Section "Results and discussion". The prioritisation of MPMSs was performed on the basis of internal and external GDM. The results showed that both GDM were almost the same. Finally, the validation of the results was achieved objectively. The statistical results indicate that the MPMS prioritisation results undergo systematic prioritisation based on internal and external aggregation GDM.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

1. Iqbal, S. et al., Real-time-based E-health systems: design and implementation of a lightweight key management protocol for securing sensitive information of patients. Health Technol. (Berl).:1–19, 2018.
2. Alanazi, H. O. et al., Meeting the Security Requirements of Electronic Medical Records in the ERA of High-Speed Computing. J. Med. Syst. 39(1):165, 2015.
3. Nabi, M. S. A. et al., Suitability of Using SOAP Protocol to Secure Electronic Medical Record Databases Transmission. Int. J. Pharmacol. 6(6):959–964, 2010.
4. Kiah, M. L. M. et al., An Enhanced Security Solution for Electronic Medical Records Based on AES Hybrid Technique with SOAP/XML and SHA-1. J. Med. Syst. 37(5):9971, 2013.
5. Nabi, M. S., et al., Suitability of adopting S/MIME and OpenPGP email messages protocol to secure electronic medical records. In: Second International Conference on Future Generation Communication Technologies (FGCT 2013), pp. 93–97, 2013.
6. Kiah, M. L. M. et al., Open source EMR software: Profiling, insights and hands-on analysis. Comput. Methods Prog. Biomed. 117(2):360–382, 2014.
7. Zaidan, B. B. et al., A Security Framework for Nationwide Health Information Exchange based on Telehealth Strategy. J. Med. Syst. 39(5):51, 2015.
8. Zaidan, B. B. et al., Impact of data privacy and confidentiality on developing telemedicine applications: A review participates opinion and expert concerns. Int. J. Pharmacol. 7(3):382–387, 2011.
9. Kiah, M. L. M. et al., MIRASS: Medical Informatics Research Activity Support System Using Information Mashup Network. J. Med. Syst. 38(4):37, 2014.
10. Mohsin, A. H. et al., Based Blockchain-PSO-AES Techniques in Finger Vein Biometrics: A novel Verification Secure Framework for Patient Authentication. Comput. Stand. Interfaces, 2019.
11. Mohsin, A. H. et al., Blockchain authentication of network applications: Taxonomy, classification, capabilities, open challenges, motivations, recommendations and future directions. Comput. Stand. Interfaces, 2018.
12. Mohsin, A. H. et al., Based medical systems for patient's authentication: Towards a new verification secure framework using CIA standard. J. Med. Syst., 2019.
13. Mohsin, A. H. et al., Real-Time Medical Systems Based on Human Biometric Steganography: a Systematic Review. J. Med. Syst. 42(12):245, 2018.
14. Mohsin, A. H. et al., Real-Time Remote Health Monitoring Systems Using Body Sensor Information and Finger Vein Biometric Verification: A Multi-Layer Systematic Review. J. Med. Syst. 42(12):238, 2018.
15. Albahri, O. S. et al., Systematic Review of Real-time Remote Health Monitoring System in Triage and Priority-Based Sensor Technology: Taxonomy, Open Challenges, Motivation and Recommendations. J. Med. Syst. 42(5), 2018.
16. Abdulnabi, M. et al., A distributed framework for health information exchange using smartphone technologies. J. Biomed. Inform. 69:230–250, 2017.
17. Salman, O. H. et al., Novel Methodology for Triage and Prioritizing Using 'Big Data' Patients with Chronic Heart Diseases Through Telemedicine Environmental. Int. J. Inf. Technol. Decis. Mak. 16(05):1211–1245, 2017.
18. Zaidan, A. A. et al., Challenges, Alternatives, and Paths to Sustainability: Better Public Health Promotion Using Social Networking Pages as Key Tools. J. Med. Syst. 39(2):7, 2015.
19. Mat Kiah, M. L. et al., Design and Develop a Video Conferencing Framework for Real-Time Telemedicine Applications Using Secure Group-Based Communication Architecture. J. Med. Syst. 38(10):133, 2014.
20. Kalid, N. et al., Based on Real Time Remote Health Monitoring Systems: A New Approach for Prioritization 'Large Scales Data' Patients with Chronic Heart Diseases Using Body Sensors and Communication Technology. J. Med. Syst. 42(4), 2018.

21. Shuwandy, M. L. et al., Sensor-Based mHealth Authentication for Real-Time Remote Healthcare Monitoring System: A Multilayer Systematic Review. J. Med. Syst. 43(2):33, 2019.
22. Talal, M. et al., Smart Home-based IoT for Real-time and Secure Remote Health Monitoring of Triage and Priority System using Body Sensors: Multi-driven Systematic Review. J. Med. Syst. 43(3):42, 2019.
23. Hussain, M. et al., The landscape of research on smartphone medical apps: Coherent taxonomy, motivations, open challenges and recommendations. Comput. Methods Prog. Biomed. 122(3):393–408, 2015.
24. Hussain, M. et al., Conceptual framework for the security of mobile health applications on Android platform. Telemat. Informatics 35(5), 2018.
25. Hussain, M. et al., A security framework for mHealth apps on Android platform. Comput. Secur. 75:191–217, 2018.
26. Cameron, J. D., Ramaprasad, A., and Syn, T., An ontology of and roadmap for mHealth research. Int. J. Med. Inform. 100:16–25, 2017.
27. Pawar, P. A., and Mohammad, S. P., Review of quality of service in the mobile patient monitoring systems. In: 2017 IEEE Region 10 Symposium (TENSYMP), pp. 1-6, 2017.
28. De la Oliva, A., Bernardos, C. J., Calderon, M., Melia, T., and Zuniga, J. C., IP flow mobility: smart traffic offload for future wireless networks. IEEE Commun. Mag. 49, 2011.
29. Varga, N., Bokor, L., and Takács, A., Context-aware IPv6 Flow Mobility for Multi-sensor Based Mobile Patient Monitoring and Tele-consultation. Procedia Computer Science 40:222–229, 2014.
30. Villarreal, V., Urzaiz, G., Hervas, R., and Bravo, J., Monitoring architecture to collect measurement data and medical patient control through mobile devices, 2011.
31. Ren, Y., Werner, R., Pazzi, N., and Boukerche, A., Monitoring patients via a secure and mobile healthcare system. IEEE Wirel. Commun. 17, 2010.
32. Pawar, P., Jones, V., Van Beijnum, B.-J. F., and Hermens, H., A framework for the comparison of mobile patient monitoring systems. J. Biomed. Inform. 45:544–556, 2012.
33. Jones, V., Gay, V., and Leijdekkers, P., Body sensor networks for mobile health monitoring: Experience in europe and australia. In: Digital Society, 2010. ICDS'10. Fourth International Conference on, pp. 204-209, 2010.
34. Hussain, A., Wenbi, R., da Silva, A. L., Nadher, M., and Mudhish, M., Health and emergency-care platform for the elderly and disabled people in the Smart City. J. Syst. Softw. 110:253–263, 2015.
35. Martínez-Alcalá, C. I., Muñoz, M., and Monguet-Fierro, J., Design and customization of telemedicine systems. Computational and Mathematical Methods in Medicine 2013, 2013.
36. Paliwal, G., and Kiwelekar, A. W., A comparison of mobile patient monitoring systems. International Conference on Health Information Science:198–209, 2013.
37. Khatari, M. et al., Multi-Criteria Evaluation and Benchmarking for Active Queue Management Methods: Open Issues, Challenges and Recommended Pathway Solutions. Int. J. Inf. Technol. Decis. Mak.:S0219622019300039, 2019.
38. Zaidan, A. A. et al., Evaluation and selection of open-source EMR software packages based on integrated AHP and TOPSIS. J. Biomed. Inform. 53:390–404, 2015.
39. Zaidan, A. A. et al., Multi-criteria analysis for OS-EMR software selection problem: A comparative study. Decis. Support. Syst. 78: 15–27, 2015.
40. Zaidan, B. B. et al., A new digital watermarking evaluation and benchmarking methodology using an external group of evaluators and multi-criteria analysis based on 'large-scale data. Softw. Pract. Exp. 47(10):1365–1392, 2017.
41. Yas, Q. M. et al., Towards on develop a framework for the evaluation and benchmarking of skin detectors based on artificial intelligent models using multi-criteria decision-making techniques. Int. J. Pattern Recognit. Artif. Intell. 31(03):1759002, 2017.
42. Abdullateef, B. N. et al., An evaluation and selection problems of OSS-LMS packages. Springerplus 5(1):248, 2016.
43. Keeney, R. L., and Raiffa, H., Decisions with multiple objectives: preferences and value trade-offs. Cambridge: Cambridge University Press, 1993.
44. Zaidan, B. B. et al., A new approach based on multi-dimensional evaluation and benchmarking for data hiding techniques. Int. J. Inf. Technol. Decis. Mak.:1–42, 2017.
45. Zaidan, B. B., and Zaidan, A. A., Software and hardware FPGA-based digital watermarking and steganography approaches: Toward new methodology for evaluation and benchmarking using multi-criteria decision-making techniques. J. Circuits, Syst. Comput. 26(07):1750116, 2017.
46. Rahmatullah, B., et al., Multi-complex attributes analysis for optimum GPS baseband receiver tracking channels selection. In: 2017 4th International Conference on Control, Decision and Information Technologies. CoDIT 2017, 2017, pp. 1084–1088, 2017.
47. Jumaah, F. M. et al., Technique for order performance by similarity to ideal solution for solving complex situations in multi-criteria optimization of the tracking channels of GPS baseband telecommunication receivers. Telecommun. Syst.:1–19, 2017.
48. Qader, M. A. et al., A methodology for football players selection problem based on multi-measurements criteria analysis. Meas. J. Int. Meas. Confed. 111:38–50, 2017.
49. Yas, Q. M. et al., Comprehensive insights into evaluation and benchmarking of real-time skin detectors: Review, open issues & challenges, and recommended solutions. Measurement 114:243–260, 2018.
50. Malczewski, J., GIS and multicriteria decision analysis. Hoboken: John Wiley & Sons, 1999.
51. Petrovic-Lazarevic, S., and Abraham, A., Hybrid fuzzy-linear programming approach for multi criteria decision making problems. arXiv preprint cs/0405019, 2004.
52. Zaidan, B. B., and Zaidan, A. A., Comparative study on the evaluation and benchmarking information hiding approaches based multi-measurement analysis using TOPSIS method with different normalisation, separation and context techniques. Measurement 117:277–294, 2018.
53. Zaidan, A. A. et al., A review on smartphone skin cancer diagnosis apps in evaluation and benchmarking: coherent taxonomy, open issues and recommendation pathway solution. Health Technol. (Berl). 8(4):223–238, 2018.
54. Alsalem, M. A. et al., Systematic Review of an Automated Multiclass Detection and Classification System for Acute Leukaemia in Terms of Evaluation and Benchmarking, Open Challenges, Issues and Methodological Aspects. J. Med. Syst. 42(11):204, 2018.
55. Tariq, I. et al., MOGSABAT: a metaheuristic hybrid algorithm for solving multi-objective optimisation problems. Neural Comput. & Applic. 30:1–15, 2018.
56. Enaizan, O. et al., Electronic medical record systems: decision support examination framework for individual, security and privacy concerns using multi-perspective analysis. Health Technol. (Berl)., 2018.
57. Salih, M. M. et al., Survey on Fuzzy TOPSIS State-of-the-Art between 2007–2017. Comput. Oper. Res., 2018.
58. Kalid, N. et al., Based Real Time Remote Health Monitoring Systems: A Review on Patients Prioritization and Related" Big Data" Using Body Sensors information and Communication Technology. J. Med. Syst. 42(2):30, 2018.

59. Zionts, S., MCDM—if not a roman numeral, then what? Interfaces 9:94–101, 1979.
60. Jumaah, F. M. et al., Decision-making solution based multi-measurement design parameter for optimization of GPS receiver tracking channels in static and dynamic real-time positioning multipath environment. Measurement 118:83–95, 2018.
61. Albahri, A. S. et al., Real-Time Fault-Tolerant mHealth System: Comprehensive Review of Healthcare Services, Opens Issues, Challenges and Methodological Aspects. J. Med. Syst. 42(8. Springer US):137, 2018.
62. Albahri, O. S. et al., Real-Time Remote Health-Monitoring Systems in a Medical Centre: A Review of the Provision of Healthcare Services-Based Body Sensor Information, Open Challenges and Methodological Aspects. J. Med. Syst. 42(9): 164, 2018.
63. Talal, M. et al., Comprehensive Review and Analysis of Anti-Malware Apps for Smartphones. Telecommun. Syst., 2019.
64. Oliveira, M., Fontes, D. B., and Pereira, T., Multicriteria decision making: a case study in the automobile industry, 2013.
65. Jadhav, A., and Sonar, R., Analytic hierarchy process (AHP), weighted scoring method (WSM), and hybrid knowledge based system (HKBS) for software selection: a comparative study. In: Emerging trends in engineering and technology (ICETET), 2009 2nd international conference on, pp. 991-997, 2009.
66. Zaidan, A. A. et al., Based Multi-Agent learning Neural Network and Bayesian for Real-Time IoT Skin Detectors: A new Evaluation and Benchmarking Methodology. Neural Comput. & Applic., 2019.
67. Albahri, A. S. et al., Based Multiple Heterogeneous Wearable Sensors: A Smart Real-Time Health Monitoring Structured for Hospitals Distributor. IEEE Access 7:37269–37323, 2019.
68. Albahri, O. S. et al., Fault-Tolerant mHealth Framework in the Context of IoT-Based Real-Time Wearable Health Data Sensors. IEEE Access 7:50052–50080, 2019.
69. Mühlbacher, A. C., and Kaczynski, A., Making good decisions in healthcare with multi-criteria decision analysis: the use, current research and future development of MCDA. Applied Health Economics and Health Policy 14:29–40, 2016.
70. Abdullateef, B. N., Elias, N. F., Mohamed, H., Zaidan, A., and Zaidan, B., An evaluation and selection problems of OSS-LMS packages. SpringerPlus 5:248, 2016.
71. Adunlin, G., Diaby, V., and Xiao, H., Application of multicriteria decision analysis in health care: a systematic review and bibliometric analysis. Health Expect. 18:1894–1905, 2015.
72. Zhu, G.-N., Hu, J., Qi, J., Gu, C.-C., and Peng, Y.-H., An integrated AHP and VIKOR for design concept evaluation based on rough number. Adv. Eng. Inform. 29:408–418, 2015.
73. Raviv, G., Shapira, A., and Fishbain, B., AHP-based analysis of the risk potential of safety incidents: Case study of cranes in the construction industry. Saf. Sci. 91:298–309, 2017.
74. Zhao, H., Guo, S., and Zhao, H., Comprehensive benefit evaluation of eco-industrial parks by employing the best-worst method based on circular economy and sustainability. Environ. Dev. Sustain. 20:1229–1253, 2018.
75. Chou, S.-Y., Chang, Y.-H., and Shen, C.-Y., A fuzzy simple additive weighting system under group decision-making for facility location selection with objective/subjective attributes. Eur. J. Oper. Res. 189:132–145, 2008.
76. Singh, A., and Malik, S. K., Major MCDM Techniques and their application-A Review. IOSR Journal of Engineering (IOSRJEN), ISSN (e): 2250-3021 4:2278–8719, 2014.ISSN
77. Jablonsky, J., MS Excel based software support tools for decision problems with multiple criteria. Procedia Economics and Finance 12:251–258, 2014.
78. Ahmad, W. N. K. W., Rezaei, J., Sadaghiani, S., and Tavasszy, L. A., Evaluation of the external forces affecting the sustainability of oil and gas supply chain using Best Worst Method. J. Clean. Prod. 153:242–252, 2017.
79. Gupta, H., and Barua, M. K., Supplier selection among SMEs on the basis of their green innovation ability using BWM and fuzzy TOPSIS. J. Clean. Prod. 152:242–258, 2017.
80. Rezaei, J., Best-worst multi-criteria decision-making method. Omega 53:49–57, 2015.
81. Rezaei, J., Best-worst multi-criteria decision-making method: Some properties and a linear model. Omega 64:126–130, 2016.
82. Gupta, H., Evaluating service quality of airline industry using hybrid best worst method and VIKOR. J. Air Transp. Manag. 68:35–47, 2018.
83. Opricovic, S., and Tzeng, G.-H., Extended VIKOR method in comparison with outranking methods. Eur. J. Oper. Res. 178: 514–529, 2007.
84. Opricovic, S., and Tzeng, G.-H., Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. Eur. J. Oper. Res. 156:445–455, 2004.
85. Mahjouri, M., Ishak, M. B., Torabian, A., Manaf, L. A., Halimoon, N., and Ghoddusi, J., Optimal selection of Iron and Steel wastewater treatment technology using integrated multi-criteria decision-making techniques and fuzzy logic. Process Saf. Environ. Prot. 107:54–68, 2017.
86. Diaby, V., Campbell, K., and Goeree, R., Multi-criteria decision analysis (MCDA) in health care: a bibliometric analysis. Operations Research for Health Care 2:20–24, 2013.
87. Tian, Z.-p., Wang, J.-q., and Zhang, H.-y., An integrated approach for failure mode and effects analysis based on fuzzy best-worst, relative entropy, and VIKOR methods. Appl. Soft Comput., 2018.
88. Ren, J., Selection of sustainable prime mover for combined cooling, heat, and power technologies under uncertainties: An interval multicriteria decision-making approach. Int. J. Energy Res., 2018.
89. Serrai, W., Abdelli, A., Mokdad, L., and Hammal, Y., An efficient approach for Web service selection. In: Computers and Communication (ISCC), 2016 IEEE Symposium on, pp. 167-172, 2016.
90. Shojaei, P., Haeri, S. A. S., and Mohammadi, S., Airports evaluation and ranking model using Taguchi loss function, best-worst method and VIKOR technique. J. Air Transp. Manag. 68:4–13, 2018.
91. Serrai, W., Abdelli, A., Mokdad, L., and Hammal, Y., Towards an efficient and a more accurate web service selection using MCDM methods. J. Comput. Sci. 22:253–267, 2017.
92. Pamučar, D., Petrović, I., and Ćirović, G., Modification of the Best–Worst and MABAC methods: A novel approach based on interval-valued fuzzy-rough numbers. Expert Syst. Appl. 91:89–106, 2018.
93. Migdadi, M., Knowledge management enablers and outcomes in the small-and-medium sized enterprises. Ind. Manag. Data Syst. 109:840–858, 2009.
94. Zaidan, A., Zaidan, B., Al-Haiqi, A., Kiah, M. L. M., Hussain, M., and Abdulnabi, M., Evaluation and selection of open-source EMR software packages based on integrated AHP and TOPSIS. J. Biomed. Inform. 53:390–404, 2015.
95. Zaidan, A., Zaidan, B., Hussain, M., Haiqi, A., Kiah, M. M., and Abdulnabi, M., Multi-criteria analysis for OS-EMR software selection problem: A comparative study. Decis. Support. Syst. 78: 15–27, 2015.
96. Kiah, M. L. M., Haiqi, A., Zaidan, B., and Zaidan, A., Open source EMR software: profiling, insights and hands-on analysis. Comput. Methods Prog. Biomed. 117:360–382, 2014.
97. de Paiva Guimarães, M., and Martins, V. F., A checklist to evaluate Augmented Reality Applications. In: 2014 XVI Symposium on Virtual and Augmented Reality (SVR), pp. 45-52, 2014.

98. Huang, P. H., and Moh, T.-t., A non-linear non-weight method for multi-criteria decision making. Ann. Oper. Res. 248:239–251, 2017.
99. Kalid, N., Zaidan, A. A., Zaidan, B. B., Salman, O. H., Hashim, M., Albahri, O. S. et al., Based on Real Time Remote Health Monitoring Systems: A New Approach for Prioritization "Large Scales Data" Patients with Chronic Heart Diseases Using Body Sensors and Communication Technology. J. Med. Syst. 42:69, March 02 2018.
100. Qader, M. A., Zaidan, B. B., Zaidan, A. A., Ali, S. K., Kamaluddin, M. A., and Radzi, W. B., A methodology for football players selection problem based on multi-measurements criteria analysis. Measurement 111:38–50, 2017.
101. Jones, V., Van Halteren, A., Dokovsky, N., Koprinkov, G., Bults, R., Konstantas, D., et al., Mobihealth: Mobile health services based on body area networks. In: M-Health, ed: Springer, pp. 219-236, 2006.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.