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SYSTEMS-LEVEL QUALITY IMPROVEMENT

Mobile Patient Monitoring Systems from a Benchmarking Aspect: Challenges, Open Issues and Recommended Solutions

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Abstract
This paper presents comprehensive insights into mobile patient monitoring systems (MPMSs) from evaluation and benchmarking aspects on the basis of two critical directions. The current evaluation criteria of MPMSs based on the architectural components of MPMSs and possible solutions are discussed. This review highlights four serious issues, namely, multiple evaluation criteria, criterion importance, unmeasurable criteria and data variation, in MPMS benchmarking. Multicriteria decision-making (MCDM) analysis techniques are proposed as effective solutions to solve these issues from a methodological aspect. This methodological aspect involves a framework for benchmarking MPMSs on the basis of MCDM to rank available MPMSs and select a suitable one. The benchmarking framework is discussed in four steps. Firstly, pre-processing and identification procedures are presented. Secondly, the procedure of weight calculation based on the best–worst method (BWM) is described. Thirdly, the development of a benchmark framework by using the VIKOR method is introduced. Lastly, the proposed framework is validated.

Keywords Multi-criteria analysis · Evaluation and benchmark · Mobile patient monitoring systems (MPMSs)

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Introduction

eHealth is the use of information and communication technologies for health [1–18]. mHealth, a component of eHealth, is healthcare through mobile phones, personal digital assistants (PDAs) and other wireless devices and provides a potentially cost-effective solution [19–25]. Mobility provides healthcare providers and recipients freedom from temporal and spatial limitations thus facilitates healthcare participation [26]. mHealth includes mobile applications ('apps') for medical and public health practices supported by mobile technologies to provide health information, check patients, monitor physiological signs and offer direct care and patient education [27]. Mobile patient monitoring (MPM) is a special type of mHealth service that is used to measure, collect and transmit bio-signal data provided by wearable sensors from patients to hospitals or other healthcare centres [28]. MPM systems (MPMSs) are emergent mHealth applications that perform continuous and frequent measurement and analyses of bio-signals of remote or mobile patients through mobile computing, wireless communication and network computing technologies [29]. MPMSs use environmental sensors to provide surrounding environmental conditions, such as room temperature, humidity, lighting level and location, to patients [30].

Most MPMSs are designed for a specific group or community of people suffering from chronic diseases, such as diabetes [31], hypertension [32], cardiovascular diseases [33], dementia [34] and depression [35]. Several systems are designed for elderly patients [36] and large-scale accidents [37].

Many MPMSs have been developed recently to provide healthcare services to patients. Each MPMS comprises various components depending on its architecture and thus presents different characteristics. The growing number of available MPMSs is considered a problem for users because of the difficulty in selecting an appropriate MPMS that would fulfil the requirements of users efficiently. Therefore, evaluation and comparison of MPMS are required to determine the available MPMS that is better than others. Evaluation and comparison in this area are considered challenges and gaps in existing literature. Most existing studies, such as Ref. [38–42], compared MPMSs on the basis of their individual aspects whilst disregarding other characteristics. Thus, such comparisons do not completely reflect the quality of these systems. Comparing MPMSs is difficult because multiple criteria should be considered. The comparisons performed in the aforementioned studies do not completely reflect system performance because they were conducted partially and thus fail to provide a clear picture of system operations. Therefore, a comprehensive review of literature is essential in determining the limitations of using previously established criteria for research. This work provides comprehensive insights into MPMSs and their evaluation and benchmarking, as shown in Fig. 1. The rest of this paper is organised as follows. The MPMS concept and its generic architecture are presented in Section 2. Common MPMSs are discussed in Section 2.2. The evaluation criteria of MPMSs are explained based on MPMS architectural components in Sections 2.2 and 2.3. The challenges and open issues in MPMS evaluation and comparison are reported in Section 3. The possible solutions developed for future research are presented in Section 4. These solutions aim to standardise basic and advanced requirements for the evaluation and benchmarking of MPMSs. The methodological aspect is described in Section 5, and the study's conclusions are provided in Section 6.

MPMSs are primarily implemented to quantify the physiological parameters of patients during the critical periods of biological functions. The main goal of patient monitoring systems is to standardise all aspects ranging from medical terminologies to network protocols so that medical records can be stored electronically and sent immediately to doctors [43]. Recent MPMS development includes using mobile devices and wireless sensor technologies [44]. Existing MPMSs differ in terms of the types and number of features that they support. MPMSs collect and monitor patients' vital signs, such as blood pressure and body temperature, and observe their physical activities, such as walking and running [45]. MPMSs can use environmental sensors to provide surrounding environmental conditions, such as room temperature, humidity, lighting level and location, to patients [30].

Generic architecture of MPMS

Figure 2 illustrates the extended architecture of the MPMS developed during the Mobile Health Project, which has been mainstreamed to accommodate MPMSs.

As shown in Fig. 2, an MPMS consists of a body area network (BAN) and a back end system (BESys). BAN is a set of interconnected devices that are worn on the body and provide an integrated set of personalised services to patients. It consists of a mobile base unit (MBU) and several BAN devices (e.g. sensors, actuators and other wearable devices used for medical purposes). MBU acts as a processing platform and a storage and communication gateway and is implemented on a PDA or smartphone. The communication between BAN components is known as intra-BAN communication, which can be wired, wireless or a mixture of both. Bio-signal data from sensors are directly transmitted to MBU. Several sensors require a sensor data acquisition device called SFE. The connection between SFE and MBU can be wired or wireless. In the latter, analogue bio-signals are digitised and filtered by SFE before transmission to MBU. Extra-BAN communication refers to the communication between BANs and BEsys, and the communication should be wireless. Back-end server(s) and supplementary applications are included in BEsys to process bio-signals and other data received by servers. The architectural components of MPMSs are described in Table 1.

Common MPMSs

Many MPMSs at present use a representative selection for comparison. The evaluation criteria utilised in the comparison are communication technology utilisation, practical trials and availability of sufficient published scientific information based on these evaluation criteria. Below are the most common MPMSs [38–40].

Intelligent mobile health monitoring system (IMHMS)

This system provides patients with feedback through their mobile devices by using wearable wireless sensors to collect data from patients, mine data and intelligently predict patients' health status. IMHMS allows patients to access their health information flexibly anywhere and at any time. This system provides patients the opportunity to participate in the healthcare process through their personal devices. The system architecture contains three parts, namely, wearable body sensor network (WBSN), patient's personal home server (PPHS) and intelligent medical server (IMS). In WBSN, bio-signals are transmitted as electromagnetic radio frequency (RF)

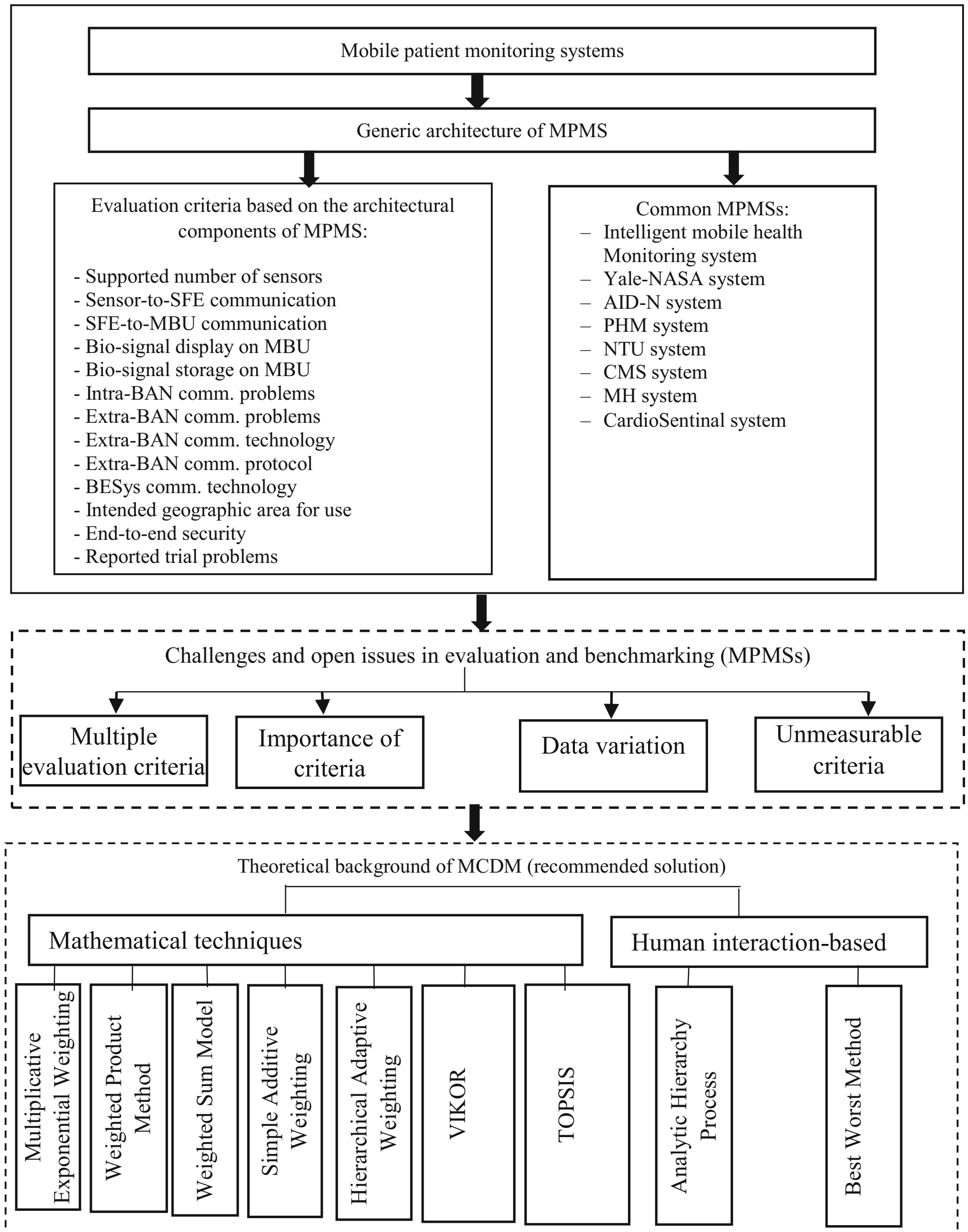

Fig. 1 Framework of comprehensive insights into MPMSs with focus on evaluation and benchmarking

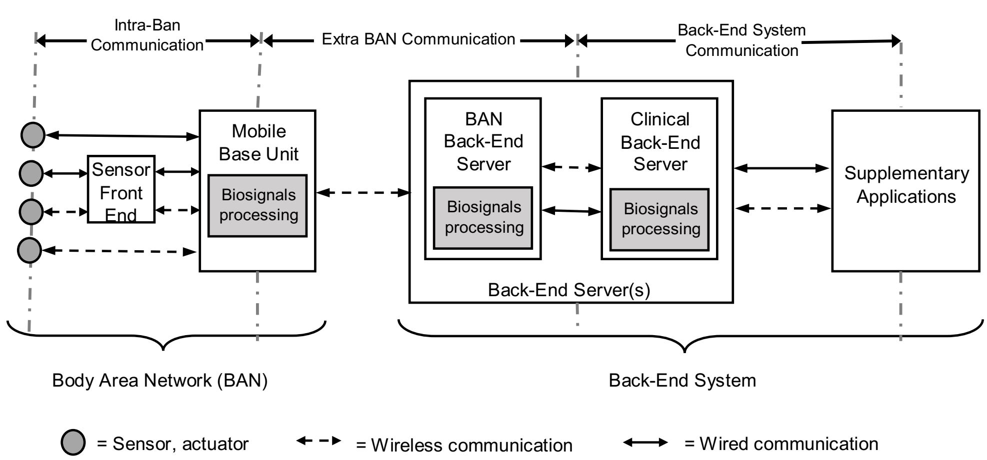

Fig. 2 Generic architecture of MPMS (Pawar et al., 2012)

Table 1 Architectural components of MPMSs

Parameter	Description
Sensor/actuator set	Sensors, actuator types or any other wearable devices
SFE	Details of SFE (bio-signal processing functions, models and features)
MBU	Features of MBU (bio-signal processing functions, supported applications and network)
Intra-BAN communication	- Link type between BAN components; communication can be (wired/wireless) - Bio-signal processing (on MBU and communication path) - QoS of data transformation - Protocols used in communication
Extra-BAN communication	- Communication techniques between MBU and BESys - Bio-signal processing (on BESys and communication path) - QoS of data transformation - Protocols used in communication
BAN back-end server and contributory applications	- Server implementation and deployment (technology options) - Contributory applications using bio-signals and health-related data
Clinical back-end server and contributory applications	- Server implementation and deployment (technology options) - Contributory applications using bio-signals and health-related data
BEsys communication	- Mechanism for data generation at back-end servers and its availability to contributory applications - Data transfer technologies and protocols
Trial patient group	- Selected patient groups are monitored by MPMS
Trial information	Information from previous trials used to validate the mobile patient control system in terms of patient number and trial duration
Reported findings/problems	Reported problems and critical technical findings

waves. Communication between WBSN and PPHS can be through any wireless protocol, such as Bluetooth, WLAN (802.11) or ZigBee, depending on the coverage distance. PPHS can be a personal device (cell phone/PDA) or a personal computer. It acts as a gateway through which medical information collected from body sensors are transmitted to IMS by using logics. Specifically, PPHS determines whether the medical information needs to be sent to IMS or not. Communication between PPHS and IMS is performed over the Internet. IMS acts as the backbone of the system that receives data from PPHS and learns through data mining techniques after analysing and processing the data; feedback is then provided to PPHS or the health organisation [42, 46].

Yale–National Aeronautics and Space Administration (NASA)

The Yale–NASA Himalayan climber monitoring system was developed by NASA and Yale University [47]. The Yale–NASA Commercial Space Centre for Medical Informatics and Technology Applications Consortium realised that high-altitude mountaineers experience numerous issues, such as physiological stress, and that their consequent adaptation to a remote and extreme environment presents medical challenges that are different from those faced by astronauts in space. In 1998, the capacity of the technology was demonstrated with the inaugural Yale telemedicine project known as the Everest Extreme Expedition (E3). This project improved the capability of telemedicine to provide advanced care by connecting a team in a remote and severe environment with a medical centre. E3 focused on humanitarian and scientific aspects by providing medical support from the humanitarian aspect and conducting medical and technology research from the scientific aspect.

The mission had three objectives, namely, (1) to establish a telemedicine clinic from the base camp at 17,800 ft at Mount Everest Base Camp that could provide advanced medical support to climbing expeditions, (2) to evaluate the performance of the vital sign monitoring system (designed by Fit Sense Technologies, Wellesley, MA) in monitoring the physiologic ciphers and vital signs of climbers and (3) to follow up on climbers' cardiovascular adaptation to hypoxia at great heights. Bio-signals were presented in standard ASCII data format. The bio-signals experienced a loss of transmission rate from 3% to 12%. However, the maximum loss of bio-signals was less than 35 min or 7 serial recordings. No signals were lost in all monitoring devices for more than 4 consecutive readings or 20 min. This condition only occurred on one occasion. The bio-signals were lost due to severe weather conditions. Bio-signal monitoring functioned from 95% to 100% of the time. Low Earth-orbiting satellites can be effective in determining patient location and eliminating the requirement for RF repeaters in monitoring patients in remote areas.

Advanced health and disaster aid network (AID-N)

AID-N is a system developed collaboratively by a number of institutions, including John Hopkins University, University of

California and Harvard University [37]. It has an electronic triage and sensing system that comprises low-power embedded devices. The physiological characteristics of each patient are efficiently monitored and tracked with a fault-tolerant communication infrastructure. Patient data are collected by embedded medical systems. Thereafter, patient information is distributed to response team members on platforms tailored to fit individual workflow needs. Laptops display patient information that is suitable for use by treatment officers localised to a particular treatment area. PDAs with GPS serve as a portable platform to collect patient demographics. A central server allows authenticated users to log on and review critical information from the field. The primary benefits of the AID-N electronic triage include continuous monitoring of triage levels, physiological status and location of patients and automated distribution of patient data in real time to response team members on and off the disaster site [37].

Major incidents or disasters are medical emergencies with many casualties. The initial and critical step in emergency response is the rapid and accurate specification of casualties. This process refers to the classification of patients according to their need for medical intervention. Accurate and specific information must be reported and continuously updated to multiple parties in response teams [39]. Ref. [48] reported that the use of the AID-N system relative to paper tags provides first responders three times the opportunity to re-triage patients. During disasters, the quality and quantity of patient care can be increased by using AID-N. Several challenges have been reported during the implementation and deployment of AID-N. Firstly, the need to track indoor locations with minimum setup time and a resolution of up to 1 m accuracy during disasters presents difficulties. Secondly, the high data rates of ECG waveforms cause serious delays during the operation of several parallel movements in an ad-hoc mesh network. Thirdly, technical challenges arise because casualties sometimes wander in and out of wireless coverage areas [39].

Personal health monitor (PHM) system

The PHM system was developed by the University of Technology Sydney. This system is designed for patients who have suspected cardiovascular diseases and need to be monitored round the clock [49]. The PHM system proposes the use of off-the-shelf sensor systems that include a built-in SFE. This approach allows PHM system users to use their Microsoft Windows mobile phones to buy or rent the required sensors according to their status. Patients download the PHM application on their mobile phones and use it easily, similar to any other mobile application [39].

PHM detects life-threatening arrhythmias locally using smartphones. If the patient is in danger, the system contacts an ambulance automatically. In normal situations, the system monitors and records sensor data for inclusion in patients' health records. These records are used for further analysis by specialists. The system is designed in consideration of personalisation. For instance, a heart specialist can select one or more sensors to be used for a particular patient and configure the corresponding threshold levels for that patient. This application generates alarms or warnings when thresholds are reached [49]. Ref. [49] reported that the trial version of the PHM system is easy to use. In most cases, the bio-signals received by cardiologists demonstrate sufficient quality for an appropriate evaluation. Furthermore, a healthcare professional can select one or more sensors to be used for a particular patient when providing personal monitoring and treatment. PHM trials highlighted the need for personal comments. The results indicated that a number of patients did not appreciate the interaction with the application because they found the process cumbersome. Meanwhile, several elderly patients who lived alone requested for a feature that would allow them to receive notifications and warnings.

An additional feasibility study was conducted on the use of the PHM system for non-invasive cardiac rhythm management [50]. Thus far, the system has been applied to 70 low-risk heart patients. Preliminary results revealed the commercial potential of this system to identify and diagnose arrhythmias. The results of the feasibility study [50] have been used to identify the possible applications of the PHM system in various areas, such as athletic performance, community healthcare, cardiac rehabilitation and monitoring of lifestyle changes [39]. The PHM system also targets patients who have had a heart attack or are at a high risk for one. Discussions with cardiologists show that these patients are worried about suffering from another heart attack. Thus, these patients are motivated to wear a device that can monitor and reassure them; intrusiveness does not appear to be an issue for these patients [49].

CMS mobile patient monitoring system

In Singapore, the Institute of InfoComm Research and other partners collaborated to develop a wireless system that can provide continuous management of patients with dementia [51]. Incontinence is the inability to control or manage urination or defecation. This condition is common amongst the elderly, especially those who suffer from dementia. The CMS system was developed for elderly people who are suffering from incontinence and living in nursing homes [51]. The BAN consists of a receiver connected to a humidity sensor built into a 2.4 GHz mote module mounted near the patient's bed or wheelchair. A humidity sensor is inserted into the diaper worn by the patient to detect incontinence. CMS includes the use of a distributed and expandable sensor network to support the potentially large spread of humidity sensors in different institutions, such as elderly care centres, hospitals and nursing homes [51]. Using wireless sensor networks facilitates the monitoring of the elderly suffering from incontinence either inside or outside the ward (on the bed or on the wheelchair). The mechanism used to transmit the bio-signals of patients indicates that patients have freedom of movement in healthcare institutions. The trial of the CMS system indicated no false alarms, but the humidity detection ratio was only 50%. This low ratio was attributed to several causes, namely, deliberate reduction of the sensitivity of the humidity sensor to remove false alarms, incorrect placement of the sensor inside the diaper and differences in the absorption properties of various types of diapers. The trial also highlighted various problems, such as limited coverage and need to train caregivers to properly deal with daily system operations [39].

National Taiwan University (NTU) mobile patient monitoring system

NTU developed a wireless PDA monitoring system [48]. Patient transportation within hospitals (e.g. radiology room) generally involves moving large medical surveillance equipment along with patients' trolleys. Transporting such equipment with many wires connected to sensors can lead to difficult situations and inconvenience. The NTU system was designed as an alternative solution to the use of medical surveillance equipment during inpatient transport by utilising advanced mobile technologies for continuous patient monitoring [48]. The NTU system has powerful security features, such as user authentication, secure wireless transport and the advanced encryption standard algorithm, in addition to the error-free transmission of bio-signals using TCP/IP. The distinctive aspects required by the NTU system are the improvement of the mobility of patient monitoring equipment during inpatient transport and increased usability and flexibility for patient monitoring using wireless communication [48]. The NTU system is user friendly, convenient and feasible for intra-hospital patient transport. Proposed improvements to the NTU system include the utilisation of advanced algorithms for determining many health-related parameters using a few sensors and replacement of the RS232 connection via Bluetooth for enhanced flexibility [39].

MobiHealth (MH) system

The MH system was developed during the MH project and is supported by the EU Commission under the fifth research framework under project number IST-2001-36,006 [38]. The primary impetus behind developing MH was to provide medical care everywhere by mobile surveillance using BANs and wireless technology. BAN technology was first used by the MH project in patient monitoring applications; thus, it is the foundation of the BAN Health Concept [38, 52, 53]. The system has been developed in many European and Dutch projects [54]. Instead of focusing on patients with particular health conditions, MH focuses on general BAN development that can be customised for any particular type of remote monitoring or telemedicine application by integrating a specific set of sensors and other devices into the appropriate application function. During the MH project, a general BAN was allocated for various conditions, such as cardiovascular diseases, trauma, high-risk pregnancies and chronic obstructive pulmonary diseases. Wired and wireless sensors were used in MH BAN [55]. Bluetooth was utilised for intra-BAN communication in both cases [53].

Healthcare organisations and doctors reported a positive experience in applying the MH trial version. However, technical failures (instability), non-optimal interface design and difficulty of the (re)start sequence caused irritation and confusion to users of the initial version. Although the trials showed the feasibility of using the system, numerous problems were encountered. For example, in several cases, measurements were disrupted by movement artefacts; as a result, the bio-signals of ambulatory surveillance were more successful than those of others [52]. The limited bandwidth provided by WWAN technologies (2.5G) was insufficient for applications that require the simultaneous transmission of bio-signals to each user. In cases where 3G (UMTS) was provided, the MH trials did not experience the same restriction [39].

CardioSentinal (CS)

The main objective of the CS system is to provide 24-h cardiac services and monitoring on demand for the elderly and outpatient clinics. Users carry biomedical sensors that contain many other sensors, such as ECG and sensors for motion, humidity and temperature, to obtain a full context of heart activity. Physiological data collected from biomedical sensors are transmitted to a smartphone via Bluetooth modules [56]. CS provides surveillance services through bio-sensors, short-range wireless communication, mainstream computing, cellular networks and modern data centres. Machine learning classification algorithms are implemented in the system to identify patterns of ECG deflection and support decision making. The bio-signals collected by the system lack precision (up to 96% in several cases) compared with hospital standards. The system requires improvement in terms of power, reliability of communication, accuracy, energy consumption and security [42].

Evaluation criteria based on architectural components of MPMSs

This section describes 13 criteria used to evaluate the selected MPMS on the basis of the generic architectural components of the MPMS in Fig. 2 [39].

1- Supported number of sensors (C1): The types and numbers of actuators, sensors or any other wearable devices used in each MPM system differ in terms of the indicators and readings needed by each system. Specifically, a range of sensors is integrated into BAN. The vital signs of patients (e.g. blood pressure) can be monitored using (wearable) wireless sensors (e.g. ECG, accelerometer, oximeter, weight scale and blood pressure monitor). The information from the used sensor is collected and transferred wirelessly to a smartphone; several of the sensors are Bluetooth enabled or integrated into smartphones (e.g. GPS) [49]. Several studies [38–40, 42] used this criterion in their MPMS evaluation.
2- Sensors-to-SFE communication (C2): SFE and intra-BAN communication type (wired/wireless). A set of sensors/actuators and a set of wearable devices are connected (wired/wireless) to the SFE [53]. As such, they affect patients' freedom of movement. The communication type should be considered in relation to application requirements. Numerous studies [38–41] used this criterion in their MPMS evaluation.
3- SFE-to-MBU communication (C3): Data from sensors are processed by the SFE before transmission to the MBU. A group of front ends can be associated with an MBU to enable BAN customisation. The SFE communicates with the MBU using wired/wireless communication. Before transmitting the bio-signals to the MBU using a communication link (e.g. wired, serial, RF and BT), the SFE digitises and filters the raw analogue signals [38]. Patients' freedom of movement is considered. A number of studies [38–41] used this criterion in their MPMS evaluation.
4- Bio-signals displayed on the MBU (C4): The MBU consists of data collection, communication and data transmission modules. Several types of wireless devices (e.g. RF transmitter and wireless sensor node) can be used as an MBU. The ability of the MBU to display bio-signals locally can be improved if the device that implements the MBU can. The MBU creates an adaptive user interface that can be displayed and locally stored to help healthcare professionals in configuring the monitored parameters in accordance with patients' profiles [57]. Feedback can be monitored by the patient and transmitted to the health centre. A number of studies [38, 39, 42] used this criterion in their MPMS evaluation.
5- Bio-signal storage on the MBU (C5): The storage of bio-signals on the MBU in the case of extra-BAN communication problems between the MBU and back-end system increases the system's applicability and availability [57]. Several studies [38, 39, 42] used this criterion in their MPMS evaluation.
6- Intra-BAN communication problems (C6): Intra-BAN communication can be wired or wireless. Wired media include copper wires, optical fibre and other wearable computing solutions (e.g. spectacles and jewellery). Wireless media include microwave, radio and infrared light. The most widely used short-range wireless communication types are Bluetooth (IEEE 802.15.1) and Zigbee (802.15.4) [53]. When the communication type is wireless, a wireless data security mechanism must be applied to protect patients' bio-signals and personal data. Problems in communication using these technologies and the loss of bio-signal data during communication necessitate a thorough discussion. A number of studies [38–40, 42] used this criterion in their MPMS evaluation.
7- Extra-BAN communication problems (C7): A wireless network suffers from problems in transmitting signals due to the lack of sufficient bandwidth, unavailability of wireless network coverage and high delay. A research has proposed the use of a context-aware handover mechanism in MPMSs to solve these problems [58]. A number of studies [38–40, 42] used this criterion in their MPMS evaluation.
8- Extra-BAN communication technology (C8): In terms of quality of service (QoS) requirements, the bandwidth requirements for bio-signal delivery were stated during system trials; however, delays and breaks in signals were ignored [37, 47, 48]. Point-to-point or ad-hoc networks and other wireless technologies can facilitate extra-BAN connectivity (C9). Several studies of [38–41] used this criterion in their MPMS evaluation.
9- Extra-BAN communication protocols: Wireless connectivity involves many protocols with advantages and disadvantages. Social, mobile, analytics and cloud (SMAC) is the preferred communication protocol. WLAN or WWAN technologies are used for extra-BAN connectivity at present. Therefore, the transmission of bio-signals is carried out by using IP-based communication protocols. Bio-signals are transmitted continuously from the MBU to the BESys. A number of studies [39–41] used this criterion in their MPMS evaluation.
10- BESys communication technology (C10): The most common technology choices for the communication of back-end system components are service-oriented architectural and web-based technologies (e.g. web services, HTTP and TCP/IP) [59]. A number of studies [38–41] used this criterion in their MPMS evaluation.
11- Intended geographical area of use (C11): Determining patient location is important in providing the services required by mHealth applications. The location determination technology used by mHealth applications is affected by the indoor or outdoor environment. GPS with a precision of 10 m or more is widely available; however, several problems associated with using the GPS technique have been reported [60]. The major problem facing localisation is the indoor coverage of satellite

signals. Several approaches can solve this problem. A survey and a comparison of wireless indoor localisation techniques were performed in [61]. RSS-based WLAN localisation can be used in MPM. It identifies a patient's current location with a precision of 1–5 m. A number of studies [38–40] used this criterion in their MPMS evaluation.

12- End-to-end security (C12): Bio-signals are transmitted using a wireless techniques via extra-BAN communication. However, the privacy of patient information should match QoS requirements. Such a need may be realised by developing end-to-end security solutions. Efforts should ensure that the QoS requirements for bio-signal delivery are properly elicited and met by the extra-BAN communication path. Moreover, end-to-end security solutions should be developed for the transmission of bio-signals. Data loss or corruption of the patient data transferred from the MBU to the clinical back end should be avoided. Transmission should be secure and accurate, and patient data should not be mixed. Data security, integrity and privacy during transmission are important challenges that emerge when using wireless communication in MPMSs [52]. A number of studies [39, 42] used this criterion in their MPMS evaluation.
13- Reported trial problems (C13): Problems and critical technical findings regarding trial patient group(s), clinical specialties/settings and clinical applications (monitoring/telemonitoring) have been reported [38]. Several studies [38, 39] used this criterion their MPMS evaluation.

The thorough investigation of related literature indicates that five studies have used these evaluation criteria in the comparison of MPMSs. However, the usage differed from one study to another. Table 2 presents the comparison criteria and processes used in previous studies.

Acronyms:

C1: Supported number of sensors C2: Sensor-to-SFE communication.

C3: SFE-to-MBU communication C4: Bio-signal display on the MBU.

C5: Bio-signal storage on the MBU C6: Intra-BAN comm. Problems.

C7: Extra-BAN comm. Problems C8: Extra-BAN comm. Technology.

C9: Extra-BAN comm. Protocol C10: BESys comm. Technology.

C11: Intended geographical area for use C12: End-to-end security.

C13: Reported trial problems.

Table 2 presents all related studies on the evaluation and benchmarking of MPMSs according to the evaluation criteria based on the architectural components of MPMSs. This table highlights five studies, with the symbol (√) indicating the fulfilment of the criteria and the symbol (X) specifying unimplemented criteria. The findings obtained from the studies explored in Table 1 are summarised as follows. (1) The evaluation and benchmarking processes of MPMSs are individually implemented. (2) Each MPMS has a specific number of evaluation criteria that should be considered in comparisons of applications. (3) No study has provided an integrated platform for comparing MPMSs and selecting the best one. Therefore, the following challenges and open issues in comparing MPMSs should be dealt with to address the gap.

Challenges and open issues in benchmarking MPMSs

This section discusses problems in comparing and ranking MPMSs to select the best one [38–40, 42]. A ranking is a standard or point of reference in which things can be compared [62, 63]. Ranking in information technology and computer systems involves comparing the output values of different systems on the basis of a given set of criteria to ensure the quality, improvement, contribution or performance of the system [64]. The primary challenge is ranking MPMSs and selecting the best one. This challenge is affected by four major issues, namely, multiple evaluation criteria, importance of criteria, data variation and unmeasurable values. These issues are explained in the following sub-sections.

Multiple evaluation criteria

Multiple criteria should be considered when comparing MPMSs. Ref. [38] used several criteria depending on the function of the system; each system has a number of criteria that may be different from those or do not exist in other systems (e.g. number or type of sensors and communication technology). Ref. [41] compared systems using different criteria. For example, more than one criteria were found for communication in each system (i.e. extra-BAN and BESys communication technologies); additionally, MPMSs involve different criteria, and each MPMS is different in terms of architecture and functions [38–40, 42]. Multiple criteria complicate the comparison amongst MPMSs because a system might meet several criteria that the other systems might not. Two or more systems can be compared according to a few criteria. However, selecting the acceptable system amongst a number of systems by depending on multiple criteria simultaneously is difficult.

Importance of criteria

The importance of criteria is a serious issue in this study. Each application of MPM involves multiple attributes that should

Table 2 Literature survey based on the evaluation criteria used in MPMSs

Author and year	Criteria used													Brief descriptions	Strengths and weaknesses
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13		
Val Jones, Valerie Gay, Peter Leijdekkers, 2010 [38]	√	√	√	√	√	√	√	√	X	√	√	X	√	This study described two mobile health systems: one developed in the Netherlands and one developed in Australia.	Most of the criteria were used (except for two). However, the used criteria were not dealt with as an integrated platform.
Pravin Pawar, Val Jones, Bert–Jan F. van Beijnum, Hermie Hermens, 2012 [39]	√	√	√	√	√	√	√	√	√	√	√	√	√	This study proposed a generic architecture, associated terminology and a classificatory framework for comparing six MPMSs according to 13 selected criteria using epilepsy monitoring as a case study.	All criteria were used. However, the used criteria were not dealt with as an integrated platform.
Gaurav Paliwal and Arvind W. Kiwelekar, 2013 [42]	√	X	X	√	√	√	√	X	X	X	X	√	X	This study performed a survey to identify the causes of low deployment and a comparison amongst 12 MPMSs according to a set of functional and non-functional requirements.	Most of the criteria were unused.
Aamir Hussain, Rao Wenbi, Aristides Lopes da Silva, Muhammad Nadher, Muhammad Mudhish, 2015 [40]	√	√	√	X	X	√	√	√	√	√	√	X	X	This study proposed a people-centred sensor platform for healthcare for the elderly and people with disabilities. This platform aims to monitor the health of the elderly and people with disabilities and provide them with an emergency response service in the event of an abnormal health condition.	Most of the criteria were used (except for four). However, the used criteria were not dealt with as an integrated platform.
Niloofar Mohammadzadeh and Reza Safdari, 2016 [41]	X	√	√	X	X	X	X	√	√	√	X	X	X	MH opportunities were expressed in patient monitoring by introducing different systems, specifically in chronic diseases. The health challenges of MH are in patient monitoring in general and specific aspects.	Most of the criteria were unused.

Table 3 Examples of data variation

MPMs Criteria	MPM1	MPM2	MPM3	MPM4	MPM5	MPM6
C1	5	3	>7	1	2	>10
C2	Radio frequency	Serial	Bluetooth	Wired	Serial	Bluetooth
C3	Radio frequency	Multi-hop ad-hoc	GSM, 3G	Multi-hop ad-hoc	WLAN	3G, WLAN, GPRS

be considered. Thus, ranking processes become difficult. Several criteria are important to patients, whereas others are important to specialists; examples include the number of sensors, communication type between components and design of wrist-worn sensors in terms of size and power consumption [65]. Technically, the ranking of MPMSs requires simultaneous consideration of multiple attributes (e.g. communication technology, communication protocols and communication problems). The communication type between SFE and MBU is a criterion that is important to patients; if it is wireless, then patients have freedom of movement. By contrast, extra-BAN communication protocols and technology criteria are important to specialists in terms of QoS requirements and bandwidth for bio-signal delivery [37, 47, 48].

Data variation

A wide variation exists in the data of different MPMSs. Table 3 shows an example of the data variation amongst systems in the same criteria. As shown in the second criterion (C2), more than one communication type is used. In the third criterion (C3), several communication technologies are used. Selecting and providing healthcare services through suitable MPMSs on the basis of varying available criteria represent a sophisticated decision problem. This selection process involves looking at data from multiple attributes simultaneously, resulting in data discrepancies, which represent a problem in multiple decision making [66].

Other examples of data variation include the mechanism and type of communication amongst system components that can be wired/wireless or both [54]. The technology used in data transmission varies (bio-signal transmission). The variation amongst evaluation criteria is an important issue in decision making [66]. Such variation complicates the comparison and selection processes. Therefore, a suitable technique must be used to handle these issues [67]. MCDM has been recommended in previous studies as a pathway solution to solve the above-mentioned issues and address the challenge of selecting the best MPMS [68]. An overview of MCDM methods and recommended solutions is provided in the next section.

Table 4 Unmeasurable criteria

Alternative	Criteria			
	C1	C2	C3	C4
AID-N	Yes	WLAN	TCP/IP	Indoor
PHM	No	RF	HTTP	Outdoor
MH	Yes	3G	SMAC	Indoor

Unmeasurable values

Communication technology criteria are unmeasurable. Existing literature utilised many unmeasurable evaluation criteria, including categorical (interval values and ranges), text (communication technology), binominal (yes/no) and polynomial (colours). These types of evaluation criteria are constant, and no procedure is performed to evaluate the alternatives (MPMSs) using the aforementioned criteria. Nonetheless, these evaluation criteria are widely used in selection. Table 4 presents an example of MPMS selection consisting of three MPMSs. The evaluation criteria are communication problem (C1), communication technology (C2), communication protocols (C3) and intended geographical area (C4). These linguistic evaluation criteria need to be re-presented to be applicable to the MCDM technique [38, 40–42].

The values of the used data must be digitalised for use in MCDM. The data also require re-presenting, which is difficult to perform when the data are not homogeneous [69].

Theoretical background of MCDM (recommended solution)

The recommended solution of MPMS selection is presented in this section. The appropriate MPMS is selected after comparing numerous available systems (Rocha et al., 2013). The comparison involves the consideration of several evaluation criteria simultaneously. Ranking and selection are achieved with decision-based methods. The recommended solution for this research is the MCDM method.

MCDM: Definition and importance

MCDM is defined as 'an extension of decision theory that covers any decision with multiple objectives. A methodology for assessing alternatives on individual, often conflicting criteria, and combining them into one overall appraisal' [70]. Stewart and Belton defined MCDM as 'an umbrella term to describe a collection of formal approaches, which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter' [71].

MCDM is the most popular amongst the decision-making methods; it handles decision problems involving different criteria, which are part of the research process [72, 73]. MCDM includes structure, layout and problem solving of a similar type [72]. MCDM can be proposed as a feasible solution for such problems of decision makers [74], [68, 75–79]. MCDM is more rational, more efficient and clearer than traditional processes in improving the quality of decisions, hence its wide use [80–86]. The objectives of MCDM are (i) to prioritise alternatives in a descending order of performance, (ii) to classify valid alternatives and (iii) to help data miners select appropriate alternatives, [87–93]. The best and most appropriate alternatives are recorded. MCDM has easily become common in healthcare [67, 81–83, 94–97]. Healthcare decision makers can enhance decision making by systematically obtaining appropriate solutions through many of the current MCDM techniques [68, 98].

MCDM methods

Many MCDM theories have been identified [75, 81]. The most commonly used MCDM techniques are mathematical-based and human interaction-based methods, which use different notations (Fig. 3), [67, 96, 99–105]. The most popular methods of MADM using different concepts include analytic hierarchy process (AHP), best worst method (BWM), multiplicative exponential weighting (MEW), weighted product method (WPM), weighted sum model (WSM), simple additive weighting (SAW), hierarchical adaptive weighting (HAW), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and technique for order of preference by similarity to ideal solution (TOPSIS) [76].

To the best of our knowledge, no MCDM method has been used to rank MPMSs in terms of providing healthcare services. This condition presents a theoretical gap. In several studies, numerous MCDM methods, such

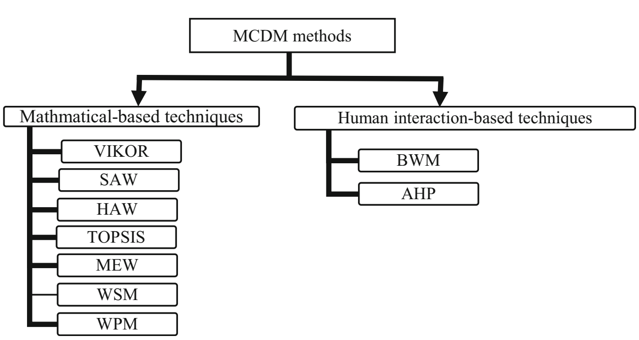

Fig. 3 MCDM methods

as AHP and BWM, have been proposed and used to calculate criterion weights [106–110]. AHP allows DMs to structure the decision-making problem into a hierarchy tree and facilitates the understanding of the problem. This method is time consuming because of the substantial pairwise comparisons, and it requires mathematical calculations that increase as the number of attributes and alternatives increase or change. AHP is significantly restrained by the human capacity for information processing; thus, 7 ± 2 is regarded as the ceiling for comparison. However, scoring and ranking in AHP depend on the alternatives considered for evaluation, and the removal or addition of alternatives may change the final ranking (rank reversal problem). Compared with existing pairwise comparison-based methods, BWM requires fewer comparisons and saves time when making decisions and producing substantial reliable and consistent results [111–114]. BWM also yields more coordinated results than AHP does and has fewer pairwise comparisons; thus, it is used in the current study [115]. MEW and WPM can eliminate any element to be measured and utilise proportional values instead of real (actual) ones. Nevertheless, these methods do not provide a solution with an equal decision matrix (DM) weight. WSM and HAW are easy to use and understand. With an increasing number of criteria, both become difficult to use 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/attributes, makes decisions intuitively and offers simple calculation. However, this method does not commonly discover the real situation, and all criterion values must be positive and maximum. TOPSIS and VIKOR are applied to situations that involve several alternatives and criteria. These methods are particularly suitable for use with quantitative or objective data, and they entail the application of a compromise priority approach to achieve multiple responses [116–118]. 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 [94, 117, 119]. By contrast, VIKOR functionally relates to emergent problems. This method is one of the most practical ways to handle real-world problems. VIKOR can find the best alternative quickly [116]. Thus, VIKOR is suitable for situations that involve several alternatives and features. However, this method cannot elicit weights and examine the consistency of judgment [94].

Several studies [115, 119–124] applied BWM with VIKOR to improve the consistency of weights and resolve the uncertainties related to the research problem. These studies also provided ranking and selection for alternatives. The use of BWM with VIKOR has been widely suggested because

VIKOR cannot calculate weights and check consistency on its own [113, 114, 122].

BWM

Working on decision making with multiple criteria when using MCDM methods aims to determine the most important and desirable alternative. The comparison of decision criteria indicates that the weights are elicited for them [113]. BWM results in low pairwise comparison, thereby resulting in the highest degree of consistency in the weight gain process [114]. In [113], the author aimed to obtain weights for decision criteria and alternatives with respect to various multiple criteria through pairwise comparisons but required a number of comparisons; thus, the author focused on improving the consistency of the weight determination process [125, 126]. In BWM, the weight extraction process is based on reference comparisons, which lead to reduced comparisons; thus, it focuses on determining the best criterion and preference for this criterion across all other criteria and preferring all criteria over the worst one [125]. BWM exhibits several advantages, such as easy use, provision of reliable results with few comparisons and reduced comparison time. This method uses a scale from one to nine when determining preferences amongst criteria [113, 127]. BWM also contains a consistency index for measuring the reliability of reference comparisons between criteria. Selecting the best criteria is easy, but the manner by which to determine the level of importance for the best criterion based on other criteria is difficult, as is the importance of all the criteria over the worst one. Weight elicitation by BWM is conducted in five sequential steps [113, 114, 119, 122, 128, 129], as demonstrated in Fig. 4.

VIKOR method

VIKOR was developed by Serafim Opricovic [130]. The main issues of this method are ranking and selection of alternatives, especially when decision making is difficult amongst multiple criteria [117, 131]. A compromise ranking of the alternatives is performed according to the proximity of the alternatives to the ideal solution; in other words, the alternatives are arranged from near to optimal to the farthest [132]. VIKOR compares available alternatives on the basis of multiple criteria to rank alternatives and select the best amongst them even when using different measurement units for the criteria [133]. The VIKOR method must determine the elements in the compromise ranking, that is, the solution that can settle and stabilise the weight intervals for preference stability [117]. Several studies [131, 134, 135] reported that VIKOR is a common method and has been used for alternative ranking. This method has a decision matrix, which is the structure of alternatives and decision criteria; the rows of this matrix represent several decision criteria, and the columns represent a number of alternatives [122, 133]. The VIKOR method is implemented in six sequential steps [117, 122, 130, 132, 134], as demonstrated in Fig. 5.

Methodology aspects

This section introduces the description and explanation of the methodological aspects of the proposed framework for comparing MPMSs. Developing the framework includes four steps. The first step is pre-processing. The second step is the identification of the decision matrix on the basis of the evaluation criteria. The third step is the development of a new framework for comparing the MPMSs on the basis of the integrated BWM and VIKOR. The final step is the validation process. The steps of the proposed framework are presented in Fig. 6.

Identification and pre-processing

These steps identify the data that are used to test the proposed framework. The decision matrix shown in Table 5 is adopted from the most relevant study [39]. This table includes the data used in our study that cover all of the evaluation criteria based on the generic architecture of MPMS in terms of communication aspects.

As shown in Table 5, the MPMSs are evaluated based on the following 13 criteria: criterion 1 presents the set of sensors that are integrated into the BAN (its values are numbers); criterion 2 shows the communication used between sensors and SFE and has two values or features (RF or wired); criterion 3 has three features (RF, serial, BT and wired) and presents the communication used between SFE and MBU; criterion 4 demonstrates the ability of the MBU to display

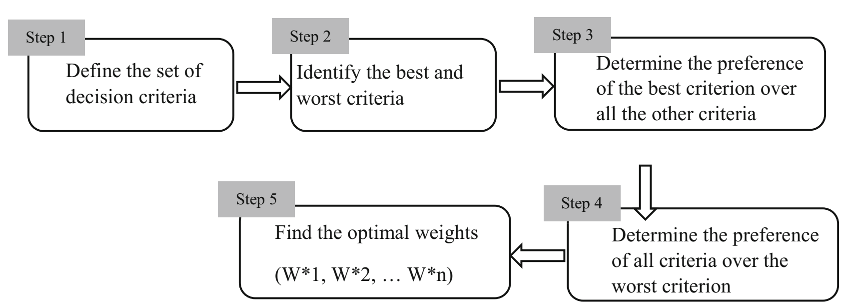

Fig. 4 Steps of the BWM method

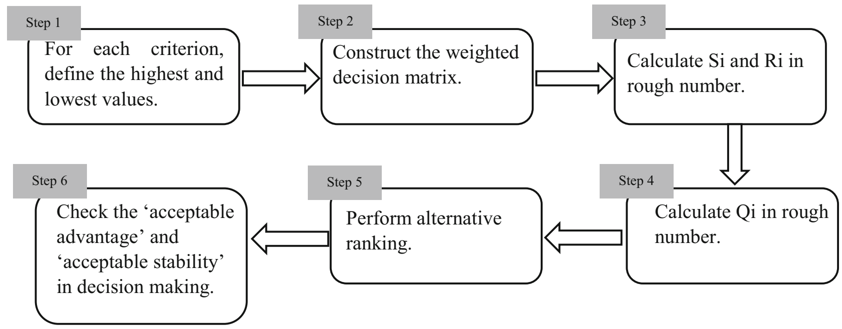

Fig. 5 Steps of the VIKOR method

biosignals (its value is yes or no); criterion 5 illustrates the ability of the MBU to store biosignals (its value is yes or no); criteria 6 and 7 present the availability of problems in communication in intra-BAN and extra-BAN, respectively (their values are yes or no); criterion 8 has six values (features) and present the extra-BAN communication technology (RF, multi-hop ad-hoc, 3G, GSM, WLAN or GPRS); criterion 9 presents three choices of extra-BAN communication protocol (SMAC, TCP/IP or HTTP); criterion 10 presents BESys communication technology with five choices (TCP/IP, web services, IP, HTTP or jinni); criterion 11 shows three choices of intended geographical area for use (outdoor, indoor or indoor/outdoor); criterion 12 presents the availability of security solutions for the transmission of biosignals (its value is yes or no); and criterion 13 presents the availability of technical and communication problems and

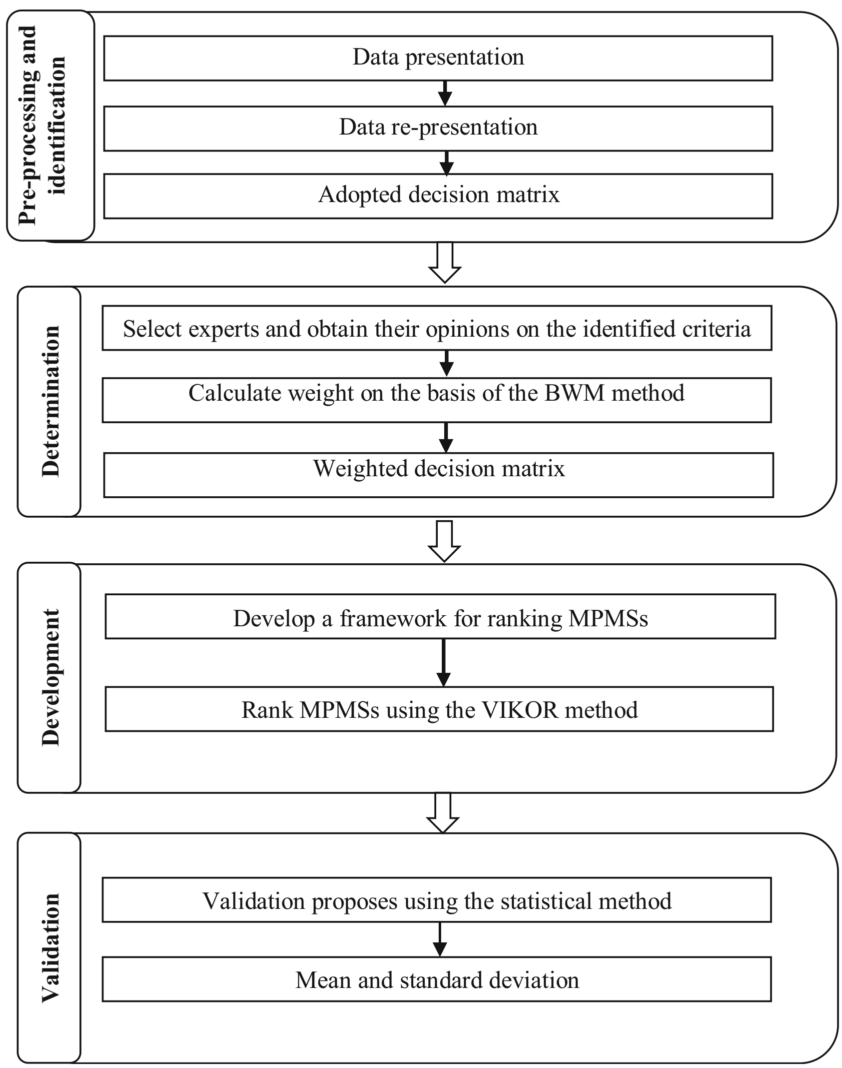

Fig. 6 Proposed framework

Table 5 Adopted data provided by [39]

Criteria MPMS	Support number of sensors	Sensors to SFE communication	SFE to MBU communication	Biosignal display on the MBU	Biosignal storage on the MBU	Intra-BAN comm. Problems	Extra-BAN comm. Problems	Extra-BAN comm. Technology	Extra-BAN comm. Protocol	BESys comm. Technology	Intended geographical area for use	End-to-end security	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	Multi-hop 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	Multi-hop 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

user acceptance during the trial version that it concentrates on (its value is yes or no).

Several of the criteria need pre-presenting to be applicable in MCDM. Applying multi-criteria decision-making theory on the raw data in Table 5 is mathematically impossible due to the following reasons: (1) the values in these raw data are in an inconsistent format (strings and numbers) and (2) different communication technologies and protocols are used. The values of the used data must be digitalised to be used in weighting the criteria.

Data re-presentation

The data re-presentation process must be designed and applied between raw data in the decision matrix. The values (features) in Table 5 need to be digitalised to be used in multi-criteria decision-making analysis techniques. Therefore, these data are re-presented depending on experts' opinion. Experts provide the weights of the values (features) that need to be re-presented on the basis of BWM. Table 6 illustrates the criteria that include values (features) that require re-presentation.

Integer values are designated by the data re-presentation to each extracted feature. These values represent the state of the feature in ranking based on the decision matrix. Tables 5 and 6 demonstrate that criteria 1, 4, 5, 6, 7, 12 and 13 are already used as evaluated and represented as two types. The first type is integer values that can be represented as numbers, as in criterion 1. The second type is a yes/no choice that can be represented as 1/0, as in criteria 4, 5, 6, 7, 12 and 13. The measurements of parameters with multiple choices, which can be observed in criteria 2, 3, 8, 9, 10 and 11 according to Tables 5 and 6, cannot be represented and need experts' opinion according to BWM standards. These criteria have variable data that need to be digitalised. The expert decides on the best and worst choices in each criterion. Then, a pairwise comparison between the best and the other choices is conducted to determine the predilection of the best choice over all other choices. Lastly, a pairwise comparison between the other choices and the worst one is performed to identify the preference of all choices for the least important choice.

Weight determination

This step aims to calculate the weight of the attribute that will be used as evaluation criteria in our decision matrix. This weight will determine the importance of each criterion, which will help in the ranking. Ranking is difficult when all criteria have the same importance. The importance of each criterion must be considered. BWM is used to calculate the weight because it is reliable and needs few comparisons of data [113]. This task consists of three steps. The first step is to design an expert questionnaire for collecting experts' opinions. This step considers the compatibility of this

Table 6 Criteria that include values that require re-presentation

Criteria	Evaluation according to its value
Criterion 1	The values should be ready for use.
Criterion 2	The values need re-presentation based on experts' opinion according to BWM standards.
Criterion 3	The values need re-presentation based on experts' opinion according to BWM standards.
Criterion 4	The values do not need expert opinion.
Criterion 5	The values do not need expert opinion.
Criterion 6	The values do not need expert opinion.
Criterion 7	The values do not need expert opinion.
Criterion 8	The values need re-presentation based on experts' opinion according to BWM standards.
Criterion 9	The values need re-presentation based on experts' opinion according to BWM standards.
Criterion 10	The values need re-presentation based on experts' opinion according to BWM standards.
Criterion 11	The values need re-presentation based on experts' opinion according to BWM standards.

questionnaire with BWM and the comparison between criteria. The second step includes the selection of experts and obtainment of their opinions on the identified criteria. The third step elicits the weight for the criteria using BWM, as shown in Fig. 7.

The opinions of experts in the field of research must be obtained to gather the necessary data for performing BWM analysis. A form is designed to determine the preference of respondents for the MPMS criteria (from communication aspects) and elicited according to their responses. This task is conducted to collect the weights for the criteria according to the BWM standard. Practitioners and industry experts face multi-criteria mode choices in their daily life. Researchers also face the decision of selecting the multi-criteria mode when conducting related studies. The selection of three industrial and academic experts [76, 77, 136, 137] depends on their opinions about the following criteria: (1) data representation in the previous step and (2) assignment of criterion weights. Moreover, experts with good experience (minimum of 5 years) in communication aspects are selected [138].

The BWM procedure for setting the appropriate weights for multiple criteria includes the following five steps [113, 139].

Step 1: Determine a set of decision criteria

Before deciding on the best alternative, the criterion set must be determined (C_1, C_2, …, C_n), which will be used by decision makers. In this study, the criterion set is obtained from [38–40] during the literature review. Table 7 illustrates the selected criteria whose weights will be calculated.

Step 2: Determine the best and worst criteria

Depending on the decision, the highly desirable or important criterion is treated as the optimal one, whilst the less

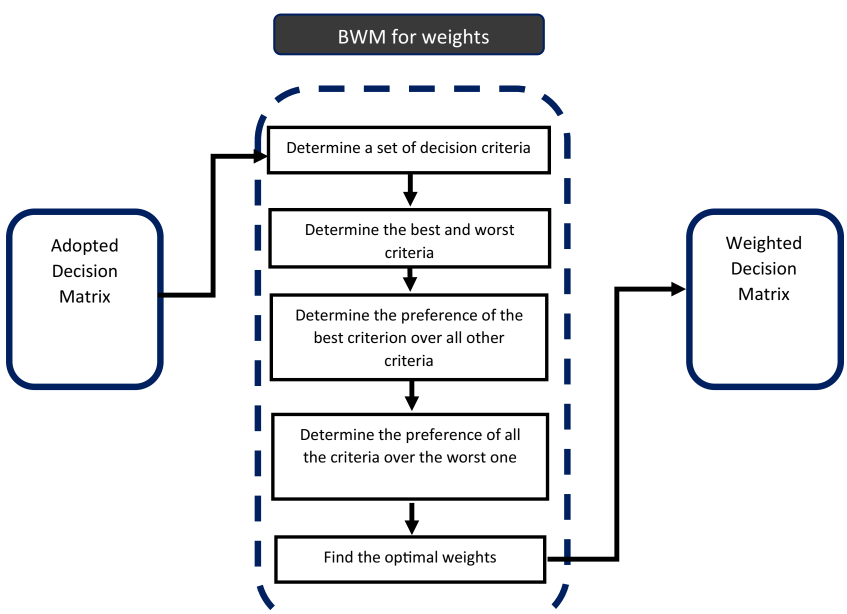

Fig. 7 Weighting decision matrix

Table 7 Selected criteria

Criterion set	Criterion description
C_1	Supported number of sensors
C_2	Sensors 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 comm. Problems
C_7	Extra-BAN comm. Problems
C_8	Extra-BAN comm. Technology
C_9	Extra-BAN comm. Protocol
C_{10}	BESys comm. Technology
C_{11}	Intended geographical area for use
C_{12}	End-to-end security
C_{13}	Reported trial problems

desirable or important one is viewed as the worst. The definition of the best and worst criteria depends on the decision maker's viewpoint.

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

In this step, a pairwise comparison is performed between the identified best criterion and the other criteria to determine their predilection, as shown in Fig. 8. A value from one to nine must be specified by the expert to symbolise the importance of the best criterion over the others. A factor known as 'best-to-others' is obtained in this procedure, as follows:

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

where a_{Bj} indicates the importance of the best criterion B over criterion j and $a_{BB} = 1$.

Step 4: Process the pairwise comparison between the other criteria and the worst one, as shown in Fig. 3-3.

Determine the preference of all criteria for the least important criterion by comparison. The expert identifies the importance of all criteria on the worst criterion. Values from one to nine are used to specify the importance. A factor known as 'others-to-worst' is obtained from this step, which is performed as follows:

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

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

Figure 8 clarifies the two types of reference comparisons, namely, 'best-to-others' and 'others-to-worst' criteria.

Step 5: Elicit the optimal weights (W^*1, W^*2, …W^*n)

The perfect weight for the criteria is the one where $W_B/W_j = a_{BJ}$ and $W_j/W_w = a_{jw}$ for each pair of W_B/W_j and W_j/W_w.

A solution for the maximum absolute differences must be obtained to achieve these conditions for all j.

$$\left|\frac{W_B}{W_j} - a_{Bj}\right| \text{and} \left|\frac{W_i}{W_w} - a_{Bjw}\right| \tag{3}$$

where all j are minimised. Considering the non-negativity and sum condition for the weights, the following problem is created.

$$\begin{aligned} &\text{minmax}_j \left\{ \frac{W_B}{W_j} - a_{Bj}|, |\frac{W_j}{W_w} - a_{jw} \right\} \\ &s.t. \\ &\sum_j W_{j=1} \\ &W_j \geq 0, \text{ for all } j \end{aligned} \tag{4}$$

Problem (5) can be transferred to the following problem.

$$\begin{aligned} &\min \xi \\ &s.t. \\ &|\frac{W_B}{W_J} - a_{Bj}| \leq \xi, \text{ for all } j \end{aligned} \tag{5}$$

$$\begin{aligned} &|\frac{W_j}{W_w} - a_{jw}| \leq \xi, \text{ for all } j \\ &\sum_j W_{j=1} \end{aligned} \tag{6}$$

The perfect weights w*1; w*2;;w*n and ξ n are achieved by solving Problem (5).

The value for 휇* reflects the reliability of outcomes depending on the extent of consistency in the comparisons. The closest value to zero exhibits high consistency and reliability. The consistency ratio is calculated using ξ^* and the corresponding consistency index as follows:

$$\text{Consistency ratio} = \frac{\xi^*}{\textit{Consistency index}} \tag{7}$$

As proposed by [113], the larger ξ^* is, the more consistent the factors are.

Table 8 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

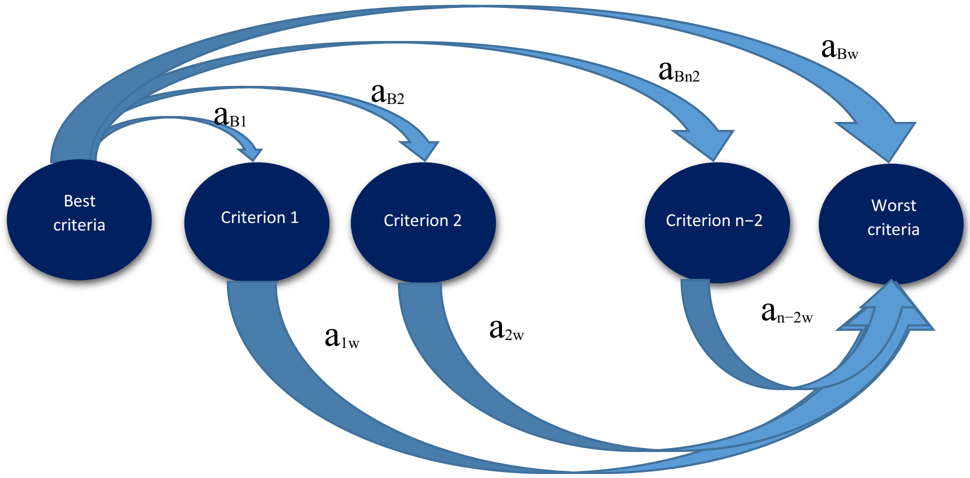

Fig. 8 Reference comparisons in the BWM method

Development step

This step aims to develop a framework for comparing and ranking the MPMSs on the basis of the determined importance. A new framework is developed based on MCDM techniques. The VIKOR method is used to rank the various alternatives (MPMSs) of the decision matrix presented in step two. The steps of this framework are presented below. Figure 9 illustrates the new framework for the ranking.

Adaptive VIKOR method for ranking

VIKOR is applied to rank selected MPMSs in this step because of its suitability for the decision cases with many alternatives and multiple criteria. The advantages of this method include the ability to provide results in a short time and specify the most suitable option. The weights of all criteria are calculated using BWM then used in VIKOR for ranking. The available decision alternative results are ranked in a decreasing order, and the MPMSs are ranked according to the selected criteria by applying the VIKOR method. VIKOR's steps include the following:

Step 1: Define the highest and lowest values for each criterion.

Identify the best f^*i and worst f^-i values of all criterion functions, i = 1; 2; ...; n. If i represents a benefit, then

$$f_i^* = \max_j fij, f_i^- = \min_j fij \quad (8)$$

Step 2: Develop the weighted decision matrix.

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

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

The following weighted matrix is produced by the previous process.

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

Step 3: Calculate S_j and R_j in rough numbers.

Compute the S_j and R_j values, $j = 1, 2, 3, \ldots., J$, $i = 1, 2, 3, \ldots, n$ by using the following:

$$Sj = \sum_{i=1}^{n} wi^*\left(f^*i{-}fij\right)/\left(f^*i{-}f^-i\right), \quad (11)$$

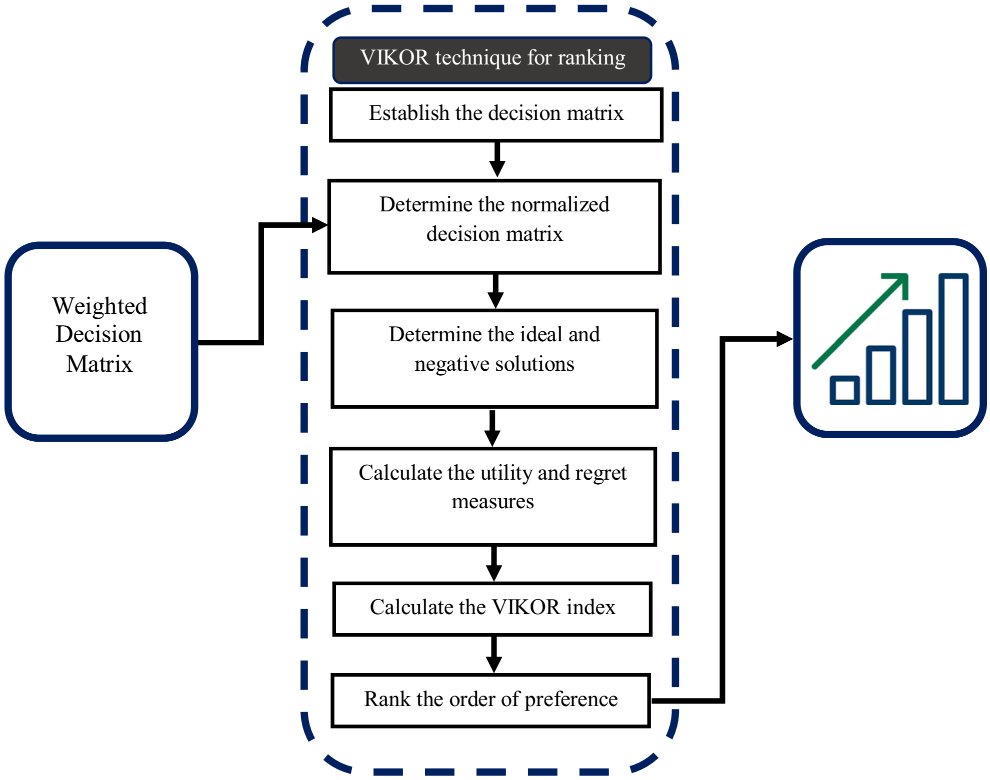

Fig. 9 New framework for ranking

$$Rj = \max_i wi*(f^*i - fij)/(f^*i - f^-i), \quad (12)$$

where *wi* are the weights of criteria expressing their relative importance.

Step 4: Calculate Q_i in a rough number.

Compute the values Q_j, $j = (1, 2, \cdots, J)$ by the following:

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

where

$$S^* = \min_j S_j, S^- = \max_j S_j \quad R^* = \min_j R_j, R^- = \max_j R_j$$

where v is the weight of the strategy of 'the majority of criteria' (or 'the maximum group utility') and $v = 0.5$.

Step 5: Perform alternative ranking.

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

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

Propose a compromise solution for the alternative (a'), 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 ranking list by Q, $DQ = 1/(J-1)$ and J is the number of alternatives.

C2. 'Stability' is acceptable in the decision-making context: Alternative a' should be also ranked the best by S and/or R.

This compromise solution is stable within the decision-making process, which could be 'voting by majority rule' ($v > 0{:}5$), 'by consensus' ($v \cong 0.5$) or 'with veto' ($v < 0.5$). Here, v is the decision-making strategy weight of 'the majority of criteria' (or 'the maximum group utility').

Validation step

Comparison of MPMSs is difficult because they depend on multiple criteria on one side and the because of the difference amongst them in terms of communication aspects and other features. The expected results of the proposed framework are validated through objective validations.

Objective validation

Two statistical methods (mean ± standard deviation) are used in this study to confirm the validity of the MPMS ranking based on the proposed comparison and ranking framework. Three similar groups present the ranking results of MPMSs [140, 141]. The expected results are expressed as mean ± standard deviation for each group.

Mean is the average result, which can be calculated as

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

Standard deviation is used to determine the amount of dispersion or variation in the value set and calculated as

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

Mean ± standard deviation are used to guarantee that the four sets of MPMS are subject to systematic ordering. The scoring of MPMSs is divided to three groups on the basis of the ranking result determined from the proposed ranking framework to validate the ranking results using the above-mentioned test. Each group contains an equal number of selected MPMSs (2) according to the scoring values of the ranking results. This process is applied using two methods on the basis of a statistical platform, which must confirm that the first group reaches the highest scoring value when the mean and standard deviation are measured. Assume that the first group has the highest mean and standard deviation amongst all groups to validate the result. The mean and standard deviation results of the second group must be lower than or equal to those of the first group. However, the mean and standard deviation results for the third group should be lower than those for the first and second groups or equal to those of the second group. The mean and standard deviation results of the third group should be lower than those of the first and second groups or equal to those of the second group. According to the results of the systematic ranking, the first group must be statistically determined to be the highest group amongst all groups.

Conclusion

This study covers various aspects of the evaluation and benchmarking processes of MPMSs. The findings are derived from collecting and analysing the evaluation criteria of MPMSs and identifying and confirming the limitations of comparison processes used in previous studies. The challenges and open issues are also emphasised. Moreover, the advantages and disadvantages of MCDM techniques in the framework of MPMS comparison are presented and discussed. BWM and VIKOR are effective techniques to solve the comparison problems of MPMSs. Four steps can be considered when developing a comparison framework for MPMSs. The first step includes data identification and pre-processing. The second step involves calculating the weights for MPMS evaluation criteria. The third step describes the procedure of applying the VIKOR method for comparing and ranking MPMSs to select the best one. The last step includes performing statistical analyses to validate the output of the proposed framework. The proposed framework will be implemented in the future as a tool for users who intend to select the appropriate MPMS.

Compliance with Ethical Standards

Conflict of Interest The authors declare no conflict of interest.

Ethical Approval All procedures performed in studies with human participation are in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki Declaration and its subsequent amendments or comparable ethical standards.

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

References

1. Furusa, S. S., and Coleman, A., Factors influencing e-health implementation by medical doctors in public hospitals in Zimbabwe. *SA J. Inform. Manag.* 20(1):9, 2018.
2. S. Iqbal 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)., pp. 1–19, 2018.
3. Mohsin, A. H. et al., Blockchain authentication of network applications: Taxonomy, classification, capabilities, open challenges, motivations, recommendations and future directions. *Comput. Stand. Interfaces*, 2018.
4. 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.
5. 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.
6. 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.
7. Nabi, M. S. et al., Suitability of adopting S/MIME and OpenPGP email messages protocol to secure electronic medical records. Second international conference on future generation communication technologies (FGCT 2013). 93–97, 2013.
8. Abdulnabi, M. et al., A distributed framework for health information exchange using smartphone technologies. *J. Biomed. Inform.* 69:230–250, 2017.
9. 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.
10. 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.

11. Zaidan, B. B. et al., A security framework for Nationwide health information exchange based on telehealth strategy. *J. Med. Syst.* 39(5):51, 2015.
12. Hussain, M. et al., The landscape of research on smartphone medical apps: Coherent taxonomy, motivations, open challenges and recommendations. *Comput. Methods Programs Biomed.* 122(3): 393–408, 2015.
13. 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.
14. Kiah, M. L. M. et al., MIRASS: Medical informatics research activity support system using information mashup network. *J. Med. Syst.* 38(4):37, 2014.
15. A. H. Mohsin et al., Based Blockchain-PSO-AES techniques in finger vein biometrics: A novel verification secure framework for patient authentication. Comput. Stand. Interfaces, 2019.
16. Hussain, M. et al., Conceptual framework for the security of mobile health applications on android platform. *Telemat. Inform.* 35(5), 2018.
17. Hussain, M. et al., A security framework for mHealth apps on android platform. *Comput. Secur.* 75:191–217, 2018.
18. Alsalem, M. A. et al., A review of the automated detection and classification of acute leukaemia: Coherent taxonomy, datasets, validation and performance measurements, motivation, open challenges and recommendations. *Comput. Methods Programs Biomed.* 158:93–112, 2018.
19. Mohsin, A. H. et al., Real-time medical systems based on human biometric steganography: A systematic review. *J. Med. Syst.* 42(12):245, 2018.
20. 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.
21. 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.
22. 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.
23. 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.
24. A. H. Mohsin et al., Based medical systems for patient's authentication: Towards a new verification secure framework using CIA standard. *J. Med. Syst.*, 2019.
25. 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.
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. Táborský, M., Linhart, A., and Skalická, H., E-health: A position statement of the European Society of Cardiology: Summary of the document prepared by the Czech Society of Cardiology. *Cor et Vasa* 59(2):e204–e207, 2017.
28. Varga, N., Bokor, L., and Takács, A., Context-aware IPv6 flow mobility for multi-sensor based Mobile patient monitoring and tele-consultation. *Proc. Comput. Sci.* 40:222–229, 2014.
29. Pawar, P.A. and Mohammad, S.P., Review of quality of service in the mobile patient monitoring systems. I2017 IEEE Region 10 Symposium (TENSYMP). 2017.
30. Paganelli, F., and Giuli, D., An ontology-based system for context-aware and configurable services to support home-based continuous care. IEEE Transactions on Information Technology in Biomedicine 15(2):324–333, 2011.
31. Logan, A. G. et al., Mobile phone–based remote patient monitoring system for management of hypertension in diabetic patients. *Am. J. Hypertens.* 20(9):942–948, 2007.
32. Miao, F. et al., Mobihealthcare system: Body sensor network based m-health system for healthcare application. *E-Health Telecommun. Syst. Netw.* 1(01):12, 2012.
33. Fortier, P. and B. Viall. Development of a mobile cardiac wellness application and integrated wearable sensor suite. The fifth international conference on sensor technologies and applications. 2011.
34. Wai, A., et al., Smart wireless continence management system for elderly with dementia. In 10th International Conference on e-health Networking, Applications and Services*,* HealthCom. 2008.
35. Dickerson, R.F., E.I. Gorlin, and J.A. Stankovic. Empath: a continuous remote emotional health monitoring system for depressive illness. .Proceedings of the 2nd Conference on Wireless Health. 2011. ACM.
36. Bourouis, A., Feham, M., and Bouchachia, A., Ubiquitous mobile health monitoring system for elderly (UMHMSE). arXiv preprint arXiv:1107.3695, 2011.
37. Gao, T. et al., The advanced health and disaster aid network: A light-weight wireless medical system for triage. *IEEE Trans. Biomed. Circ. Syst.* 1(3):203–216, 2007.
38. Jones, V., Gay, V., and Leijdekkers, P., Body sensor networks for mobile health monitoring: Experience in europe and australia. Digital Society, 2010. ICDS'10. Fourth International Conference on. 2010. IEEE.
39. Pawar, P. et al., A framework for the comparison of mobile patient monitoring systems. *J. Biomed. Inform.* 45(3):544–556, 2012.
40. Hussain, A. et al., Health and emergency-care platform for the elderly and disabled people in the Smart City. *J. Syst. Softw.* 110: 253–263, 2015.
41. Bonney, W., Mobile health technologies-theories and applications. InTech, 2016.
42. Paliwal, G. and Kiwelekar, A.W., A comparison of mobile patient monitoring systems. In International Conference on Health Information Science. 2013. Springer.
43. Massé, F., et al., Miniaturized wireless ECG-monitor for real-time detection of epileptic seizures. In Wireless health 2010. 2010. ACM.
44. Ren, Y. et al., Monitoring patients via a secure and mobile healthcare system. *IEEE Wireless Commun.* 17(1):59–65, 2010.
45. Koutkias, V. G. et al., A personalized framework for medication treatment management in chronic care. *IEEE Trans. Inform. Technol. Biomed.* 14(2):464–472, 2010.
46. Shahriyar, R., et al., Intelligent mobile health monitoring system (IMHMS). International Conference on Electronic Healthcare. 2009. Springer.
47. Angood, P. B. et al., Telemedicine at the top of the world: The 1998 and 1999 Everest extreme expeditions. *Telemed. J. e-Health* 6(3):315–325, 2000.
48. Lin, Y.-H. et al., A wireless PDA-based physiological monitoring system for patient transport. *IEEE Trans. Inform. Technol. Biomed.* 8(4):439–447, 2004.
49. Gay, V., and Leijdekkers, P., A health monitoring system using smart phones and wearable sensors. *Int. J. ARM* 8(2):29–35, 2007.
50. Leijdekkers, P., Gay, V., and Barin, E., Feasibility study of a non invasive cardiac rhythm management system. International Journal of Assistive Robotics and Systems, 2009.
51. Wai, A. A. P. et al., Smart wireless continence management system for persons with dementia. *Telemed. e-Health* 14(8):825–832, 2008.
52. Van Halteren, A. et al., Mobile patient monitoring: The mobihealth system. *J. Inform. Technol. Healthcare* 2(5):365–373, 2004.
53. Jones, V., et al., Mobihealth: Mobile health services based on body area networks, in M-Health. Springer; 219–236, 2006.
54. Jones, V.M., et al., Biosignal and context monitoring: distributed multimedia applications of body area networks in healthcare. in

Multimedia Signal Processing, 2008 IEEE 10th Workshop on. 2008. IEEE.

55. Ostmark, A., et al., Mobile medical applications made feasible through use of EIS platforms. In IEEE Instrumentation and Measurement Technology conference proceedings. 2003. IEEE; 1999.
56. Gao, M. et al., Cardiosentinal: A 24-hour heart care and monitoring system. *J. Comput. Sci. Eng.* 6(1):67–78, 2012.
57. Triantafyllidis, A., et al., An open and reconfigurable wireless sensor network for pervasive health monitoring. in Pervasive Computing Technologies for Healthcare, 2008. PervasiveHealth 2008. Second International Conference on. 2008. IEEE.
58. Pawar, P. et al., Performance evaluation of the context-aware handover mechanism for the nomadic mobile services in remote patient monitoring. *Comput. Commun.* 31(16):3831–3842, 2008.
59. Channabasavaiah, K., Holley, K., and Tuggle, E., Migrating to a service-oriented architecture. *IBM DeveloperWorks* 16: 727–728, 2003.
60. Djuknic, G. M., and Richton, R. E., Geolocation and assisted GPS. *Computer* 2:123–125, 2001.
61. Liu, H. et al., Survey of wireless indoor positioning techniques and systems. *IEEE Trans. Syst. Man. Cybernet., Part C (Applic. Rev.)* 37(6):1067–1080, 2007.
62. Nilsson, H., Nordström, E.-M., and Öhman, K., Decision support for participatory forest planning using AHP and TOPSIS. *Forests* 7(5):100, 2016.
63. Motebele, M.M., Knowledge Based Decision Support System for GSC Industries Benchmarking Perspective. In Proceedings of the World Congress on Engineering. 2018.
64. Trentesaux, D. et al., Benchmarking flexible job-shop scheduling and control systems. *Contrl Eng. Pract.* 21(9):1204–1225, 2013.
65. Anliker, U. et al., AMON: A wearable multiparameter medical monitoring and alert system. *IEEE Trans. Inform. Technol. Biomed.* 8(4):415–427, 2004.
66. Albahri, O. 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.
67. Jumaah, F. 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.
68. Abdullateef, B. N. et al., An evaluation and selection problems of OSS-LMS packages. *SpringerPlus* 5(1):248, 2016.
69. Rossi, G., In: Pavese, F., Forbes, A. B. (Eds), Data modeling for metrology and testing in measurement science. Boston: Birkhäuser, 2009.
70. Keeney, R.L. and Raiffa, H., Decisions with multiple objectives: preferences and value trade-offs. 1993: Cambridge university press.
71. Greco, S., Figueira, J., and Ehrgott, M., Multiple criteria decision analysis. 2016: Springer.
72. Malczewski, J., GIS and multicriteria decision analysis. 1999: John Wiley & Sons.
73. Petrovic-Lazarevic, S. and A. Abraham, Hybrid fuzzy-linear programming approach for multi criteria decision making problems. arXiv preprint cs/0405019, 2004.
74. Zionts, S., MCDM—If not a roman numeral, then what? *Interfaces* 9(4):94–101, 1979.
75. Zaidan, 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. Exper.* 47(10):1365–1392, 2017.
76. Zaidan, A. et al., Multi-criteria analysis for OS-EMR software selection problem: A comparative study. *Decis. Support Syst.* 78: 15–27, 2015.
77. Zaidan, 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.
78. M. Khatari 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.
79. 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.
80. Oliveira, M., Fontes, D.B., and Pereira, T., Multicriteria decision making: A case study in the automobile industry. 2013.
81. Zaidan, B., et al., A new approach based on multi-dimensional evaluation and benchmarking for data hiding techniques. International Journal of Information Technology & Decision Making. 1–42, 2017.
82. Zaidan, B., and Zaidan, 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. Circ. Syst. Comput.* 26(07):1750116, 2017.
83. Zaidan, B., and Zaidan, 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.
84. Rahmatullah, B. et al., Multi-complex attributes analysis for optimum GPS baseband receiver tracking channels selection. 2017 4th International Conference on Control, Decision and Information Technologies, CoDIT 2017 2017:1084–1088, 2017.
85. F. M. Jumaah 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.
86. 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.
87. Jadhav, A. and R. Sonar. 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. 2009. IEEE.
88. 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.
89. 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.
90. Tariq, I. et al., MOGSABAT: A metaheuristic hybrid algorithm for solving multi-objective optimisation problems. *Neural Comput. Appl.* 30:1–15, 2018.
91. Enaizan, O. et al., Electronic medical record systems: Decision support examination framework for individual, security and privacy concerns using multi-perspective analysi. Health Technol. (Berl). 2018.
92. Salih, M. M. et al., Survey on fuzzy TOPSIS state-of-the-art between 2007–2017. Comput. Oper. Res. 2018.
93. 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.

94. Diaby, V., Campbell, K., and Goeree, R., Multi-criteria decision analysis (MCDA) in health care: A bibliometric analysis. *Opera. Res. Health Care* 2(1–2):20–24, 2013.
95. Thokala, P. et al., Multiple criteria decision analysis for health care decision making—An introduction: Report 1 of the ISPOR MCDA emerging good practices task force. *Value Health* 19(1): 1–13, 2016.
96. Adunlin, G., Diaby, V., and Xiao, H., Application of multicriteria decision analysis in health care: A systematic review and bibliometric analysis. *Health Expect.* 18(6):1894–1905, 2015.
97. Yas, Q.M., et al., Comprehensive insights into evaluation and benchmarking of real-time skin detectors: Review, open issues & challenges, and recommended solutions. Measurement, 2017.
98. 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. *Appl. Health Econ. Health Policy* 14(1):29–40, 2016.
99. Zhu, G.-N. et al., An integrated AHP and VIKOR for design concept evaluation based on rough number. *Adv. Eng. Inform.* 29(3):408–418, 2015.
100. 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.
101. 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.
102. Talal, M. et al., Comprehensive review and analysis of anti-malware apps for smartphones. Telecommun. Syst., 2019.
103. 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. Appl. 2019.
104. 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.
105. 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.
106. 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.
107. 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(3):1229–1253, 2018.
108. 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. Opera. Res.* 189(1):132–145, 2008.
109. Singh, A. and Malik, S.K., Major MCDM Techniques and their application-A Review. IOSR Journal of Engineering (IOSRJEN), ISSN (e): 2250–3021, ISSN (p): 2278–8719 Vol, 2014. 4.
110. Jablonsky, J., MS excel based software support tools for decision problems with multiple criteria. *Proc. Econ. Fin.* 12:251–258, 2014.
111. Ahmad, W. N. K. W. et al., 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.
112. 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.
113. Rezaei, J., Best-worst multi-criteria decision-making method. *Omega* 53:49–57, 2015.
114. Rezaei, J., Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega* 64:126–130, 2016.
115. Gupta, H., Evaluating service quality of airline industry using hybrid best worst method and VIKOR. *J. Air Transp. Manag.* 68:35–47, 2018.
116. Opricovic, S., and Tzeng, G.-H., Extended VIKOR method in comparison with outranking methods. *Eur. J. Opera. Res.* 178(2):514–529, 2007.
117. Opricovic, S., and Tzeng, G.-H., Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *Eur. J. Opera. Res.* 156(2):445–455, 2004.
118. Mahjouri, M. et al., Optimal selection of Iron and steel wastewater treatment technology using integrated multi-criteria decision-making techniques and fuzzy logic. *Process Saf. Environ. Protect.* 107: 54–68, 2017.
119. 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. Applied Soft Computing, 2018.
120. Ren, J., Selection of sustainable prime mover for combined cooling, heat, and power technologies under uncertainties: An interval multicriteria decision-making approach. International Journal of Energy Research, 2018.
121. Serrai, W., et al., An efficient approach for Web service selection. in Computers and Communication (ISCC), 2016 IEEE Symposium on. 2016. IEEE.
122. 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.
123. Serrai, W. et al., Towards an efficient and a more accurate web service selection using MCDM methods. *J. Comput. Sci.* 22:253–267, 2017.
124. 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. Applic.* 91: 89–106, 2018.
125. Guo, S., and Zhao, H., Fuzzy best-worst multi-criteria decision-making method and its applications. *Knowl.-Based Syst.* 121:23–31, 2017.
126. Sofuoglu, M. A., and Orak, S., A novel hybrid multi criteria decision making model: Application to turning operations. *Int. J. Intell. Syst. Applic. Eng.* 5(3):124–131, 2017.
127. Aboutorab, H. et al., ZBWM: The Z-number extension of best worst method and its application for supplier development. *Expert Syst. Applic.* 107:115–125, 2018.
128. Rezaei, J., van Roekel, W. S., and Tavasszy, L., Measuring the relative importance of the logistics performance index indicators using best worst method. *Transpo. Policy* 68:158–169, 2018.
129. Salimi, N., and Rezaei, J., Evaluating firms' R&D performance using best worst method. *Eval. Program Plan.* 66:147–155, 2018.
130. Gul, M. et al., A state of the art literature review of VIKOR and its fuzzy extensions on applications. *Appl. Soft Comput.* 46:60–89, 2016.
131. Chiu, W.-Y., Tzeng, G.-H., and Li, H.-L., A new hybrid MCDM model combining DANP with VIKOR to improve e-store business. *Knowledge-Based Syst.* 37:48–61, 2013.
132. Jahan, A. et al., A comprehensive VIKOR method for material selection. *Mater. Design* 32(3):1215–1221, 2011.
133. Yang, Y.-P. O., Shieh, H.-M., and Tzeng, G.-H., A VIKOR technique based on DEMATEL and ANP for information security risk control assessment. *Inform. Sci.* 232:482–500, 2013.
134. Cavallini, C. et al., Integral aided method for material selection based on quality function deployment and comprehensive VIKOR algorithm. *Mater. Des.* 47:27–34, 2013.
135. Liou, J. J. H. et al., A modified VIKOR multiple-criteria decision method for improving domestic airlines service quality. *J. Air Transpo. Manag.* 17(2):57–61, 2011.
136. Migdadi, M., Knowledge management enablers and outcomes in the small-and-medium sized enterprises. *Indust. Manag. Data Syst.* 109(6):840–858, 2009.

137. Kiah, M. L. M. et al., Open source EMR software: Profiling, insights and hands-on analysis. *Comput Methods Programs Biomed.* 117(2):360–382, 2014.
138. 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). 2014. IEEE.
139. Huang, P. H., and Moh, T.-t., A non-linear non-weight method for multi-criteria decision making. *Ann. Opera. Res.* 248(1):239–251, 2017.
140. 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):69, 2018.
141. Qader, M. A. et al., A methodology for football players selection problem based on multi-measurements criteria analysis. *Measurement* 111:38–50, 2017.