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RESEARCH ARTICLE



A new approach to the intelligent decision support system for individual hearing aid selection and acquisition

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ABSTRACT

Background: The intelligent decision support system (IDSS) is designed for patients to acquire hearing aids that better meet their needs, because they often agree to pay from their funds for a better, more customized hearing aid.

Objective: The article aims to present the IDSS for selecting personal hearing aids in healthcare institutions.

Methods: The article proves that the SAW (simple additive waiting) multi-criteria evaluation method is the most suitable for creating the IDSS. Hearing aids are evaluated according to 12 reasonable criteria, which are differentiated into two groups. The proposed methodology is flexible, allowing for changing the significance of differentiated criteria groups.

Results: The created IDSS system helps increase the effectiveness of choosing the best hearing aid. Even 92% of the surveyed patients positively evaluated the choice of hearing aid. This situation indicates greater patient satisfaction than usual when selecting these measures.

Conclusion: The proposed IDSS is suitable for adaptation in a computer program, and such a solution greatly facilitates the selection of a hearing aid. Applying the proposed IDSS makes the choice more objective, thus better meeting patients' needs.

ARTICLE HIGHLIGHTS

- The article explains how to design and implement an intelligent decision support system (IDSS) for selecting hearing aids based on a multi-criteria evaluation.
- It also demonstrates that the SAW method is the most suitable for achieving this goal. The use of the SAW methodology is illustrated through a real patient situation according to the usual diagnosis. The proposed method is adaptable to IT, and for creating computer program. The article explains how to design and implement an intelligent decision support system (IDSS) for selecting hearing aids based on a multi-criteria evaluation.
- It also demonstrates that the SAW method is the most suitable for achieving this goal. The use of the SAW methodology is illustrated through a real patient situation based on the usual diagnosis. The proposed method is adaptable to IT and to creating a computer program. It allows adjustments to the significance of the differentiated criteria groups according to the current situation, causes of illness, diagnosis, and treatment requirements.
- The criteria are differentiated into two groups: one intended for doctors to select a hearing aid based on the patient's diagnosis (general criteria) and the other designed to consider patients' personal needs and wishes (specific criteria). All the mentioned criteria are not only explained in the article, but their application is also justified. The treating physician determines the significance values of both criterion groups.
- The suggested methodology feature highlights its flexibility, essential for better satisfying patients' needs. This result was found after conducting a study involving interviews with repeatedly visiting patients. Our proposed IDSS's new feature aims to better address the needs of hearing aid users, which has helped us achieve the intended goal to the current situation, causes of illness, diagnosis, and treatment requirements.
- The criteria are proposed to be differentiated into two groups: one intended for doctors to select a hearing aid based on the patient's diagnosis (general criteria) and the other designed to consider patients' personal needs and wishes (specific criteria). All the mentioned criteria are not only explained in the article, but their application is also justified. The treating physician decides the significance values of both criterion groups.
- The suggested methodology feature highlights its flexibility, which is essential and enables better satisfaction of patients' needs. This result was found after conducting a study by interviewing repeatedly visiting patients. Our proposed IDSS new feature aims to better address hearing aid users' needs, and this has helped us achieve the intended goal.

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1. Introduction

In 2020, more than 375 million people worldwide had hearing loss, of which 38 million were children. According to the World Health Organization (WHO) report, over 900 million people, or 10% of the world's population, will suffer from hearing loss by 2050 [1]. Hearing loss is one of the most significant global health problems and the most commonly diagnosed health disorders worldwide [2]. Hearing impairment or loss can often lead to social isolation, reduced self-esteem, fear, or even depression. Thus, the quality of life is frequently affected by those faced with this problem, and difficulties arise at work and in household and personal activities [2]. Hearing loss and any hearing impairment are both profound and great health challenges for any person, and it is a significant subject of research in the medical field [3]. Hearing can be impaired for many reasons, such as childhood diseases, prolonged exposure to noisy environments, constant stress, aging processes, etc. In even 80% of cases, a professional hearing examination and the correct selection of hearing aids solve these problems [4].

In today's world of a global economy, product manufacturers are trying to stay competitive to meet customers' needs as best as possible. That is why hearing aid manufacturers are implementing the most advanced innovative technologies, aiming to reach the users individually to meet their needs and solve their hearing improvement problems. There are many options for hearing aids available today, which can make it difficult for people to understand the differences or how to choose a hearing aid [3]. Furthermore, the choice of hearing aids is often determined by state regulatory documents, according to which only hearing aids performing defined essential functions are compensated.

Such compensable devices perform only several (few) functions. However, the main question is: which hearing aid should be chosen for a potential user of this product, and which should be offered for a patient with hearing problems? The selection of hearing aids is commonly shaped by considering the patient's age and level of hearing loss. Many audiologists, however, usually only work with hearing aids from a few manufacturers, which they typically offer for purchase, without considering the patient's wishes and possibilities. Meeting the user's needs has recently become perhaps the most essential aspect of providing hearing aids [5,6]. In addition, patients often agree to pay more to meet their needs better. So, the efforts of healthcare institutions to address patients' social needs are necessary [7].

Manufacturers, taking into account the causes of the disease and the possibilities of applying treatment methods, sometimes implement different technological solutions; a variety of hearing aids differing in types and features of technology can allow a better alignment between the nature of the hearing loss [8]. Dashti et al. [9] analyzed patients' satisfaction with hearing aids according to several factors: price, service quality, personal image, and effect of use. They found that approximately 80% of patients are satisfied or very satisfied with prescribed hearing aids. Picou [10] explained overall satisfaction with hearing aids and what drives satisfaction, and her research also found that 80% of patients are satisfied. Picou [10] raised the question of whether this is good enough. We agree with this question, which we are trying to clarify. We try to explore possibilities to increase the number above 80% by implementing an intelligent decision support system (IDSS). The article's aim is to create the modern IDSS and explain its content for use in healthcare institutions. So, we will try to increase the relative number of satisfied patients by applying the IDSS we have developed. While in many countries worldwide, patients have to pay extra for hearing aids; we want to offer a system allowing patients to receive a better-fitting hearing aid by paying an additional amount according to their wishes. Such a system has not been used yet.

2. Materials and methods

The intelligent decision can be understood as a cognitive-based system that makes an in-depth analysis of decision systems based upon their previous insights and, based on multicriteria assessment, forecasts a new intelligent, driven system for the intelligent decision-making for some particular problem [11]. The intelligent decision support system is an interactive computer-based system that uses data, experts' knowledge, and models to support decision-makers in organizations to solve complex, imprecise, ill-structured problems by incorporating artificial intelligence techniques [11,12]. IDSS provides knowledge, models, and data processing tools to help the experts make better decisions. While preparing the intelligent decision support system, we invited not only audiologists to participate but also IT scientists, who helped to enter the methodology we developed into a computer program. It was not only an interdisciplinary but also an inter-institutional activity. It was not a clinical trial but a project initiated by a private IT company with IT researchers from Vytautas Magnus University.

When choosing hearing aids, more objective results can be achieved by performing a multi-criteria evaluation. This means that the selection of hearing aids should not be based on one or two criteria but on a whole set of criteria using mathematical assessment methods. In addition, considering consumers' needs in the assessment would be preferable [9,12,13]. The assessment should be simple; the choice should be sufficiently clear for persons with hearing problems who are choosing a hearing aid and for audiologists prescribing hearing aids. The selection method should be not only simple but also objective. Therefore, the SAW (simple additive weighting) method best meets the criterion of clarity and simplicity. Many authors also design artificial intelligent systems for other areas of medicine by using the SAW method as the best [14–16]. Using the SAW methodology, ranking all the evaluated objects and finding the best one is possible.

The first step in forming the support system for multicriteria decisions is selecting and justifying the evaluation criteria [16,17]. Determining and selecting the criteria is a responsible action that can also influence the final result of the assessment.

According to many authors, the optimum number of criteria for an objective assessment should be a minimum of 10 and a maximum of 15 (a lower threshold would reduce the objectivity of the evaluation, and the upper limit is due to overly complex evaluation activities) [17,18]. There is no need to choose many criteria because, in this case, experts in the mind cannot accurately weigh the importance of the criteria. Many authors agree with 12 as the sufficient number of criteria [17–19]. Following this view and to provide an objective assessment when choosing hearing aids, it is appropriate for group 12 criteria to include both general and specific assessment criteria in the set, and such selection will best reflect the current situation. Differentiation of criteria is often used in multi-criteria evaluation, increasing the objectivity of the final decision [18,19].

Among the general criteria, we would include those specific to the individual, which cover the attitude toward particular possibilities, living conditions, and hearing impairment. The indicators of this assessment in a 10-point system should be determined by the person who needs to choose a hearing aid. Evaluation according to specific criteria related to the diagnosis of the disease should be provided by medical experts (doctors, medical technicians, nurses) who have studied the causes of hearing loss, the course of treatment, and the possibilities of recovery. Evaluation according to specific criteria should also be done in a 10-point system. As mentioned, for a more accurate selection of hearing aids, we suggest giving equal significance to both criteria groups. For that purpose, an equal number of criteria should be selected in each group. A possible case, if the disease is advanced, where hearing impairment is undeniable, and the diagnosis is precise, would be to give greater significance to the specific criteria. However, we recommend varying the dimensions of significance according to the situation while leaving a proportion of significance of at least 10% for general criteria. Such a decision increases the social importance of the choice and customer satisfaction. The general criteria would be the price of hearing aids, appropriateness of the esthetic image, comfort of wearing, compliance with the lifestyle, brand awareness, and application of modern technologies in the operation process. Specific criteria, according to which the options for eliminating hearing impairment should be evaluated in terms of effectiveness of eliminating hearing impairment problems, determination degree of hearing loss, type of hearing loss, number of channels, noise sensitivity, sufficiency of the number of functions, suitability according to the degree and nature of the hearing impairment. In the following subsections, it is appropriate to provide an explanation and justify each of the criteria of the presented groups:

2.1. General criteria

When evaluating hearing aids' properties according to general criteria, attention should be paid to the characteristics of the patient's social life, opportunities, and desires to change habits and attitudes toward specific values, as well as economic well-being. The patient's attitude toward changing fashion, customs, and traditions also impacts the evaluation according to general criteria.

2.1.1. Price

In today's world, price is an essential criterion for many individuals when choosing any product (criterion 1). Many believe a product's price is determined by its quality [19,20]. Nowadays, the price is also determined by other aspects. Still, the price of medical goods is usually determined by the consumer's ability to pay a specified amount for the desired item [19,21]. Both very cheap and prohibitively expensive prices of hearing aids always influence the choice. The task for sellers is to find the golden middle of the price, i.e., set an attractive

price for many people. Therefore, the choice of hearing aids in terms of price is determined not only by the standard of living in the country but also by a person's income, balance, other financial opportunities, and social status. The readiness to purchase one or another hearing aid in terms of price must be assessed by a person on a 10-point system (1 – impossible to buy, too expensive, 10 – the price is quite favorable, readily available). However, there are various prices for hearing aids. Still, the most significant part of the price is determined by the technological level of the device, i.e., the level of computerization of the hearing aid. The higher it is, the cleaner the sound and the more functions the device has. Devices are divided into five technological levels [22], and five price groups are also distinguished accordingly. Although a specialist makes the first step toward the choice of hearing aids, the patient can maneuver in the price field according to his financial capabilities and, with the help of a specialist, choose the most favorable solution in terms of price. Regardless of the degree of hearing impairment, a person has the freedom to select a device in terms of price that is affordable to him and meets at least the minimum required functions. Most European countries have limited support through their health insurance systems. At the same time, in the United Kingdom, the National Health Service (NHS) provides hearing aids free of charge only to certain eligible patients. Availability of reimbursement is province-dependent in USA and Canada, and many provinces offer partial coverage for adults, but children may have better access. Japan has some health insurance programs for specific hearing aids, but many patients still face significant out-of-pocket costs. In China and most African countries, hearing aids are generally not covered by public health insurance, leading to high personal device expenses. Australian and New Zealand governments provide some assistance through the Hearing Services Program for eligible individuals, but many users still face personal costs [23]. This information also proves how important the choice of hearing aids is, especially for people who pay out of their own money.

2.1.2. Appropriateness of esthetic image

Today, hearing aids are produced in various models, sizes, and colors to give patients as much variety as possible so they can choose a device with a look they like. Usually, a person with a hearing disability does not want to show that they have this defect, so they choose a device that is as inconspicuous as possible. When selecting a device, attention is drawn to its esthetic image (criterion 2) and the look when the patient wears it. Choosing according to the hearing aid's size, mounting, and color is possible. These are the key features to consider when selecting a hearing aid. The type of hearing aid model draws the most attention. Behind-the-ear hearing aids are more massive, visible devices that house the electronics outside the ear [24]. When a hearing aid is fitted, most of the body is covered by the person's ears, but the arch of the top of the hearing aid body is inevitably visible. Also, due to the sufficiently large weight of the device's body, changes in the shape of the ear occur. Although efforts are being made to reduce the body of the cochlear hearing aid, they remain large enough [22]. Another noticeable part of the cochlear hearing aid is the tube. Although colorless, it is visible when viewed closely as it connects the body of the hearing aid to the speaker and runs along the top of the ear [22,24,25]. Even though hearing aids are available in diverse sizes, they may not cause problems for the wearer; patients sometimes choose a larger one to show their disability to others. Meanwhile, in-the-ear hearing aids are small, placed in the ear canal, and almost invisible. They do not have tubes or extra parts that attach behind or next to the ear. The choice is determined not only by the model type but also by the device size. Efforts are always made to make the hearing impairment the least noticeable [14]. When choosing a hearing aid, most patients choose the tiniest and least noticeable hearing aids possible. The color of the device has a significant influence on its noticeability. Usually, the range of hearing aid color is extensive – a person can freely match any hearing aid to their skin tone, clothes, or other attributes. Moreover, a person's choice of any color they desire emphasizes their uniqueness. Thus, the suitable esthetic image of the hearing aid must be assessed only by the patient personally. Patients choose what they want and what is attractive and ideal for them [22,24,25].

2.1.3. Comfort to wear

A person should choose a hearing aid that does not cause them discomfort. The hearing aids must be comfortable to wear (criterion 3) and not cause a sensation. In such cases, the wearer will unconsciously forget about the disability, which will bring psychological relief and ensure a sufficient duration of comfortable wearing, so better results will be achieved in the fight against the disability [24,25]. The comfort of wearing can be determined by several features, according to which the most comfortable device should be chosen. For example, the size of the head of the plug must be adapted to the earlobe. Devices with an individual hearing

insert or an amplifier in the canal are manufactured according to a particular order. This means that the part placed in the earlobe is modeled according to the individual shape of the human earlobe. Individual plugs ensure maximum comfort when wearing it [25]. The weight of the device and its ability to fit the ear also affect the comfort of wearing [24,26]. When choosing a hearing aid, it is essential to pay attention to the size and shape of the ear. Another thing to consider is device control functions. During usage of the hearing aid, depending on the noise level of the environment, it may be necessary to switch the functions of the hearing aid frequently [27]. Changing functions requires physical human intervention. With the help of fingers, the button is turned or pressed as many times as possible until a person adjusts the sound according to their needs. This action is strict for people with giant fingers or hand tremors, so trying to grasp the small control parts on the device in such a situation can cause significant discomfort. The comfort when wearing is an individual criterion, so the patient should be the one to evaluate the comfort in a 10-point system.

Compatibility with lifestyle. One must consider the person's lifestyle to choose the most suitable hearing aid (criterion 4). Evaluating this is essential for the device to function efficiently and for a person to be satisfied wearing it [22]. When assessing lifestyle, four primary levels can be distinguished: very quiet, quiet, regular, and active lifestyles [27,28]. Choosing a hearing aid based on this criterion should ensure it lasts longer and meets the individual's needs. People leading a quiet lifestyle require hearing aids that rarely pick up background noises; these devices tend to be straightforward. This lifestyle can be characterized by individuals who spend most of their time at home, listen to little or no TV or radio, and occasionally leave the house for small, quiet events. A quiet lifestyle describes someone who uses hearing aids in situations where background sounds are not a primary concern and are limited. This lifestyle includes those who occasionally host guests at home, watch TV, or listen to limited music. A typical lifestyle encompasses individuals who communicate daily, drive a vehicle, and are constantly surrounded by sounds that must be heard clearly. An active lifestyle refers to someone who is continually exposed to background noise, working in a team environment, participating in meetings, and engaging intensively in sports. Therefore, the compatibility of the hearing aid with an individual's lifestyle is a personal criterion, and only the patient can make this assessment after the doctor explains the situation using a 10-point rating scale [29,30].

2.1.4. Brand awareness

When choosing a hearing aid, attention should also be paid to the manufacturer's reputation (criterion 5). Thousands of companies are making hearing aids today, and choosing the best is difficult. Essentially, when manufacturing a hearing aid, all companies focus on the device's reliability, the conversion of sound from the environment, and the device's comfort. Companies compete with each other to improve these four criteria as much as possible. However, every year, companies create more and more new functions that contribute to hearing improvement and increase their attractiveness. For a person to choose the device from the best company that meets their criteria, nominations are given to hearing aid brands every year for the features in which their devices excel in comparison to others. Though some brands are often the world's obvious market leaders, some buyers prefer products of national brands, and some people prefer only brands they already know [31]. Each producer highlights a feature in their devices that is not so emphasized in other brand devices [31]. However, one brand of hearing aids is more popular than another, even because a certain brand can offer different types of hearing aids. The more different hearing aid models a brand has, the more famous it is. It is also believed that brand popularity ensures good quality, reliability, and operational efficiency of the device. Of course, all this affects the price. The more well-known the hearing aid brand, the higher the price compared to other brands [31]. Brand popularity is an individual criterion because it is not equally important for all patients. Still, the assessment on a 10-point system would show the patient's knowledge of the market of the manufacturers of these devices.

2.1.5. Application of modern technologies of hearing aids

In this age of knowledge and information technology, it becomes obvious that the processes of operation of any equipment, based on continuous renewal and applying new and advanced technologies, ensure the survival of companies-manufacturers in a competitive environment. The application of modern technologies and artificial intelligence tools (criterion 6) facilitates equipment operation for users, reduces operating costs, and even warns of possible malfunctions and other possible problems [32]. To ensure the effective operation of hearing aids, it is necessary to correctly understand the importance of these technologies and learn how to apply them. However, using these modern technologies in hearing aids causes a split in the attitude of users

[33]. Some use all the possibilities and functions of modern technologies offered in the devices, enjoying the lower costs and aiming to be the first to try the advantages of new technologies. In this case, others are scared by more modern options, and the costs of learning to operate the upgraded aid and the basic functions are enough for them. The application of modern technologies in hearing aids is an individual criterion, the assessment of which is determined by the patient's individual characteristics. The use of modern technologies in the construction of hearing aids is often associated with the brand [31]. Some manufacturers constantly develop and adapt the latest technologies to justify the prestige of their brand. The experts who apply the latest technologies are the technical staff, who express their views when choosing a hearing aid.

2.2. *Specific criteria*

As mentioned, assessment should be carried out according to the specific criteria, considering the nature of the patient's disease and the degree of hearing loss. Only healthcare professionals can assess the results according to specific criteria.

2.2.1. *Effectiveness in solving hearing impairment problems*

Another criterion for choosing a hearing aid is the effectiveness of eliminating hearing loss problems (criterion 7). Effectiveness shows to what degree the problems of human hearing impairment are solved and whether the sound is heard sufficiently. If a person's hearing does not improve, worsens, or if sounds are not audible enough yet when wearing a hearing aid, it means that the effectiveness of the hearing aid as a means of removing the hearing impairment problems is low or that the aid is selected not properly [32,33]. How much and which hearing aid can eliminate hearing problems will show the effectiveness of the device.

2.2.2. *The type of hearing loss*

The type of hearing loss (criterion 8) always influences the choice of the device. For the brain not only to receive the sound through the hearing aids but also to process it, the individual's organism must get used to new sensations. Only when wearing a hearing aid for at least five hours a day does the patient's brain get used to listening and processing the incoming information so that it becomes meaningful and understandable information [33,34]. The person wearing hearing aids brain gets used to listening and adapting to the sounds they hear within half a year. Therefore, to perfectly hear and understand the speech of others, it is essential to wear them systematically [31]. Modern hearing aids have a function that allows the professional to determine how long the patient has been wearing the hearing aid and in what environment the patient usually spends time. Since different hearing aids eliminate hearing problems in various ways, the kind of hearing aid is an essential criterion in choosing the correct device. The type of hearing loss should always be determined by the doctor who prescribes the device, indicating the required duration of usage [32]. Thus, the type of hearing loss is a specific criterion by which hearing aids are evaluated only by the medical personnel.

2.2.3. *The number of channels*

The number of channels (criterion 9) in a hearing aid is one of the criteria to consider, as it can determine the degree of correction of hearing loss. The greater the number of channels in the hearing aid, the more accurate the correction of hearing loss will be, as it will allow to adjust the sound more precisely according to the patient's needs. Patients could have different types of hearing loss; therefore, each one needs specific adjustments depending on the audiometry results. Therefore, the more channels the hearing aid has, the greater the precision and customization when fitting [33]. In addition, modern audiological solutions usually work better in hearing aids with more channels, such as noise reducers. Clinical audiologists generally focus on improving speech understanding and audibility as a treatment goal. After all, restoration of speech audibility is one primary goal of every hearing aid fitting. Modern hearing aids provide various properties and functionality within hearing aid channels.

A person always expects that a hearing aid should last for a long time, i.e., it is appropriate to evaluate its ability to maintain serviceability until critical failure. Both indestructibility and durability indicators depend on the conditions of use [34]. Therefore, when studying longevity, the conditions under which it is achieved are always indicated. Most hearing aids have a working duration of 5–7 years. This means that with proper maintenance, the manufacturer ensures the duration of the device during this period [32].

The technical characteristics of the hearing aids usually give the duration of the operation.

Thus, when considering hearing aids and choosing the most suitable one, attention should also be focused on assessing the hearing aid's indestructibility, reparability, and durability [32]. These partial characteristics allow a person to assess the level of reliability of hearing aids and choose the most reliable device that meets their reliability standards [33]. As mentioned, hearing aid maintenance specialists and doctors should estimate the reliability of the equipment.

2.2.4. Patients' noise sensitivity

People can have different sound sensitivity, and some patients can feel intolerant to loud sounds. In this case, hearing aids can be tweaked to allow for the amplification or weakening of sound. Thus, the device's parameters also determine the choice based on the patient's sensitivity to sound (criterion 10). Like many electronic devices, a hearing aid has a battery power source. The noisier the environment, the more sounds there are, and the faster the hearing aid battery runs out of energy [33]. Therefore, patients' noise sensitivity must be a criterion when choosing a hearing aid. Considering this criterion, when choosing a hearing device, the purchaser should pay attention to which group they belong to, living an active (noisy) or passive (quiet environment) life. Accordingly, the patient is offered a choice of two types of rechargeable hearing aids: battery-replaceable or rechargeable [35]. The choice is also determined by a person's habits, daily routine, and experience in operating other devices. Comparing both types of devices in retrospect in long-term use, the operating costs of hearing aids with replaceable batteries are higher due to the constant need to replace them. Therefore, according to the assigned diagnosis, patients needing a hearing aid for the rest of their lives or more than five years can choose from models of chargeable devices [34]. Therefore, the patients' noise sensitivity is a specific criterion according to which the needs, living conditions, and habits of the patient must be considered [35]. Audiologists should evaluate certain hearing aids in a 10-point system, which can also be expressed in quantitative form.

2.2.5. The sufficiency of functions amount

As society modernizes, people's needs increase, so hearing aids also modernize, expanding their range of functions. Some people need just a few features in their hearing aids, while others need more. When choosing a device, attention should be paid to the required number of functions (11 criterion). It is often believed that the more functions a device has, the better a person can hear [35]. Unfortunately, it's wrong to say so. The more functions in the device, the more natural the sound can be; without extraneous disturbances, the brain adapts faster and stimulates the active areas responsible for hearing. Hearing aids have features related to better sound transmission, such as connecting the device to a smartphone, wearing a period timer, using a GPS system, etc. [33]. To assess the adequacy of the number of functions, it is necessary to determine how many and which functions are needed for a person [35]. They are divided into some technological levels to make it easier for a person to choose a hearing aid based on the number of functions. The higher the level, the greater the number of functions in the device. Usually, for a person to hear sound, it is enough to choose a device with 1–2 technological levels [33]. Devices of this level often do not have a noise and wind suppression system; such devices are perfect for people living in quiet environments. Level 3–4 devices are the most often chosen by people and have sound smoothing, noise reduction, whistling, and high-resolution music programs. These devices are suitable for young or, in other words, people with an active lifestyle. The highest-level devices have all the features that are only several times better than the 3–4-level hearing aids and have a lot of additional functions related to sound. Devices with this level not only provide completely natural sound and process an endless variety of sounds but also can track the patient's hearing condition by connecting it to a smartphone, computer, etc. [36]. However, although the freedom to choose the technological level can be given to the patient, the main functions of the hearing aid and their strength are determined by a medical specialist after performing an audiogram [35]. Medical specialists assess the sufficiency of the number of functions of the evaluated devices in a 10-point system.

2.2.6. Compliance with the degree of hearing loss

The most common cause of hearing disorders is the weakening of the sensory cells in the inner ear [37]. Neurosensory cell hearing loss often occurs as a person ages, is exposed to too much noise for too long, or is caused by heredity or disease. The damage is usually irreversible, and choosing the right hearing aid is the

most effective measure [32]. When choosing a hearing aid, attention is always paid to the degree of impairment (12 criteria), which is determined by the audiogram data of the stronger ear in terms of audibility [32]. Normal hearing, according to the World Health Organization's classification of hearing impairment when, is hearing from 0 to 25 dB [37]. With impaired hearing, only the loudest sounds are heard, i.e., if heard in the audiogram above 90 dB, it is diagnosed that the person is completely deaf [35]. According to this criterion, the doctor must evaluate each patient individually. When hearing specialist audiologists) programs hearing aids, they use hearing configuration as a guideline for making sure devices are designed for specific hearing needs. With the help of smart technologies, the hearing aid is selected that is suitable only for that patient, one that can eliminate the specific causes of an individual's hearing impairment, taking into account the degree of hearing impairment [36] and the nature of the impairment [33,38].

Each hearing impairment is different, so using the proposed solution system will help to select a hearing aid according to each person's needs [3,36,38]. It has already been mentioned that choosing a hearing aid is a multi-criteria task, and the application of the support system must be straightforward to the person choosing the hearing aid and the doctor prescribing it. Applying a multi-criteria evaluation system helps select the best of many evaluated objects, rank them according to suitability for performing functions, rank from the best to the worst, and determine the main features of a certain evaluated object [3,18]. According to the information provided earlier, it is clear that the significance of the discussed criteria is not the same; when choosing a hearing aid in actual conditions, the significance of the criteria is even different. Therefore, determining the significance of the criteria is the first mathematical task in multi-criteria evaluation [19,21,39].

2.3. Multi-criteria assessment of the hearing aids suitability

Subjective or objective evaluations can be used to determine the significance of the criteria. Baran and Zak [40] state that subjective assessment is usually used to determine the significance of criteria in practice, i.e., when the significance of the criteria is determined by professionals in the required field - experts and mathematical-statistical methods are used to perform the calculations. It has already been mentioned that the significance of the general criteria must be determined by the person choosing the hearing aid in consultation with the medical staff (treating doctor) and maintenance specialists.

Experts must provide their opinion on the significance of each criterion. Therefore, to make the assessment more straightforward, a 100-point scale is proposed for the experts to distribute for all criteria, and cumulative estimates are calculated. as follows [19,41]:

$$W_i = \sum_{k=1}^n W_{ik} \quad (1)$$

where W_{ik} is an estimate of the i th criterion by the k th expert; n is the number of experts; W_i is the sum of I criterion estimates by every k th expert.

The significance of the criteria η_i is determined according to the classical formula of SAW multicriteria assessment [39,40]:

$$\eta_i = \frac{W_i}{\sum_{i=1}^m W_i} \quad (2)$$

where m - number of criteria.

The sum of the significances of the criteria will always be equal to one [19,39]:

$$\sum_{i=1}^m \eta_i = 1 \quad (3)$$

The significance of specific criteria has to be determined by the mentioned medical experts.

The following formula should be applied for the ranking of valued objects [19,40]:

$$g_{ij} = K_{ij} \eta_i \quad (4)$$

where is estimate of j hearing aid according to i criterion.

It is always more convenient to evaluate with qualitative indicators (scores), but in this case, only sufficiently highly qualified experts are required to participate [40].

Quantitative management usually presents the results calculated according to tabular formulas [19,41,42]. Also, calculating according to the proposed methodology, the hearing aids can be arranged, and this will allow to choose the obviously best hearing aid according to the current situation, the most suitable hearing aid for the patient, which best meets both the patient's personal needs and the best treatment of the consequences of the illness according to the diagnosis. Another, perhaps the greatest, feature of the proposed decision support system application is that the quantitative processing of the results provided for in this decision support system makes it possible to adapt them in the environment of modern information technologies and thus facilitate the decision not only for the doctor prescribing the device but to draw attention to the person choosing the hearing device, wishes, opportunities and lifestyle. In this case, the final decision remains with the doctor who prescribes the hearing aid to the patient. The significance values of the specific criteria may be repeated if the persons who need a hearing aid are of a similar age and with the same diagnosis, so it can also not be recalculated in each case. In the computer program, constant values are entered, which the doctor can manipulate depending on the properties mentioned above of the patients. This feature of our suggested methodology dramatically speeds up the hearing aid selection process. The proportions between specific (audiological) and general (non-audiological) criteria can be manipulated depending on the situation. Although audiologists always try to give greater importance to specific criteria, we recommend giving at least 10% to general criteria to achieve patient participation in the choice (social effect) and better satisfaction.

Some patients prescribed a hearing aid require repeated visits to the doctor-otolaryngologist for some reason. They have to register with doctors and only then get a request to complete the form about the quality of hearing aids via mobile. They receive a link to the system on their mobile phone via SMS or email. This is how the system works automatically. By interviewing them about complaints about hearing aid fit, it is possible to judge the effectiveness of our newly applied, now used, intelligent decision support system. However, there is still much room for improvement. This means that information to the system comes from patients and experts (medical personnel). The system works very simply; it is controlled by voice. This reduces the labor costs of experts in selecting a hearing aid. All experts must at least once express their opinion about all hearing aids, depending on the patient's diagnosis, age, etc. Experts do it online and complete data in our system according to the patient's diagnosis. The system remembers each expert's opinion and applies it to other patients with the same diagnosis and according to other indicators. Experts were requested to work harder at the beginning of system exploitation to increase the amount of information in the system because the more information the system has, the more accurately it can choose a hearing aid. The system not only selects the best hearing aid but also instantly connects with the manufacturer of the selected hearing aid, which sends a commercial offer with the conditions for acquiring the hearing aid. Thus, the patient can either receive a state-reimbursed device or pay according to a commercial offer for a better-fitting hearing aid. The majority choose the second option.

We believe that if the patients are satisfied with the quality of the hearing aid and its performance, then the system we apply works well. The survey was also conducted online, where patients answered only questions about the quality of the prescribed hearing aid. Since the survey is very short, voluntary, and anonymous, a sufficient number of responses can be collected.

We were concerned with only one question: can the application of our proposed system help increase the degree of patient satisfaction? It has already been mentioned that, on average, 80% of patients are satisfied with the performance of hearing aids. We have also included a social factor in selecting a hearing aid, hoping for a better result. Although it was not necessary in principle, the VDU ethics commission issued permit No 2022/3331, which allowed us to continue expanding research. Therefore, many healthcare facilities ask patients about service quality without permission after the visit because permission for anonymous surveys is simply unnecessary according to the Lithuanian Data Protection Law.

3. Results

We suggest the methodology as an intelligent decision-support system for increasing the effectiveness and supplementing the existing methodological potential of hearing aid selection. In this chapter, we would only like to show in real life how our created intelligent decision-support system of hearing aid selection works in

practice and the results of its use in actual conditions. An information technology specialist developed a computer program that helps to focus the calculations into a system that allows objectively selecting the most suitable hearing aid in the current conditions.

To illustrate an example of IDSS use, we chose a patient over 60 years of age who was possibly diagnosed with hearing loss due to a ruptured eardrum resulting in recurrent ear infections. These complications compromised the internal structures of the ear. The use of a hearing aid was recommended to improve hearing function. Five experts from a medical institution and a patient who needed to choose a hearing aid participated in determining the significance of the criteria. Each expert had to distribute 100% to each criterion according to their significance. The results are presented in Table 1. The results of calculations in Table 1 are performed according to the formulas (1, 2, and 3) provided in the text.

Experts with extensive professional experience participated in the assessment: an otolaryngologist-audiologist with 15 years of work experience in the ear, nose, and throat department E1; an otolaryngologist-audiologist with 8 years of work experience in the ear, nose, and throat department E2; nurse-administrator of the same department with 20 years of work experience E3; Philips hearing aid medical technician who also works with hearing aids from other brands, E4; health care facility maintenance engineer E5; patient receiving a hearing aid, E6. Since the disease in the case under consideration was completely clear, the opportunity was used to adjust the significance of the criteria, and the experts decided to assign a higher significance of 60% to the specific criteria, leaving the significance value of 40% to the general criteria.

Therefore, the final significance of the criteria had to be specified and recalculated. The results are also presented in Table 1. They were calculated using formulas 1, 2, and 3. To explain the content of IDSS, we have chosen only five different types of hearing aids.

Audicus, Phonak, Signia, and Widex are the most accessible brands of hearing aids in Lithuania due to the possibility of representative offices and technical maintenance. Therefore, they are the most popular and perform different functions, and we have included manufacturers in our system. For comparison, we chose Styletto Connect, V-185, Silk Nx, Siemens Ha Teneo S+, and Phonak Naida Marvel hearing aids.

The results of 6 experts' eligibility assessments of hearing aids according to every criterion and results of calculations are presented in Table 2. Hearing aids are rated on a 10-point system. The selected hearing aid is the best of all evaluated; the suitability of the hearing aid chosen was recognized by the patient immediately after its testing and during other preventive medical consultations.

An otolaryngologist who is well acquainted with the opinions of other experts (especially technical staff) and thus has gained experience in applying the intelligent support system of hearing aids can provide evaluations according to specific criteria independently, therefore saving time for the device selection. In this case, it was evaluated by score, so there was no reason to normalize the dimensions. The calculations were made according to the formula 4. Information from Table 1 was also used in the calculation results of Table 2.

Table 1. Determination of the criteria significance according to six experts.

Criteria	Evaluation by experts						In total:	The primary significance of the criteria η_i	The adjusted significance of the criteria was recalculated
	E1	E2	E3	E4	E5	E6			
General η_{Gi}									$\eta_{Gi} = \eta_i \times 0,4$
1.	30	25	32	30	30	40	187	0.31	0.124
2.	25	30	20	30	20	35	160	0.27	0.108
3.	25	20	20	20	30	20	135	0.222	0.089
4.	10	5	10	10	10	2	47	0.08	0.032
5.	5	10	10	5	5	2	37	0.062	0.025
6.	5	10	8	5	5	1	34	0.056	0.022
In total:	100	100	100	100	100	100	600	1	0.4
Specific η_{Si}									$\eta_{Si} = \eta_i \times 0,6$
7.	30	25	35	28	30	30	178	0.297	0.178
8.	15	10	10	10	15	10	70	0.12	0.072
9.	10	12	10	15	10	10	67	0.11	0.066
10.	5	10	10	10	10	13	58	0.096	0.058
11.	10	13	10	10	10	10	63	0.105	0.063
12.	30	30	25	27	25	27	164	0.272	0.163
	100	100	100	100	100	100	600	1	0.6

Table 2. Results of the hearing aid assessment.

Criteria	1 j_1	2 j_2	3 j_3	4 j_4	5 j_5	6 j_6	7 j_7	8 j_8	9 j_9	10 j_{10}	11 j_{11}	12 j_{12}	Rank
	Significance η_1	Significance η_2	Significance η_3	Significance η_4	Significance η_5	Significance η_6	Significance η_7	Significance η_8	Significance η_9	Significance η_{10}	Significance η_{11}	Significance η_{12}	
Hearing aids	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$K_{ij}\eta_i$	$\sum_{j=1}^{12} K_{ij}\eta_j$
1. Styletto Connect	0.124	0.11	0.09	0.032	0.025	0.022	0.178	0.072	0.066	0.058	0.063	0.16	
	8,8,9 8,8,9	7,6,6 7,8,8	8,8,9 8,8,8	7,7,8 8,6,7	8,8,7 8,8,9	7,7,8 8,7,8	8,8,9 8,8,8	6,7,7 7,7,7	8,8,8 8,8,8	7,7,7 6,7,8	9,8,8 8,8,9	9,9,9 9,9,9	48,82
2. V-185	6,6,6 7,7,6	4,7 8,6,7	7,7,7 7,7,7	7,7,6 7,7,6	7,7,6 7,7,7	7,7,7 6,6,5	8,7,8 7,7,7	6,6,6 7,6,6	7,6,7 7,7,7	7,6,6 7,6,7	8,8,8 8,7,7	7,8,7 8,8,7	41,79
	50	52	49	43	48	45	49	41	48	42	50	54	
3. Silk Nx	7,7,7 8,7,7	5,3 8,8,8	8,8,7 8,8,7	7,7,7 7,7,8	7,7,7 7,8,8	7,7,8 7,7,7	8,8,8 8,7,8	7,7,7 6,6,7	7,7,7 7,7,7	7,7,6 7,7,7	8,8,8 8,8,8	9,9,9 9,8,9	45,47
	43	44	46	43	44	43	47	40	42	41	48	53	
4. Siemens Ha Teneo S+	6,7,7 7,6,6	7,7,8 8,7,6	7,7,7 7,7,6	7,7,7 7,7,6	7,7,6 7,7,7	7,7,6 6,6,6	8,8,8 7,7,7	6,7,6 8,6,6	7,7,7 7,7,7	7,6,6 6,7,6	8,8,8 8,7,6	8,7,7 8,7,7	42,33
	39	43	41	41	41	38	45	39	42	38	45	44	
5. Phonak Naida Marvel	7,7,7 7,8,7	5,3 6,6,6	6,6,7 5,6,6	7,6,5 6,6,6	7,6,7 6,6,6	9,8,9 8,8,9	7,7,7 6,6,6	6,6,6 6,6,5	6,7,6 6,6,6	6,6,6 6,5,5	6,6,7 6,5,7	7,7,7 6,6,6	38,08
	43	36	36	36	38	51	39	35	37	34	37	39	

The same experts participated in the final assessment. Depending on the nature of the disease, evaluation based on specific criteria can also be unified, thus saving time in the process of selecting a hearing aid. According to Formula 4, the best hearing aid was evaluated and selected.

The evaluation results showed that the Styletto Connect hearing aid is the most suitable for the mentioned patient. At the beginning of 2023, our system had information only of 5 manufacturers' of hearing aids. Therefore, our case analysis is based on such an example. There is already information from 14 manufacturers, and we plan to increase this number continuously with the possibility of using 5G Internet. Lithuania has the fastest in the world, 5G (even 6G) internet population has access everywhere and is favored to use online devices. Almost all service providers ask about the quality of their services.

Based on this intellectual support system applied at Kaunas University Hospital Polyclinic, the computer program allows the normalization of different indicators and the final evaluation result on selecting the most suitable hearing aid. Implementation of our new decision on the choice of hearing aid has not only made the process faster but also become more objective. In 2023, when applying the proposed system, hearing aids were fitted to 6696 patients, of whom 396 had to repeatedly visit the LSMU hospital polyclinic to check the treatment situation. The patient survey could show the results of our system application. The survey was entirely anonymous; it asked only about the quality of the prescribed hearing aid and nothing about any treatment. Only the result of the study about patients' satisfaction was of interest to us. All 9 audiologists of the polyclinic provided the results of the study. We had the opportunity to interview all these repeated patients by mobile. We received answers from 360 patients. Even 331 patients (92%) who visited the polyclinic once more did not comment on the selection of hearing aids. Their answer was "very satisfied" or "satisfied." These results show that our system works well. We have achieved the desired goal because our result is higher than the average of satisfied patients mentioned.

Patients aged 60 and older were the most likely to answer this way (85% of the respondents); 10% were 50–60, 4% were 40–50, and only 1% were younger than 40. A few patients (25) only needed to adjust the hearing aid and were satisfied with the selection. According to our system, only four patients expressed a desire to choose a hearing aid again, but after receiving the same results, these patients were also satisfied.

This distribution of patients by age corresponds to the total ratio of all patients applying to the Kaunas University Polyclinic for hearing impairment. However, the age ratio of the patients did not concern us at all. Most importantly, our system's implementation has generally improved the number of satisfied patients! The results showed that we are working in the right direction, although we still have many ideas for further improvement of the achieved results.

4. Discussion

It should be noted that there is not much scientific literature on using intelligent decision support systems to select hearing aids. Only Anwar with Oakes tried to use the Naïve Bayesian analysis results for hearing aid selection [13]. However, the Naïve Bayesian analysis can only represent simple distributions and give probabilistic estimations. The mentioned authors assessed only two types of hearing aids (ITE or BTE) to find which is better in certain situations. However, comparing more objects can make the overall result more objective [11,14]. Amlani et al. [14] also offered an interesting solution to the choice of hearing aids. They developed an artificial intelligence system to select the right hearing aid based on the patient's articulation index. We found that only one (or two) criteria are not enough for objective assessment. Other researchers also agree with this point of view [7,11,12]. Most types of artificial intelligence were consistently used for specific purposes, such as logistic regression and other statistical machine learning tools (e.g., support vector machine, multilayer perceptron, random forest, deep belief network, decision tree, k-nearest neighbor, or LASSO) for automated audiometry and clinical predictions; convolutional neural networks for radiological image analysis; and large language models for automatic generation of diagnostic reports [43]. Artificial intelligence is increasingly being integrated into medical diagnostics, offering promising enhancements in accuracy and efficiency [12,13]. So, artificial intelligence can also be used to diagnose hearing diseases [13]. Still, we describe the current situation in the field of hearing aid selection as follows: there is an unquestionable need to increase the validity and practicality of decisions when choosing appropriate hearing aids in healthcare institutions because the research field of decision support systems is characterized by the diverse of methods and models proposed by researchers and only episodic application of this methodological potential in practical activities. The inconsistency of

the situation encouraged the search for reasons why the relatively considerable methodological potential is not in demand in medical practice. Medical activity requires responsibility not only based on knowledge and clinical skills but also in managing a vast amount of information related to patient care [11]. Experts can consistently build a strong welfare policy through the appropriate treatment of information. IDSS suits many healthcare settings and users, including audiologists, nurses, and other medical staff [12,13]. Arguably, these are the most common ones: demanding required information management resources, the lack of healthcare sector workers' skills in the application of more complex, however objectively more suitable methods, too many relatively unproductively used resources, and lagging decision-making [9]. Some authors formulate this objection as the lack of a suitable support system for solutions to increasing requirements [10]. So, a tool proven in practice in many fields is used - the intelligent decision support system. Therefore, our proposals are purposefully based on the support from the decision.

Objectively choosing the most suitable hearing aid in the current conditions is possible only by assessing the situation from various aspects comprehensively and applying a set of criteria. The evaluation result may differ according to different criteria, so it does not allow one to line up the evaluated objects in a row after finding the best result in various aspects. Therefore, it is precisely the need for mutual comparison of hearing aids in various aspects that presupposes treating the search for this solution as a multi-criteria evaluation task. In addition, specific criteria may be refined, for example, by assessing the possibilities of adapting and manufacturing certain implants. This is really an important condition in some cases.

A further direction of our research is related to applying online search capabilities in the proposed intelligent decision support system for hearing aid selection. This provides a choice not from a limited number of hearing aid models distributed in a specific region but allows one to choose according to the most suitable parameters from all the world's manufacturers, who present the characteristics of their hearing aids on their websites. Thus, connecting our proposed intelligence decision support system to the internet greatly expanded the application possibilities and accelerated hearing aid selection. As a result of our approach, an intelligence system controlled by voice is created, which allows us to reduce the time of hearing aid selection to a minimum and ensure the suitability of the hearing aid and the objectivity of the selection. In the future, we will try to use the characteristics of at least 50–100 manufacturers' hearing aids in the system from the Internet. The system has to choose the best hearing aid with an instant response regarding the price, delivery terms, and other conditions. After patient confirmation on a mobile device, modern logistic capabilities allow delivery of parcels within 3–5 business days, even from another continent. Experience shows that such conditions satisfy patients, and the application of this system reduces the cost of selecting a hearing aid and ensures the objectivity of the selection. The limitation of our system is that there is a lot of communication with hearing aid manufacturers about the benefits of the system and connection order. Also, as a limitation of the system development, we initially saw the reluctance of doctors to fill in tables about patients because they saw it as an additional task.

Also, we hope to collect as much information as possible from more patients, giving the system a more accurate choice of a hearing aid and making doctors' work easier. When assessing hearing loss according to the proposed criteria, a hearing aid can also be selected for patients with asymmetric hearing loss. The methodology we have suggested can be used in any other area of medicine to select different objects, but some other corresponding criteria must be chosen.

In addition, the introduced social aspect of choosing a hearing aid was of great interest to representatives of the psychology field. They are interested in why and how the number of satisfied patients has improved. We have already started working with psychologists in this direction as well. Our suggested artificial intelligent support system is the first of its kind and has no analog. The proposed mathematical solutions have not been applied so far; moreover, the differentiation of criteria also expresses the superiority of the proposed system.

5. Conclusion

Today, hearing impairment is a significant global concern; a hearing aid is often the only option for addressing these impairments. Due to the numerous hearing aid manufacturers and the variety of modifications available, choosing the most suitable hearing aid that meets the nature of the impairment and the individual characteristics of the diagnosed person can be challenging. Our interdisciplinary efforts have led to creating and implementing an intelligent decision support system based on the multi-criteria evaluation. This mathematical

methodology enables us to organize the evaluated options effectively. Simultaneously, it allows for identifying the best option based on several criteria in the current context. According to the methodology presented in this article, hearing aids should be evaluated based on 12 reasonable criteria, categorized into two groups (general and specific). This differentiation of criteria marks a significant advancement in multi-criteria evaluation, enhancing our ability to meet patients' needs. The proposed methodology is adaptable, allowing adjustments to the significance of the differentiated groups of criteria according to the current situation, causes of illness, diagnosis, and treatment requirements. A practical example of applying the intelligent support system demonstrates its real-world application. The practical scenario validates the selection of the most suitable hearing aid through mathematical methods. Implementing the proposed intelligent decision support system streamlined the process of selecting a hearing aid, making it more objective and better addressing patients' needs. We have also observed that utilizing our proposed system has contributed to increased patient satisfaction. Currently, other clinics are expressing interest in joining our system, which would help ease the workload of audiologists.

Author contributions

RD, SV: contributions study supervision. DK, RD, SV, ED: conceptualization ideas. RD, SV, ED, GM, and AK: data collection. RD, SV, ED: methodology. RD, SV, ED: data analysis. GM, AK: visualization. VE, RD, SV, ED, GM, and AK: manuscript preparation. All authors contributed to the article and approved the submitted version. [Tables 1](#) and [2](#) express the opinions of the experts.

Institutional review board statement

The study was conducted by the Declaration of Helsinki and approved by the VDU ethics commission 2022-02-15 issued (permit No 2022/3331) for studies involving humans.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

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Data availability statement

All data generated or analyzed during this study are included in this published article.

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