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LINEAR ORDERING OF SELECTED GERONTECHNOLOGIES USING SELECTED MCGDM METHODS

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Abstract. For over last 20 years, significant changes have been observed in the age structure of the world's population. The percentage of working-age population is steadily decreasing all over the world, and a relative number of retired people is increasing. It confirms that our society is ageing. Moreover, according to the United Nations population forecast the situation will get worse. The increasing number of seniors is also connected with the need to provide them with institutional support in the form of care. One of the key elements of helping older adults may be gerontechnology – an interdisciplinary field of research that uses technology to implement the aspirations and abilities of seniors.

On the basis of a meticulous literature review, 9 groups of gerontechnology have been identified that have been rated with respect to 30 criteria. In the period December 2019 – January 2020 a representative sample of 1.152 Poles aged over 40 (acting as decision makers) took part in the research consisting of completing the prepared questionnaire. Based on selected Multiple Criteria Group Decision Making methods, linear ordering of gerontechnologies was prepared and the most preferred by respondents participating in the study was indicated.

Keywords: ageing population, gerontechnology selection, decision maker, Multiple Criteria Group Decision Making, SAW, TOPSIS.

JEL Classification: C44, O32, O33.

Introduction

For over the last 20 years, significant changes have been observed in the age structure of the world's population. The percentage of working-age population is steadily decreasing all over the world, and the relative number of retired people is increasing. As of 1 January 2000, the world population numbered 6,143,494,000, in 2010 it grew to 6,956,824,000, and in 2020 –

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up to 7,794,799,000 (United Nations, 2017). In 2000, the share of seniors (65+) was 6.87%, in 2010 – 7.57%, and in 2020 – 9.33% of the world population.

According to the United Nations population forecast (United Nations, 2017), in ten years about 12% of the world's total population and about 23% of the European population will be people over 65 years of age.

By 2050, the over-65s will have represented 15.9% of the world's population and 28.14% of Europe's society. In Poland, in turn, it is forecast that in 2050 people over 65 years of age will constitute as much as 31.13% of the population (Table 1). The median age of life in Poland in 2050 will be as much as 51.2 years.

Table 1. Population by age groups [%] (United Nations, 2017)

Year	2030		2040		2050	
Age	15–64	65+	15–64	65+	15–64	65+
World	64.71	11.67	63.76	14.14	62.97	15.91
Europe	62.08	22.97	59.96	25.87	57.27	28.14
Poland	62.83	23.22	61.59	25.84	55.99	31.13

Such predictions as to the age structure of the population pose difficult challenges for the Polish and European economies. The growing number of senior citizens is associated with the need to provide them with institutional support in the form of care and, in particular, a low level of independence. Attention is drawn to the need for health and digital education, the development of care services, the creation of safe and functional housing, or access to public transport. It is also necessary to develop technical solutions supporting the functioning of older people. However, this requires the recognition of knowledge coming from such areas as anthropotechnics (in the field of relations: man-computer), cognitive psychology, neuroscience, artificial intelligence, as well as IT, electrical and communication engineering. One of the key elements of helping older adults may be gerontechnology, which deals with the development of ways to facilitate access of older people to all goods, services and infrastructure.

Based on the literature review, it can be clearly stated that no comprehensive studies taking into account a broader research context can be found in the field of gerontechnology. According to the authors' knowledge, such research has not yet been undertaken, either in the Polish scientific literature or in foreign literature. Until now, concerns have been devoted primarily to individual technological solutions. The variety of needs and expectations of older people on the one hand and the variety of available technologies with very diverse functionalities on the other, require a holistic view of the problems of gerontechnology with an indication of those groups of technologies that can meet specific categories of the needs of their users. Therefore, it is necessary to analyses, assess – in terms of various criteria – several types of technologies that improve the quality of life of seniors. It is also necessary to rank these technology classes as well as select the gerontechnology group that meets the highest expectations of users.

The aim of the paper and its main contribution is to assess and rank the nine gerontechnology groups/classes identified on the basis of literature review, such as health (A_1), education (A_2), interpersonal communication (A_3), safety (A_4), mobility (A_5), care (A_6), leisure (A_7), housing (A_8), digital accessibility (A_9). The groups of gerontechnologies are evaluated taking into account various criteria regarding e.g. their functionality, usability and ease of use, competitiveness and innovation, social and ethical aspects. It is therefore important to identify those that are characterized by heterogeneity. So far, no research has been carried out to assess and select such gerontechnology types (Nazarko, 2017; Chodakowska & Nazarko, 2017). In this paper, these 9 groups of gerontechnology have been rated with respect to 30 criteria. Next, based on these questionnaires, a ranking of 9 groups of gerontechnology was prepared using selected Multiple Criteria Group Decision Making (MCGDM) methods and the most preferred by the respondents participating in the study was indicated.

The evaluation of technologies improving the quality of life of elderly people was conducted in Poland on the basis of a representative sample. The result of the survey may vary from country to country. Therefore, the gerontechnology ranking may be different in different countries. It should be emphasized that so far no research has been conducted in Poland or in the world concerning the evaluation of technologies improving the quality of life of elderly people in Poland using various criteria. Most often, gerontechnology users (people over 60 years old) evaluated one type of a specific technology in terms of acceptance. It is important that the article assesses 9 different groups of technologies improving the quality of life of elderly people in Poland according to 30 criteria. These criteria included innovation, demand for technology, improving the quality of life of elderly people, socio-ethical aspects, usability, functionality, ease of use and risk of use. A novelty was also the fact that in the article these technologies were evaluated both by current (people over 60 years old) and future users (people over 40 years old).

Another essential element of the article, apart from the evaluation of technologies improving the quality of life of elderly people in Poland, involves developing a ranking of these groups. In order to determine the ranking, the authors used selected Multiple Criteria Decision Making (MCDM) methods. The results of the research indicated which technologies are most desired by both current and future users. The results can be used both by the creators of technologies improving the quality of life of elderly people and future producers of these technologies.

Multiple Criteria Decision Making methods have become very popular in recent years and are frequently applied in many real-life situations (Kaplinski et al., 2019; Zavadskas & Turskis, 2011; Behzadian et al., 2012; Keršulienė & Turskis, 2014; Zavadskas et al., 2015a, 2015b, 2016). In the literature, the authors can find various MCDM methods, including AHP, SAW, TOPSIS, VIKOR, EDAS, MABAC, MAIRCA, ELECTRE, DEMATEL and so on (Hwang & Yoon, 1981; Opricovic & Tzeng, 2004; Ahmadi & Amin, 2019; Alikhani et al., 2019; Muravev & Mijic, 2020; Petrovic & Kankaras, 2020). The authors can say that due to the multitude of MCDM methods, indicating the appropriate method to solve a given problem is also an MCDM problem.

This paper incorporates TOPSIS method, i.e. Technique for Order Preference by Similarity to Ideal Solution, introduced in 1981 by Ching-Lai Hwang and Kwangsun Yoon. The authors chose this method because it is widely used to solve real-life problems. The original version of TOPSIS was based on a decision matrix built by a single decision maker (DM) or expert. Due to the increasing complexity of decision problems, they are more and more often analyzed by a group of decision makers or experts. The result is that MCDM problems have been extended to Multiple Criteria Group Decision Making, where the starting point are individual decision matrices built by each of the decision makers or experts.

Two different modifications of the TOPSIS method for Group Decision Making (GDM) were used to determine the linear ordering of gerontechnology and to identify the best one. The first group is based on aggregation operators of individual decision matrices, while the second modification does not require aggregation and was proposed by Kacprzak (2020).

The remaining part of the paper is organized as follows. Section 1 of the article provides definitions of gerontechnology in literature. This is followed by the selection of nine groups of gerontechnologies, based on a thorough review. These were further analysed and provided with corresponding examples of specific technologies improving the quality of life of elderly people. Section 2 of the article describes the research methodology (criteria for the evaluation of gerontechnology groups, techniques used in the study, the number of respondents and sample distribution). The rest of the article (Section 3) discusses the methods used to build rankings. Next, in Section 4, the above-mentioned methods are used in developing and comparing these rankings. Ultimately, the last Section presents conclusions and sets future research directions.

1. Literature review

Literature provides different definitions of gerontechnology (Table 2). Two approaches to gerontechnology can be distinguished: more general, broader, and more detailed with an emphasis on technology. In a broader sense, gerontechnology is an interdisciplinary field of research in which technology is oriented towards the aspirations and capabilities of older adults (definitions 1, 4 and 6 in Table 2). It is the science of technology and ageing that ensures good health, full participation in a society and independent living in the course of life (Halicka, 2019). The aim of gerontechnology is good health, full participation in a society and independent living until old age, regardless of the tools – be it research, development or design of products and services that improve the quality of life.

In a narrower sense, gerontechnology refers to a technology that meets the needs of an ageing society (definitions 2, 3, 5, 7 and 8 in Table 2). It means technologies that facilitate access for older people to all goods, services, and infrastructure, and meet the ambitions and needs of seniors. The authors of this article have adopted the latter approach to research and define gerontechnologies as technologies that improve the quality of life of older people, facilitating access for older people to all goods, services and infrastructure.

Gerontechnology is a very dynamically developing discipline. This is reflected in a constantly growing number of publications in this area. Over the past 30 years, 467 publications indexed in the Scopus database for "gerontechnology" have been issued. The first publications in this field appeared in 1992. Until 2010, no more than 20 related articles were published annually. Only since 2011 has the interest in gerontechnology increased, reflected in the number of publications in the Scopus database. Most publications (92) were published in 2018.

The authors of this article have analysed all publications found in the Scopus database. They noticed that in the world literature about research on gerontechnologies, the authors focus on such areas as (1) *health*, (2) *education*, (3) *interpersonal communication*, (4) *safety*,

Table 2. Definition of gerontechnology

No.	Source	Gerontechnology is ...
1	Bouma, 1992	a research area focusing on developing technologies to improve the lives of older people.
2	Sale, 2018	assistive technologies in the field of health and social affairs that can help older people identify and slow down the effects associated with age and with the modification of nervous and musculoskeletal systems.
3	Jansson & Kupiainen, 2017	technology that allows research and development of devices, services, and environments that can support older people and prevent functional impairment caused by ageing.
4	Graafmans et al., 1998	the science of technology and ageing to improve the daily lives of older people.
5	Ross et al., 2018	implementing successful ageing and helping older adults with housing, communication, health, safety, comfort, mobility as well as leisure and work.
6	Millán-Calenti & Maseda, 2011	an interdisciplinary field of research and applications including gerontology and technology; using technology to prevent, delay, or compensate for perceptual, cognitive, and physical ageing.
7	McWhorter et al., 2020	information and communication technologies, as well as technologies to facilitate and increase the participation of older people in everyday life.
8	Bronswijk et al., 2009	technologies that combine existing and evolving technologies that meet the aspirations and needs of older people.

(5) *mobility*, (6) *care*, (7) *leisure*, (8) *housing*, (9) *digital accessibility*. In further studies, the authors treat these areas as gerontechnology groups/classes.

Examples of technologies in the *health* area are: a video chat with a doctor, mHealth, mobile applications, an electronic drug dispenser, or a telemedicine band. Alvarez et al. (2020) developed software to prevent delirium in hospitalized older adults. In turn, Karaca Şalgamcıoğlu (2020) presented examples of mobile applications on the phone enabling monitoring the health conditions of older adults. Dhillon et al. (2016), in turn, presented the possibility of using HMS (Health Management System) online systems by means of a prototype of such a system, evaluated by potential users – older adults. Still, Lebron et al. (2015) presented a wireless device for tracking the activity of older adults. Based on data on body weight and blood pressure as well as undertaken daily activities, burned calories and traveling distances, the system assessed the health and fitness of the user of such technology. Chen et al. (2011) presented Care Delivery Frame (CDF). CDR is a device that combines two different functions: a home telehealth system and an information channel for older people who have problems with using computers and the Internet.

In the area of *education*, examples of gerontechnology include online courses for seniors and learning through various platforms. Lipphardt et al. (2018) presented four e-learning programs on ICT, culture, mentoring, and well-being of older people. In their publication, the authors discussed the results of research on the possibilities of learning by older people with the use of ICT. The results indicate that older people are very good at various aspects of e-learning and benefit from the functionality and benefits of the software. The conducted research proved the high usefulness of e-learning for older adults and their potential in the field of digital integration.

Among technologies improving the quality of life of older people in the area of *interpersonal communication*, there are smartphones or Facebook for seniors that are simplified in use. Dinh and Brown (2019) presented communication technology usage among older adults with aphasia. The aim of the research conducted by Kaufman et al. (2018) was to identify associations of demographic characteristics and game use patterns with socioemotional and cognitive benefits of digital gameplay perceived by older adults. This game aimed to develop and maintain interpersonal contacts. Older people met new people while playing, established contacts, talked to each other, exchanged observations, etc. In turn, Lee et al. (2015) presented a project of a digital inbox connected to a mobile application. This device enables easier communication between older adults and their family members. In their work, Gobeil et al. (2019) presented the AMELIS interactive calendar installed on the patient's and caregiver's phone, which can be useful in the care of people with Alzheimer's disease. The calendar helps in organizing daily life through an emotional virtual agent. A virtual agent can be created according to one's preferences (appearance, expressiveness, environment, role, etc.), which makes interaction with it natural for older adults.

Gerontechnology in the field of *safety* may include, among other things, senior monitoring systems and notifying the family/services. Galambos et al. (2019) proposed intelligent sensors used at home to improve the safety of older adults. In turn, Marcelino et al. (2015) presented the eServices platform. It is a platform enabling care for older adults. It was designed to combine several services aimed to meet the needs of older people. This platform monitors basic vital signs, environmental variables and uses personal location technology. In addition to sensor-based services, the eServices solution includes digital services tailored to emotional and social needs. One of the main features of e-Services is detecting threat situations and taking appropriate actions. It also collects data from sensors, location procedures, and interactions between seniors and services provided to detect behavioral deviations with an aim to act preventively. The results of the experiments showed that the proposed platform was well received and is easy to use by seniors.

Gerontechnologies in the *mobility* area make it easier for older adults to move around. Among other things, there are strollers, scooters, mobility devices, and exoskeletons. Piezzo and Suzuki (2017) introduced the Pepper robot, which is used, for instance, to motivate older people to walk, and assists older people in walking. Hsu et al. (2010) and Gomi and Griffith (1998) presented smart wheelchairs. Further examples of technologies facilitating total or partial movement of older people are artificial limbs (Bhattacharyya et al., 2014), lifting and walking robots, robotic beds (Choi et al., 2014), active orthose (Yan et al., 2015) and exoskeletons (Kazerooni, 2005).

Among gerontechnologies in the *care* area, there are robots taking care of seniors (Ejdys & Halicka, 2018) and telecare. Robots such as Wakamaru and Twenty-One can be used to provide care for older people. Wakamaru can "take care" of older people, e.g., it can remind them of unrealized tasks (e.g., taking medicines) as well as checking information about the current weather forecast. Wakamaru can read news and emails. This robot maintains eye contact with the senior and when he has nothing to do, he buzzes around the house, "watches" television with the household members. Twenty-One can have limited conversations with older people. He can talk, bring a meal, give clothes or a walking stick. Twenty-One can help older people to get up from a chair or bed. In turn, Mahoney (2004) presented a remote monitoring system enabling care for older adults. Worker Interactive Networking (WIN) provides online status reports and e-mail/pager alerts in the event of exceeded customized parameters. Signals from motion sensors are sent to a transponder, which, via wireless cellular communication, is sent to the project server, thus not interfering with the use of the older person's phone.

Examples of technologies that improve the quality of life of older adults in the *leisure* area are, among others, virtual travel, special electronic books and games. Dilara, Hernandez, and Astell (2018) presented touch-screen applications enabling seniors to be entertained, reading a newspaper, browsing online resources, reminding of tasks/setting reminders. Kaufman et al. (2018) showed that recreational activities such as digital games help in the aspect of social and cognitive well-being of older people. Digital Storytelling for people suffering from dementia allows for self-expression, positive communication and social contact. Sayago et al. (2016) presented the conceptualization, design and evaluation of video games that are sufficiently attractive, easy to play, and meaningful for older people. To facilitate the development of these games, they designed and evaluated a platform for the creation of online games that enabled 99 older people of different cultural backgrounds to create, play, and contribute to games. Mc Carthy et al. (2007) presented a project for a mobile application resembling an ageing application called MemoryLane. Robots such as Paro or Unazuki Kabochan can also be used to improve the mood of older people. Paro is seal-shaped, soft to touch, reacts to touch, light, temperature, and sound, can build short sentences, and sing (Shibata & Wada, 2011). Unazuki Kabochan looks like a 3-year-old boy from a "cartoon". He provides relaxation for seniors through communication. He is capable of speaking, singing, and moving lightly in response to the touch and spoken words of the owner.

Gerontechnology in the *housing* area should include all technologies that facilitate everyday functioning at home. Namanee and Tuaycharoen (2019) investigated the effect of color lighting in the bedroom on the comfort of living of older people. However, the purpose of the research conducted by Arthanat et al. (2019) was to examine the ownership of SH technology by older adults, their readiness to adopt Smart Home technology, and identify client factors relating to its adoption. In contrast, Rahmawati and Jiang's paper (2019) presents guidelines for the design of older adults' bedrooms. When assessing the designed bedrooms, the following factors were taken into account: independent, requiring a cane, and requiring a wheelchair.

Typical gerontechnologies in the area of *digital* accessibility include an on-screen keyboard dedicated to older people and speech recognition programs. Ettore et al. (2016) presented and subsequently assessed mobile user interfaces for seniors. In turn, Charness et al. (2016) discussed mobile interfaces for older adults. They proposed a SIG project aimed at mapping the current state of affairs, and then built a community of experts from related fields and raising awareness in the community. Jenko et al. (2007) presented a user-oriented approach to multimedia convergence UI, best suiting older adults and the disabled. The proposed solution combines multimedia services provided via digital interactive television via the Internet protocol, with digital text or photo enlargement. UI, as one of the most important features of telecommunications equipment evaluated from the user's point of view, is to be simple, user-friendly, easy to use, ergonomic, etc.

The conducted literature studies indicate that gerontechnology research is dominated by a focus on specific individual technological solutions. Only Woolrych et al. (2018) integrated gerontechnologies in different areas into their research. The researchers analysed the intentions of older people with respect to the use of six different new technologies (e.g., autonomous vehicles, support robots and smart home technologies) that could enable seniors to better manage their health and remain independent. The data was collected on a representative sample of technologically advanced Internet users in the US, aged 65 and over. Conforming to the survey, 19% of seniors were willing to use autonomous vehicles, 24% expressed a desire to use auxiliary robots, while 37% of respondents were willing to use devices connected to the home. In contrast, 48% of seniors were inclined to use home surveillance cameras with an internet connection, 29% were inclined to use a smart home with a built-in personal digital assistant, and 15% were inclined to use virtual reality. According to the authors, the most promising clinical applications of the technologies are: (1) housing and safety to guarantee older people stay in their own homes, (2) mobility and rehabilitation to improve mobility and gait, and (3) communication and quality of life by reducing isolation, improving management of medications and transportation. However, the study does not present any research or opinions of future users. The conclusions were developed based on a review of the possibilities of selected technologies (Halicka, 2020; Nazarko, 2016).

2. Methodology of research

Based on the literature review, seven groups of gerontechnology evaluation criteria were identified (Nazarko et al., 2017): (1) innovation, (2) demand, (3) socio-ethical aspects, (4) usability, (5) functionality, (6) ease of use and (7) risk of use. The criteria were developed in the form of questions. The criteria catalogue prepared by the authors consisted of 30 questions. Five questions in each category concerned the aspects of innovation (I1–5) and demand for gerontechnologies (D1–D5), the next four questions concerned socio-ethical aspects (S1–S4) and the risk of use (R1–R4). Three questions were related to usability (U1–U3) and ease of use (E1–E3) and six questions were related to functionality (F1–F6). The list of criteria used for the assessment of gerontechnologies is presented in Table 3.

To assess gerontechnology, a survey was conducted. Taking into account the level of ICT adaptation by the surveyed groups of respondents, 2 research techniques were used: CAWI (Computer-Assisted Web Interview) and CATI (Computer-Assisted Telephone Interviewing). The questionnaire briefly describes the gerontechnology groups/classes assessed by the respondents and gives several examples of specific gerontechnologies for each group. The study involved people over 40 years of age. The selection of people at the indicated age is related to the fact that gerontechnology issues concern these people at present in the context of their parents' use of gerontechnology, whereas in the perspective of the next 20–30 years they will be potential users of such technologies. The research was conducted at the beginning of 2020, a representative sample Poles (as of January 2020 – 19,658,976 people, confidence interval 0.95 and measurement error 5%). The survey was distributed with the use of social media and snowball sampling techniques. In the sample structure, 26.3% (303 persons) were people aged 40–49, 28.6% (329 respondents) people aged 50–59, and 45.1% (520 persons) over 60.

Table 3. Catalogue of technology assessment criteria

Acr.	Name of criterion
INNOVATION	
I1	To what extent is the use of this group of gerontechnologies for elderly care an innovative solution that is in demand?
I2	To what extent will the application of this group of gerontechnologies in elderly care significantly improve the quality of the existing care system?
I3	To what extent is the use of this group of gerontechnologies for elderly care a worldwide breakthrough?
I4	To what extent is the use of this group of gerontechnologies for elderly care a breakthrough solution on a global scale?
I5	To what extent can the use of this group of gerontechnologies for elderly care significantly improve the comfort of life of older people?
DEMAND FOR GERONTECHNOLOGY	
D1	To what extent is there a demand of older people for gerontechnologies from this group?
D2	To what extent is there a demand of family members for gerontechnologies from this group to support elderly care?
D3	To what extent is there a global demand for this group of gerontechnologies for elderly care linked to a temporary fashion?
D4	To what extent will the use of this group of gerontechnologies for elderly care not require new expertise?
D5	To what extent will the appearance of this group of gerontechnologies be relevant to the scale of their use in everyday life?
SOCIO-ETHICAL	
SE1	To what extent will the widespread use of this group of gerontechnologies in elderly care bring about measurable social benefits?
SE2	To what extent will the widespread use of gerontechnologies for elderly care create new jobs?
SE3	To what extent will the widespread use of these gerontechnologies in elderly care bring about measurable benefits for human health and quality of life?
SE4	To what extent can the widespread use of gerontechnologies in elderly care be a source of social problems?
USABILITY	
U1	To what extent will the use of gerontechnologies in this group improve the quality of elderly care services?
U2	To what extent will the use of these gerontechnologies for elderly care improve safety for older people?
U3	To what extent will the use of these gerontechnologies for elderly care contribute to spending time pleasantly and enjoyably?
FUNCTIONALITY	
F1	To what extent do gerontechnologies in this group mean that older people will not have to do heavy work?
F2	To what extent will the functionality of gerontechnologies in this group enable interaction with others?
F3	To what extent will the functionality of this group of gerontechnologies enable older people to inform their loved ones about their health?

End of Table 3

Acr.	Name of criterion
F4	To what extent will the functionality of gerontechnologies in this group enable older people to call for help?
F5	To what extent will the functionality of this group of gerontechnologies make it easier and more efficient for older people to move around?
F6	To what extent will the use of these gerontechnologies improve the daily functioning of older people?
EASE OF USE	
E1	To what extent does the use of this group of gerontechnologies require breaking down mental barriers?
E2	To what extent should the use of these gerontechnologies be easy and intuitive?
E3	To what extent would you find it difficult to learn to use this group of gerontechnologies?
RISK OF USE	
R1	To what extent can the use of this group of gerontechnologies for elderly care be a source of danger?
R2	To what extent can the use of this group of gerontechnologies for elderly care expose users to loss of health or life?
R3	To what extent can this group of gerontechnologies pose risks to human relationships?
R4	To what extent would you be able to trust gerontechnologies in this group?

45.7% (527 persons) of the respondents were men and 54.3% (625 persons) women. More than half of the questionnaires – 58.3% are supervised by older people. The respondents of each technology group/class assessed the following criteria using a 9-stage scale, where 1 meant strongly disagreeing, 9 – strongly agreeing.

3. Preliminaries

This section briefly presents the classical TOPSIS method and its selected extensions for GDM, used in numerical analyses for ranking gerontechnologies. Moreover, it presents the entropy method for determining objective criteria weights.

Assuming that the we have set of m alternatives $\{A_i : i = 1,\ldots,m\}$ (i.e., gerontechnologies in subject analyses) and set of n criteria $\{C_j : j = 1,\ldots,n\}$ and decision maker or expert creates decision matrix, as follows:

$$X = \left[x_{ij}\right]_{m\times n} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{array}, \tag{1}$$

where x_{ij} denotes her/his evaluation of the alternative A_i due to the criterion C_j. Moreover, let

$$w = \left(w_1, w_2, \ldots, w_n\right) \tag{2}$$

be the weight vector of criteria, where $w_j \in \mathbb{R}^+$ and $w_1 + w_2 + \ldots + w_n = 1$.

3.1. Classical TOPSIS method

The TOPSIS method was introduced in 1981 by Ching-Lai Hwang and Kwangsun Yoon. Mathematically, the calculation steps of TOPSIS are characterized as follows.

Step 1: Construction the decision matrix $X = \left[x_{ij} \right]_{m \times n}$ in the formula (1) and the vector of criteria weights w in the formula (2).

Step 2: Calculation the normalized decision matrix $Z = \left[z_{ij} \right]_{m \times n}$ with the use of vector normalization as follows:

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}. \tag{3}$$

Step 3: Calculation the weighted normalized matrix:

$$V = \left[v_{ij} \right]_{m \times n}, \tag{4}$$

where $v_{ij} = z_{ij} \cdot w_j$.

Step 4: Determination the ideal solution A^+ in the formula:

$$A^+ = \left(v_1^+, v_2^+, \ldots, v_n^+ \right) = \left\{ \left(\max_i v_{ij} \mid j \in B \right), \left(\min_i v_{ij} \mid j \in C \right) \right\} \tag{5}$$

and the negative ideal solution A^- in the formula:

$$A^- = \left(v_1^-, v_2^-, \ldots, v_n^- \right) = \left\{ \left(\min_i v_{ij} \mid j \in B \right), \left(\max_i v_{ij} \mid j \in C \right) \right\}, \tag{6}$$

where A and C denote the sets of benefit and cost criteria, respectively.

Step 5: Calculation separation measure of each alternative A_i from the A^+:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+ \right)^2} \tag{7}$$

and from the A^-:

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2}. \tag{8}$$

Step 6: Calculation the relative closeness of each alternative A_i from the A^+:

$$RC\left(A_i \right) = \frac{d_i^-}{d_i^+ + d_i^-}. \tag{9}$$

Step 7: Ranking of alternatives using the value of $RC(A_i)$. Bigger $RC(A_i)$ reflects that the alternative A_i is better.

3.2. Objective weights of criteria using entropy method

In most applications of MCDM methods in real-life situations, only subjective criteria weights provided by the DM or experts are used. However, there exist situations, as in our research, when it can be difficult to determine the weights of particular criteria. In such cases the authors can use equal weights or calculate objective weights. The entropy method is one of the methods of determining objective weights. Its starting point is decision matrix (1), where $x_{ij} \in \mathbb{R}^+$ and the calculation steps are characterized as follows.

Step 1: Calculate the normalized matrix $Z = \left(z_{ij}\right)$, using the formula:

$$z_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}. \quad (10)$$

Step 2: Construct the vector of entropy $e = \left(e_1, e_2, \ldots, e_n\right)$, where:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} z_{ij} \ln z_{ij}, \quad (11)$$

and $z_{ij} \ln z_{ij}$ is defined as 0 if $z_{ij} = 0$.

Step 3: Calculate the vector of diversification degrees $d = \left(d_1, d_2, \ldots, d_n\right)$, where:

$$d_j = 1 - e_j. \quad (12)$$

Step 4: Calculate the vector of objective criteria weights $w = \left(w_1, w_2, \ldots, w_n\right)$, where:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}. \quad (13)$$

3.3. TOPSIS method for GDM with the aggregation of individual decisions

Because of the complexity many real-life problem, also considered in this paper, are discussed by a GDM. Let $DM_k \left(k = 1, 2, \ldots, K\right)$ be a set of decision makers or experts. Mathematically, the TOPSIS method for GDM with the aggregation of individual decisions can be described in the following steps.

Step 1: Each decision maker DM_k provided his/her decision matrix, called individual matrix or individual decision, in the formula:

$$X^k = \left[x_{ij}^k\right]_{m\times n} = \begin{array}{c} DM_k \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11}^k & x_{12}^k & \cdots & x_{1n}^k \\ x_{21}^k & x_{22}^k & \cdots & x_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1}^k & x_{m2}^k & \cdots & x_{mn}^k \end{bmatrix} \end{array}. \quad (14)$$

Step 2: Calculation the normalized decision matrix:

$$Z^k = \left[z_{ij}^k\right]_{m\times n} = \begin{array}{c} DM_k \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} z_{11}^k & z_{12}^k & \cdots & z_{1n}^k \\ z_{21}^k & z_{22}^k & \cdots & z_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1}^k & z_{m2}^k & \cdots & z_{mn}^k \end{bmatrix} \end{array} \quad (15)$$

using the formula (3) for each $k = 1, 2, \ldots, K$.

Step 3: Calculation the weighted normalized matrix:

$$V^k = \left[v_{ij}^k \right]_{m \times n} = \begin{matrix} DM_k \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{bmatrix} v_{11}^k & v_{12}^k & \cdots & v_{1n}^k \\ v_{21}^k & v_{22}^k & \cdots & v_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1}^k & v_{m2}^k & \cdots & v_{mn}^k \end{bmatrix} \end{matrix}, \tag{16}$$

where $v_{ij}^k = z_{ij}^k \cdot w_j$ for each $k = 1,2,\ldots,K$.

Step 4: Calculation the aggregated matrix:

$$V = \left[v_{ij} \right]_{m \times n} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix} \end{matrix} \tag{17}$$

using:

- **ART** – arithmetic mean (Chen, 2000; Wang & Chang, 2007; Roszkowska & Kacprzak, 2016), where:

$$v_{ij} = \frac{1}{K} \sum_{k=1}^{K} v_{ij}^k, \tag{18}$$

- **GEO** – geometric mean (Shih et al., 2007; Ye & Li, 2009), where:

$$v_{ij} = \left(\prod_{k=1}^{K} v_{ij}^k \right)^{\frac{1}{K}}. \tag{19}$$

Remark 3.1

It should be noted that in the aggregation operators (18) and (19), each DMs has the same influence on the matrix *V* (17), i.e., their weights are the same. Literature offers aggregation methods which take into account different weights of DMs, such as the so-called weighted mean (Yue, 2011; Liu et al., 2016; Kacprzak, 2019). Because when large groups of decision makers are at stake, the weighted mean gives results similar to the arithmetic mean, and was omitted in the numerical analyses.

Step 5: Ranking of alternatives.

Based on the matrix *V* and using STEPS 4–7 of the classical TOPSIS method presented in Subsection 3.1, ranking of alternatives is created and the best one is indicated.

3.4. TOPSIS method for GDM without aggregation of individual decisions

In 2020 Kacprzak proposed new extension of TOPSIS for GDM, which does not need aggregation. Mathematically, his method can be described in the following steps. Steps 1–3 are identical to those presented in Subsection 3.3.

Step 4: Calculation the matrix for each alternative $A_i\ (i=1,2,\ldots,m)$, as follows:

$$A^i=\left[v_{ij}^k\right]_{K\times n}=\begin{matrix} A_i \\ DM_1 \\ DM_2 \\ \vdots \\ DM_K \end{matrix}\begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{bmatrix} v_{i1}^1 & v_{i2}^1 & \cdots & v_{in}^1 \\ v_{i1}^2 & v_{i2}^2 & \cdots & v_{in}^2 \\ \vdots & \vdots & \ddots & \vdots \\ v_{i1}^K & v_{i2}^K & \cdots & v_{in}^K \end{bmatrix} \end{matrix} \tag{20}$$

using matrices $V^k\ (k=1,2,\ldots,K)$.

Step 5: Determination the ideal solution A^+ in the formula:

$$A^+=\left[v_j^{k+}\right]_{K\times n}=\begin{matrix} \\ DM_1 \\ DM_2 \\ \vdots \\ DM_K \end{matrix}\begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{bmatrix} v_1^{1+} & v_2^{1+} & \cdots & v_k^{1+} \\ v_1^{2+} & v_2^{2+} & \cdots & v_n^{2+} \\ \vdots & \vdots & \ddots & \vdots \\ v_1^{K+} & v_2^{K+} & \cdots & v_n^{K+} \end{bmatrix} \end{matrix}, \tag{21}$$

where $v_j^{k+}=\max_i v_{ij}^k$, and the negative ideal solution A^- in the formula:

$$A^-=\left[v_j^{k-}\right]_{K\times n}=\begin{matrix} \\ DM_1 \\ DM_2 \\ \vdots \\ DM_K \end{matrix}\begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{bmatrix} v_1^{1-} & v_2^{1-} & \cdots & v_k^{1-} \\ v_1^{2-} & v_2^{2-} & \cdots & v_n^{2-} \\ \vdots & \vdots & \ddots & \vdots \\ v_1^{K-} & v_2^{K-} & \cdots & v_n^{K-} \end{bmatrix} \end{matrix}, \tag{22}$$

where $v_j^{k-}=\min_i v_{ij}^k$.

Step 6: Calculation separation measure of each alternative A_i from the A^+:

$$d_i^+=\sqrt{\sum_{k=1}^{K}\sum_{j=1}^{n}\left(v_{ij}^k-v_j^{k+}\right)^2} \tag{23}$$

and from the A^-:

$$d_i^-=\sqrt{\sum_{k=1}^{K}\sum_{j=1}^{n}\left(v_{ij}^k-v_j^{k-}\right)^2}. \tag{24}$$

Step 7: Calculation the relative closeness of each alternative A_i to the A^+:

$$RC\left(A_i\right)=\frac{d_i^-}{d_i^++d_i^-}. \tag{25}$$

Step 8: Ranking of alternatives using the value of $RC(A_i)$. Bigger $RC(A_i)$ reflects that the alternative A_i is better.

4. Case study: Rank order of gerontechnologies and selection the best one

In this section, the authors conduct numerical analyses of the following nine gerontechnologies: A_1 – Health, A_2 – Education, A_3 – Interpersonal communication, A_4 – Safety, A_5 – Mobility, A_6 – Care, A_7 – Leisure, A_8 – Housing, A_9 – Digital accessibility. The aim of these numerical analyses is to rank order gerontechnologies and indicate the most important one using MCDM methods presented in Section 3 as well as compare the obtained results. The selected gerontechnologies $\{A_1, A_2, \ldots, A_9\}$ are evaluated by a group of 1,152 decision makers, i.e. $\{DM_1, DM_2, \ldots, DM_{1152}\}$. Each decision maker evaluates each gerontechnology type regarding thirty benefit criteria divided into seven groups (for more information, see Section 2, Table 3). Due to the age of decision makers and the fact that they may have difficulties with manipulating numerical data, they used a nine-point linguistic scale from "the least important" to "the most important". Next, their linguistic evaluations were converted into numerical data from 1 to 9 respectively. It means that in our numerical analyses, when we use the scale given in advance, normalization can be omitted.

In our numerical analyses, the authors consider two cases of criteria weights: the same criteria weights, i.e. $w_j = \frac{1}{30}$ for $j = 1, 2, \ldots, 30$ and objective criteria weights obtained using the entropy method described in Section 3.2.

4.1. TOPSIS for GDM with the same criteria weights

4.1.1. TOPSIS method for GDM with the aggregation of individual decisions

Let us consider that the classical TOPSIS method for the collective matrix is used after aggregating individual matrices provided by DMs by the arithmetic mean – TOPSIS_ART and the geometric mean – TOPSIS_GEO. Table 4 presents the obtained results, where $RC(A_i)$ given by formula (9), R – ranking of the alternatives and J – normalized (i.e. summing up to 1) values of $RC(A_i)$. It should be noted that relative closeness coefficients to PIS for the arithmetic mean have higher values than for geometric mean as a result of using different aggregation methods. On the other hand, TOPSIS_ART and TOPSIS_GEO give the same ranking of gerontechnologies in the formula:

$$A_7 \prec A_2 \prec A_9 \prec A_3 \prec A_6 \prec A_8 \prec A_1 \prec A_4 \prec A_5 .$$

Figures 1 and 2 present obtained rankings of alternatives with the use of TOPSIS_ART and TOPSIS_GEO based on $RC(A_i)$ and J.

Table 4. Rankings of gerontechnologies with the use of TOPSIS_ART and TOPSIS_GEO

Alt.	Gerontechnology group	TOPSIS_ART			TOPSIS_GEO		
		$RC(A_i)$	R	J	$RC(A_i)$	R	J
A_1	health	0.6434	3	0.1141	0.5774	3	0.1151
A_2	education	0.6098	8	0.1082	0.5389	8	0.1074
A_3	interpersonal communication	0.6150	6	0.1091	0.5458	6	0.1088
A_4	safety	0.6456	2	0.1145	0.5802	2	0.1156
A_5	mobility	0.6457	1	0.1145	0.5809	1	0.1158
A_6	care	0.6286	5	0.1115	0.5584	5	0.1113
A_7	leisure	0.6029	9	0.1069	0.5279	9	0.1052
A_8	housing	0.6340	4	0.1124	0.5665	4	0.1129
A_9	digital accessibility	0.6134	7	0.1088	0.5411	7	0.1079

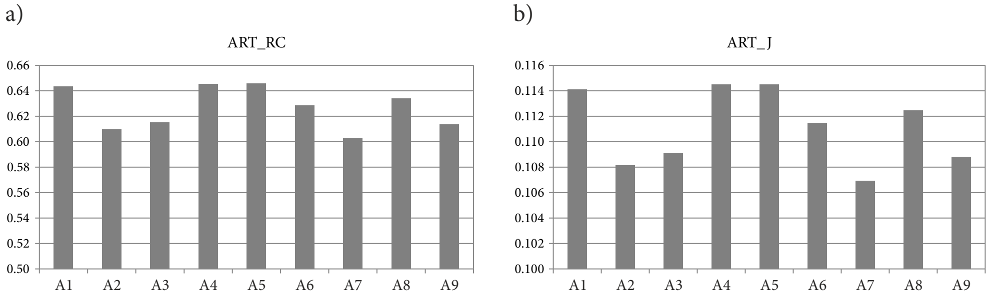

Figure 1. Rankings of gerontechnologies with the use of TOPSIS_ART based on a) $RC(A_i)$, b) J

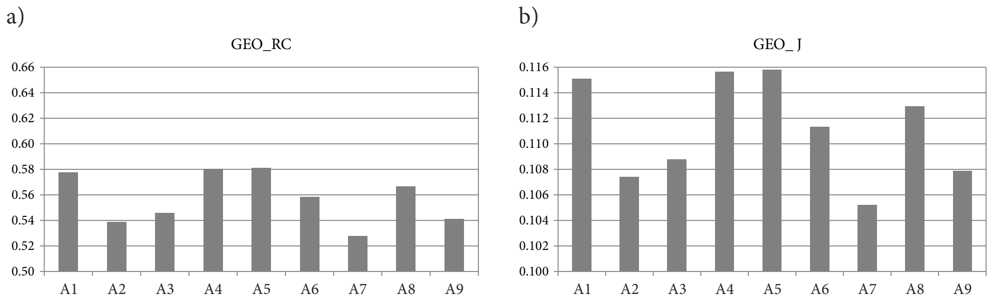

Figure 2. Rankings of gerontechnologies with the use of TOPSIS_GEO based on a) $RC(A_i)$, b) J

4.1.2. TOPSIS method for GDM without the aggregation of individual decisions

Now the authors apply an alternative TOPSIS method for GDM, which does not need aggregation, presented in Subsection 3.4. Table 5 presents the obtained results, i.e. $RC(A_i)$ and J, which are very similar to those obtained in Section 4.1.1. This method gives a ranking as follows

$$A_7 \prec A_2 \prec A_9 \prec A_3 \prec A_6 \prec A_8 \prec A_1 \prec A_4 \prec A_5$$

is identical to those obtained by other methods presented in the paper. Figure 3 presents the obtained ranking of gerontechnologies using the method described in Section 3.4 based on $RC(A_i)$ and J.

Table 5. Rankings of gerontechnologies using the method described in Subsection 3.4

Alt.	TOPSIS		
	$RC(A_i)$	R	J
A_1	0.6099	3	0.1136
A_2	0.5837	8	0.1087
A_3	0.5880	6	0.1095
A_4	0.6118	2	0.1139
A_5	0.6121	1	0.1140
A_6	0.5978	5	0.1113
A_7	0.5777	9	0.1076
A_8	0.6025	4	0.1122
A_9	0.5861	7	0.1091

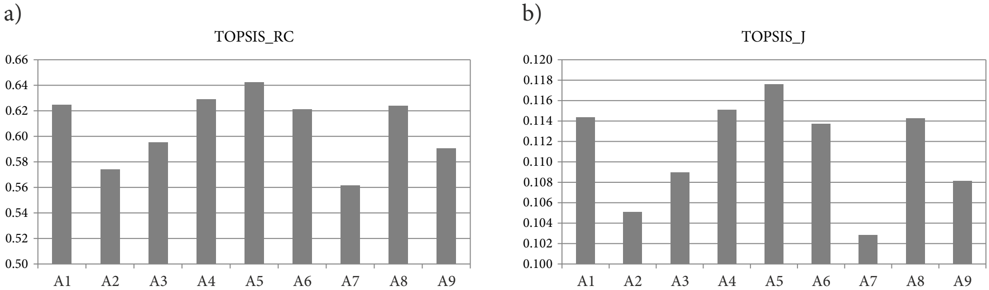

Figure 3. Rankings of gerontechnologies using the method described in Subsection 3.4

4.2. TOPSIS for GDM with objective criteria weights obtained using entropy method

4.2.1. TOPSIS method for GDM with the aggregation of individual matrices

Let us again consider the extension TOPSIS method for GDM with aggregation operators (18) and (19) However, in this case, the authors will take into account objective weights. Table 6 and Figure 4 present objective criteria weights calculated after aggregation using the arithmetic mean. Table 7 shows the obtained results, i.e. $RC(A_i)$ and J. Figure 5 presents the obtained ranking of the alternative. Table 8 and Figure 6 present objective criteria weights calculated after aggregation using the geometric mean, while Table 9 and Figure 7 show the obtained results and the ranking of the alternative.

Table 6. Objective criteria weights after the aggregation of individual matrices using the arithmetic mean

w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	w_{10}
0.0296	0.0495	0.0296	0.0245	0.0193	0.0445	0.0367	0.0222	0.0070	0.0130
w_{11}	w_{12}	w_{13}	w_{14}	w_{15}	w_{16}	w_{17}	w_{18}	w_{19}	w_{20}
0.0183	0.0172	0.0308	0.0109	0.0514	0.0773	0.0224	0.0771	0.0265	0.0751
w_{21}	w_{22}	w_{23}	w_{24}	w_{25}	w_{26}	w_{27}	w_{28}	w_{29}	w_{30}
0.0812	0.1215	0.0498	0.0067	0.0027	0.0086	0.0103	0.0180	0.0117	0.0064

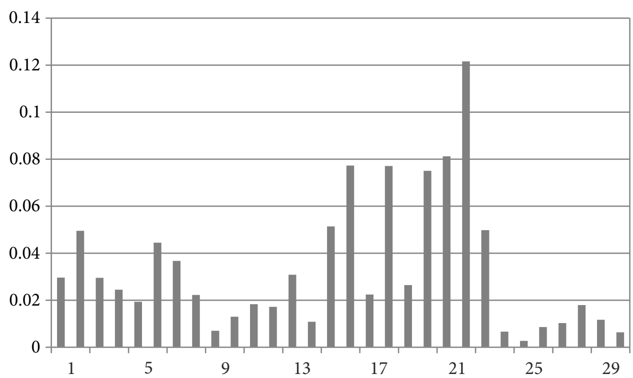

Figure 4. Objective criteria weights after using the aggregation operator (18)

Table 7. Rankings of gerontechnologies after using the aggregation operator (18) with objective criteria weights

Alt.	$RC(A_i)$	R	J
A_1	0.6628	4	0.1149
A_2	0.5986	8	0.1038
A_3	0.6253	6	0.1084
A_4	0.6684	2	0.1159
A_5	0.6855	1	0.1189
A_6	0.6592	5	0.1143
A_7	0.5834	9	0.1012
A_8	0.6632	3	0.1150
A_9	0.6203	7	0.1076

a) b)

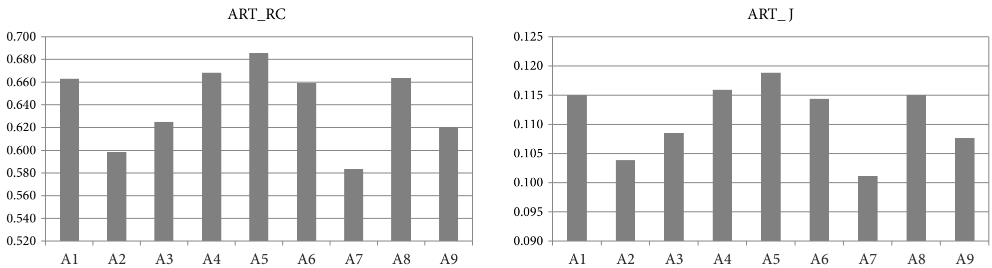

Figure 5. Rankings of gerontechnologies after using the aggregation operator (18) with objective criteria weights based on a) $RC(A_i)$, b) J

Table 8. Objective criteria weights after using the aggregation operator (19)

w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	w_{10}
0.0253	0.0443	0.0292	0.0217	0.0149	0.0370	0.0314	0.0256	0.0069	0.0115
w_{11}	w_{12}	w_{13}	w_{14}	w_{15}	w_{16}	w_{17}	w_{18}	w_{19}	w_{20}
0.0154	0.0187	0.0271	0.0091	0.0455	0.0747	0.0238	0.0883	0.0252	0.0865
w_{21}	w_{22}	w_{23}	w_{24}	w_{25}	w_{26}	w_{27}	w_{28}	w_{29}	w_{30}
0.0939	0.1370	0.0444	0.0059	0.0026	0.0114	0.0096	0.0143	0.0126	0.0062

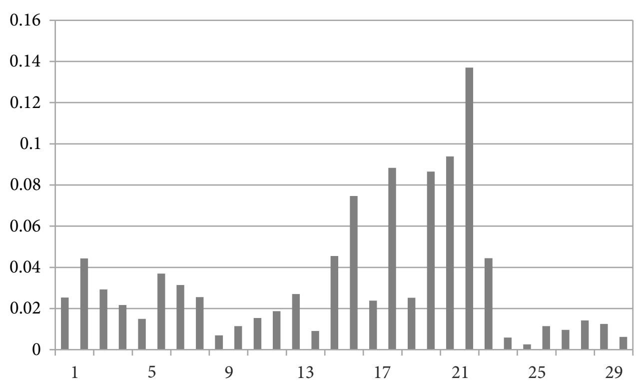

Figure 6. Objective criteria weights after using the aggregation operator (18)

Table 9. Rankings of gerontechnologies after using the aggregation operator (19) with objective criteria weights

Alt.	$RC(A_i)$	R	J
A_1	0.5925	4	0.1164
A_2	0.5130	8	0.1008
A_3	0.5508	6	0.1082
A_4	0.5979	2	0.1175
A_5	0.6205	1	0.1219
A_6	0.5915	5	0.1162
A_7	0.4884	9	0.0960
A_8	0.5935	3	0.1166
A_9	0.09126	3	0.1115

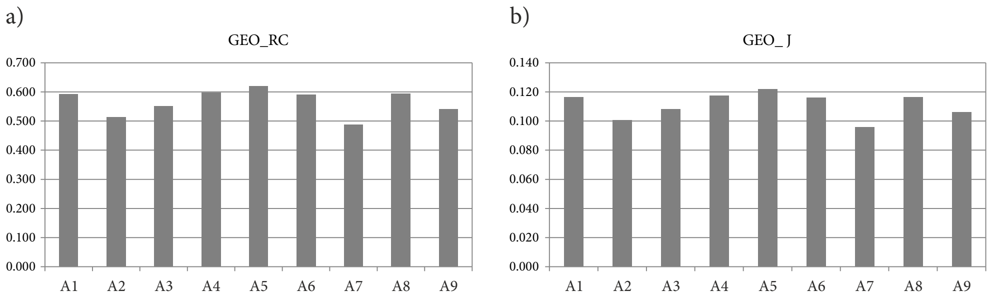

Figure 7. Rankings of gerontechnologies after using the aggregation operator (19) with objective criteria weights based on a) $RC(A_i)$, b) J

It should be noted that when the authors used objective weights of criteria, the obtained rankings of gerontechnologies for the aggregation operators (18) and (19) are identical in the form

$$A_7 \prec A_2 \prec A_9 \prec A_3 \prec A_6 \prec A_1 \prec A_8 \prec A_4 \prec A_5 .$$

When the authors compare the obtained results, taking into account objective weights, with the results presented in Subsection 4.1, the authors can notice that the obtained rankings of gerontechnologies differ only in the order of alternatives A_1 and A_8. However, taking into account the J index (see Tables 4, 5, 7 and 9), the differences in the results of these gerontechnologies are very small, especially when objective weights were used. Moreover, all the presented extensions of the TOPSIS method indicated the best gerontechnology as A_8, e.g., mobility.

4.2.2. Sensitivity analysis

Now the authors will consider the sensitivity analysis. They will change the weight of a certain criterion, adjust the weights of the remaining criteria and then analyse obtained ranking. Let w_j^m denote the modified weight w_j of the jth criterion $\left(j = 1,2,\ldots,30\right)$. Then the rest of criteria weights w_h $\left(h \neq j\right)$ are calculated using the formula.

$$w_h^m = \alpha \cdot w_h,$$

where $\alpha = \dfrac{1 - w_j^m}{1 - w_j}$.

The Table 10 shows the results of the sensitivity analysis based on the TOPSIS method for GDM after using the aggregation operator (18), where CW – criteria weights determined using the entropy method, SR – the intervals of changes of criteria weights that does not affect the ranking of gerontechnologies, BA – the intervals of changes of criteria weights that does not affect the best gerontechnologies.

Table 10. Results of the sensitivity analysis based on the TOPSIS method for GDM after using the aggregation operator (18)

C_j	CW	SR	BA	C_j	CW	SR	BA
1	0.0296	[0.0000;0.0401]	[0.0000;0.2020]	16	0.0773	[0.0172;0.0823]	[0.0000;0.1534]
2	0.0495	[0.0000;0.0549]	[0.0000;0.2626]	17	0.0224	[0.0000;0.0904]	[0.0000;0.8518]
3	0.0296	[0.0000;0.0449]	[0.0000;0.1733]	18	0.0771	[0.0754;0.0946]	[0.0000;0.2907]
4	0.0245	[0.0000;0.0446]	[0.0000;0.1865]	19	0.0265	[0.0000;0.0370]	[0.0000;0.3581]
5	0.0193	[0.0000;0.0417]	[0.0000;1.0000]	20	0.0751	[0.0447;0.0771]	[0.0000;0.1147]
6	0.0445	[0.0000;0.0565]	[0.0000;1.0000]	21	0.0812	[0.0547;0.0269]	[0.0000;0.0869]
7	0.0367	[0.0000;0.0501]	[0.0000;0.2441]	22	0.1215	[0.1200;0.1427]	[0.0886;1.0000]
8	0.0222	[0.0000;0.0366]	[0.0000;0.1339]	23	0.0498	[0.0369;0.1011]	[0.0000;1.0000]
9	0.0070	[0.0000;0.0269]	[0.0000;0.2159]	24	0.0067	[0.0000;0.0292]	[0.0000;0.1585]
10	0.0130	[0.0000;0.0379]	[0.0000;1.0000]	25	0.0027	[0.0000;0.0508]	[0.0000;1.0000]
11	0.0183	[0.0000;0.0357]	[0.0000;0.3266]	26	0.0086	[0.0000;0.0671]	[0.0000;0.1809]
12	0.0172	[0.0000;0.0344]	[0.0000;0.5832]	27	0.0103	[0.0000;0.1447]	[0.0000;0.1447]
13	0.0308	[0.0000;0.0401]	[0.0000;1.0000]	28	0.0180	[0.0000;0.1189]	[0.0000;0.1189]
14	0.0109	[0.0000;0.0966]	[0.0000;0.2843]	29	0.0117	[0.0000;0.0605]	[0.0000;1.0000]
15	0.0514	[0.0000;0.0591]	[0.0000;0.4165]	30	0.0064	[0.0000;0.0576]	[0.0000;1.0000]

Based on the results of the sensitivity analysis shown in Table 10, it should be concluded that the obtained ranking of gerontechnologies is not a stable solution. For the criterion C_{20} a small change equaling 0.0020 or for the criterion C_{22} change equaling 0.0015 give a new ranking of gerontechnologies. Let us note that if the authors use equal weights of criteria equaling 1/30, they will not belong into the interval SR for criteria C_9, C_{18}, C_{20}, C_{21}, C_{22}, C_{23} and C_{24}. This means that, in using equal weights and objective weights, the authors will get a different gerontechnologies ranking. On the other hand, a small change of criterion C_{21} equalling 0.0057 or a small change of criterion C_{25} equalling 0.0027 may result in a new the best alternative. Moreover, the authors can see that the weight of criteria C_5, C_6, C_{10}, C_{13}, C_{23}, C_{25} and C_{29} do not affect the choice of the best gerontechnologies. This means that criteria weights are an important issue in selecting gerontechnologies.

Conclusions

The aim of the paper and its main contribution is to rank the order of gerontechnologies identified in the literature review. For this purpose, various extensions of the TOPSIS method for Group Decision Making, were used. As a result of the authors' numerical analyses, it can be concluded that all methods used in the paper gave almost the same ranking of gerontechnologies (they only differ in the order of alternatives A_1 and A_8, but these differences are very small) in the form:

$$A_7 \prec A_2 \prec A_9 \prec A_3 \prec A_6 \prec A_8 \prec A_1 \prec A_4 \prec A_5,$$

which means that DMs gave the highest rating for *mobility*. The second place in the ranking was taken by technologies improving the quality of life of older people from the *safety* class. Therefore, taking into account various criteria, the most desired by current and future users are the gerontechnologies of *mobility* and *safety* classes. Thus, both creators and producers should primarily focus on technologies from these two groups. The least important group in gerontechnology, on the other hand, is the *leisure*.

Based on Tables 4–5 and in Figures 1–3 (especially in part b), the analysis of the obtained results indicates that gerontechnologies can be divided into two subgroups: $\{A_1, A_4, A_5, A_8\}$, which were rated higher than the average (mean that they are more important to DMs) and $\{A_2, A_3, A_7, A_9\}$, which were rated lower than the average, (that means that are less important for DMs). Gerontechnologies from the *care* (A_6) group received ratings close to the average. The following technologies improving the quality of life of elderly people were rated above the average (see Figure 8): *health* (A_1), *safety* (A_4), *mobility* (A_5), *housing* (A_8). Thus, technologies from these groups are more useful for future and current users. Below the average are technologies from the groups: *education* (A_2), *interpersonal communication* (A_3), *leisure* (A_7), *digital accessibility* (A_9).

It should be noted that the results obtained for different gerontechnologies with the use of various extensions of the TOPSIS method for Group Decision Making are very similar. Taking into consideration the indicator J – Figure 8, it can be observed that the obtained values differ only slightly. Considering the above observations, it can be concluded that all used various extensions of the TOPSIS method give the same results.

According to the authors, the conducted research is very valuable, this type of research has not been presented so far either in the Polish or foreign literature, but it has some limi-

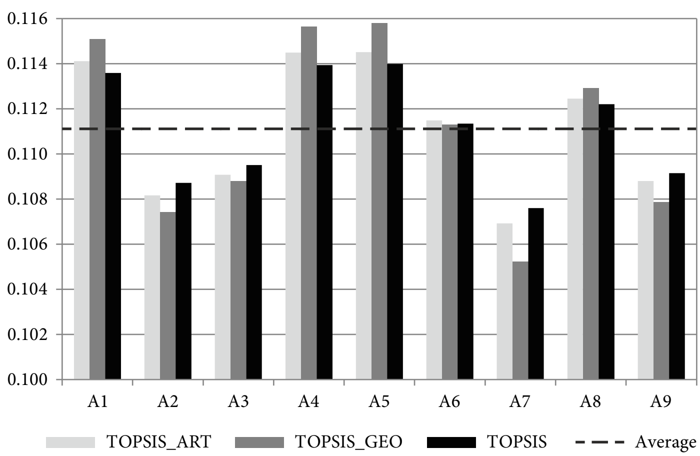

Figure 8. Comparison of the value of indicator J obtained by the TOPSIS for GDN with the same criteria weights for each gerontechnology type

tations. First of all, the research has been conducted only on Polish citizens. Moreover, the methods to build the ranking were chosen arbitrarily – there was no evaluation of various MCMD methods. Only the most commonly used method was selected.

In their future research, the authors plan to extend the analysis to a larger sample and other countries. Moreover, they intend to use other MDCM methods and subjective criteria weights provided by decision makers or experts. They also plan to take into account other technology assessment criteria, such as Technological Readiness Levels (TRL), Life Cycle Analysis (S-LCA).

The authors also intend to use different data formats than exact numerical values, such as interval numbers, fuzzy numbers, an intuitionistic fuzzy set, a single-valued neutrosophic set and others.

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Author contributions

KH was responsible for the study conception and design. DK performed the computation and analysis. KH and DK were responsible for data interpretation. KH and DK discussed the results and contributed to the final manuscript.

Disclosure statement

The authors declare that not the have a competing financial, professional, or personal interests from other parties.

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