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# Overview of Multi-attribute Decision-analysis Tools for Selecting Investment Options in Municipal District Heating Systems

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*Abstract.* Municipal district heating systems in Polish cities constitute important elements of these municipalities (and not only of their technical infrastructures). Due to the nature of the basic service that is provided – providing heat (and perhaps year-round comfort in the future) – these systems can be perceived as important parts of the social infrastructures of the cities, creating the appropriate conditions for the existence of people, the functioning of social infrastructure facilities, and the operations of enterprises. The need for heating companies to adapt to any changes in the requirements that arise as a result of the economic, social, environmental, and (increasingly) political and legal changes that take place in its immediate and distant environment requires the implementation of investments. However, the effects of such investments are multidimensional and largely difficult to measure; they depend on the passage of time and complex conditions that are related to the pursuit of sustainable development and security. Their reliable assessment therefore requires the use of appropriate tools. This paper is devoted to an analysis of the practical usefulness of multi-attribute decision-analysis tools in this context, taking various types of such tools into account as well as the conditions for their effective applications. The most promising of these tools is also introduced and discussed.

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## 1. INTRODUCTION

Due to climatic conditions, a *municipal district heating system* (MDHS) is a typical element of the infrastructures of every Polish city. Their task is basically to provide heat during the multi-month heating season, ensuring appropriate living conditions for the populations and the functioning of enterprises and other institutions that operate in the cities. It is worth paying attention to the fact that the heating systems of Polish cities are currently obligated to perform an important function that is related to environmental protection in some fashion. This involves helping to reduce the low emissions and pollution that are generated by outdated individual heating devices that are fired with fossil fuels. *Ustawa z dnia 10 kwietnia 1997 r. Prawo energetyczne* [Polish Energy Law Act of April 10, 1997] (1997), imposes an obligation to connect consumers to heating networks whenever possible.

The existence of buildings that are still not connected to heating networks and the appearances of new potential heat-collection places due to city development result in a need for making the investments by the companies that manage the networks. The complex nature of such investments requires the prediction of various investment scenarios and a multidimensional assessment of their potential effects. Local and global conditions mean that the effects of such investments are influenced by many factors of various natures: political, economic, social, technical, environmental, and legal. Such effects may also be difficult to measure, and information regarding their determinants is often imperfect. Therefore, it is worth using the possibility of structuring the issues of developing heating networks for their proper holistic approaches thanks to the use of the PESTEL framework analysis (Political-Economic-Social-Technical-Environmental-Legal analysis) (Walsh, 2005). The multidimensional nature of potential investment effects means that their rational assessment requires the use of specific tools that take this fact into account. Many tools are provided by the decision-analysis methodology (Goodwyn & Wright, 2014) – especially its multi-attribute approach (MADA – multi-attribute decision analysis). Due to the richness of the MADA tools, these will reviewed in this work; also, we will take the availability of their computer implementations into account as well as their applications for solving the decision-making issues that are related to urban thermal energy. On the basis of this review, the best tool will ultimately be recommended.

The second part discusses the basic types of MADA techniques. The third section is devoted to their current applications in urban thermal energy. The conclusions on the suitability of techniques for assessing and analyzing any investment alternatives were finally presented.

## 2. MULTI-ATTRIBUTE DECISION ANALYSIS

Numerous (often very extensive) studies have been devoted to the MADA methodology (Greco et al., 2016; Ishizaka & Nemery, 2013; Trzaskalik, 2014). Basically, this methodology involves an analysis and assessment of the adopted decision making alternatives of action (decisions) that are the subjects of certain decisions and described by a specific set of parameters (attributes). Following Roy (2016), it can be stated that there are four basic applications of MADA:

1) describing issue under consideration (P.$\delta$ problematics);
2) choosing (most appropriate) decision option (P.$\alpha$ problematics);
3) grouping (similar) decision decision making alternatives (P.$\beta$ problematics);
4) ordering (ranking) decision making alternatives (P.$\gamma$ problematics).

Let us note that, while the last three types of problem are intended for specific actions on a set of decision alternatives, P.$\delta$ pursues a specific goal of enriching the analysis of the considered decision-making issue; this may allow the implementation of one of the other issues in the future. What is also noteworthy is the possibility that different types of MADA issues may be considered after one another. For example, a previously determined ranking of decision making alternatives can be used for selecting the appropriate decision making alternative; when selecting or ranking decision making alternatives, the result of their previous grouping can be used, etc.

To solve specific problems that are related to the P.$\alpha$, P.$\beta$, and P.$\gamma$ MCDA applications, numerous MADA tools have been developed. Based on the principles that they utilize, these can be divided into four groups (Greco et al., 2016; Ishizaka & Nemery, 2013):

1) full-preference aggregation techniques;
2) outranking relation-based techniques;
3) aspiration- and reference-level techniques;
4) specific techniques based on other foundations.

Note that the most popular MADA techniques belong solely to the first three groups.

### 2.1. Full-preference aggregation techniques

The idea of the full aggregation of preferences is related to the concepts of multi-attribute value theory (MAVT) and multi-attribute utility theory (MAUT) that were introduced by Keeney and Raiffa (1976). This involves the use of a weighted, additive, or multiplicative aggregation of the partial preferences of decision-making alternatives to evaluate them. Due to the place of the origin of this idea, this is called the American school of decision analysis.

One of the most commonly used tools that directly implements the above idea is simple additive weighting (SAW), which uses additive formulas. This also has a much-less-popular multiplicative counterpart – in the form of simple multiplicative weighting (SMW).

When it comes to more-complex techniques, Saaty's AHP (Analytic Hierarchy Process) is the most popular one (Saaty & Vargas, 2012). It seems that, apart from its universal nature, the basic reason for such a position is its use of a simple evaluation mechanism (i.e., pairwise comparisons), thus facilitating the use of imperfect information and the simplicity of the calculations and structuring of decision-making problems by using the hierarchical relationships between the components of the problem model. The methodology (proposed by Saaty) also allows one to take the more-complex two-way relationships between the model components into account. This is achieved by replacing the hierarchical structure of their connections with a network structure that is used by the network equivalent of AHP in the form of ANP (analytic network process) (Saaty & Vargas, 2011). An important advantage of the above techniques is the availability of software that fully supports the implementation of complex analyses. For example, one can use a computer application called *SuperDecisions* to facilitate advanced AHP analyses of complex decision-making cases. This software is available for free at https://www.superdecisions.com.

Among the remaining tools for the full aggregation of preferences, those techniques that improve the methodology that is used in the AHP technique stand out. These include the MACBETH technique (Measuring Attractiveness by a Categorical-Based Evaluation Technique) (Bana E Costa & Vansnick, 1994) and REMBRANDT (Ratio Estimation in Magnitudes or deciBells to Rate Alternatives that are Non-DominaTed) by Lootsma (1992). Because of their more complex nature, however, their use is only possible through the use of specialized software (unlike the original).

Summarizing the subject of those techniques that use the idea of a full aggregation of preferences, it can be said that their main purpose is to organize and rank decision making alternatives. These techniques also have a compensatory nature that consists of the possibility of improving the overall assessment of a decision making alternative that is inferior to another decision making alternative in terms of certain attributes thanks to the advantage of the result from a better assessment in terms of its specific attributes. It is worth noting that this feature of the techniques is not welcomed when looking for the global-best-decision alternative.

### 2.2. Outranking relation-based techniques

The superiority relationship allows one to identify cases of the type of domination of individual decision making alternatives over other decision making alternatives. In order to determine whether this actually occurs between decision making alternatives that are compared within a pair, the detailed relationships that correspond to the clear advantage of one decision making alternative over the other (preference relationship), the identity (indistinguishability relationship), and the incomparability (incomparability relationship) of the compared decision making alteratives are usually used. Due to their European origins, these techniques make up the so-called European school of multi-attribute decision support.

Basically, two basic families of techniques can be distinguished in this group (Brans & De Smet, 2016; Figueira et al., 2016): ELECTRE (ELimintion Et Choix Tranduisant REalité), and PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation). It is true that there are many other available techniques that use the idea of superiority relationships, but they are derivative in nature. Both families of techniques consist of numerous technique alternatives, which, unlike those techniques that use the idea of a full aggregation of preferences, offer not only the possibility of ranking but also grouping decision alternatives and a direct recommendation of the most appropriate one among them.

The techniques of the ELECTRE family are based on the direct comparison of decision making alternatives in the context of their partial assessments (expressed in the levels of their attributes). At the same time, it is possible to use various mechanisms to prevent a too-hasty acknowledgement of the advantage of one decision making alternative over the other in doubtful cases; these include the preference, indistinguishability, and veto thresholds. The final decision on the detailed relationship between the compared decision making alternatives is made on the basis of the relationship between two indicators: compliance (concordance index), and noncompliance (disconcordance index). It should be noted that the use of the pairwise comparison mechanism by the families of the ELECTRE techniques facilitates also includes the possibility of a direct comparison of the decision making alternatives in the context of those attributes that are difficult to measure.

In the case of the PROMETHEE family techniques, comparisons of decision alternatives do not rely on their attribute levels; the differences in their attribute levels are used for this purpose. To reduce all of the partial evaluations of any decision making alternatives to a common denominator, these differences are expressed in values that are within a mutually closed interval $[0, 1]$. The transformation of the absolute value of the difference into a number from the unit interval is performed by using a specific unitarization formula, which can take various forms (both continuous and discontinuous [stepped]) while also taking the threshold values of the preferences and veto into account. The concept of a weighted preference flow is used to determine the forms of the detailed relationships that connect the decision making alternatives. In the case of a specific pair of decision making alternatives, this may take a positive form (positive preference flow), whose results stem from a partial advantage over the second decision making alternative, and a negative form (negative preference flow), whose results stem from a partial advantage of the second decision making alternative. The PROMETHEE family of techniques is also equipped with an advanced graphic tool – GAIA (Geometrical Analysis Interactive Aid) – which is designed for interactive visualizations of analysis results.

Due to the tedious nature of the analyses and calculations, the use of superiority relationship techniques requires computer support; fortunately, software is available to implement such techniques. A good example of such a tool is the attractive (not only visually) Visual PROMETHEE application (available at: http://www.promethee-gaia.net/phone/visualpromethee.html). This tool was developed by B. Mareschal – the principal researcher who was involved in the process of the actual development of the PROMETHEE technique.

### 2.3. Aspiration- and reference-level techniques

Among tools of this type, two techniques are worth paying special attention to: TOPSIS (Hwang & Yoon, 1981), and VIKOR (Opricović, 1990). They use the idea of aspiration and reference levels by using pairs of abstract objects: a pattern (ideal), and an anti-pattern (anti-ideal). The basic advantage of these techniques (and the main reason for their popularity) is the use of geometric interpretations of the similarities between objects. They use a specific representation of decision making alternatives in the form of points in a multidimensional space of their attributes. As a result, this allows one to express the similarity of decision-making alternatives (also in relation to the pattern and anti-pattern) using the distance of the points that represent them. Moreover, these techniques do not require complex calculations.

The names of both techniques clearly reflect their basic purposes. In the case of the first one (known as the technique of ordering decision making alternatives based on the similarity to a pattern – Technique for Order Preference by Similarity to Ideal Solution – TOPSIS), it is about ordering (ranking) the decision making alternatives. In the case of the second one – the multi-criteria optimization and compromise solution VIKOR (VIseKryterijumska Optimizacija i kompromisno Resenje), compromise-based indication of the most appropriate alternative or multiple most appropriate decision making alternatives.

The ordering of decision making alternatives in the TOPSIS technique is based on a specific metric that uses Euclidean distances of points that represent the decision making alternatives in a multidimensional space of appropriately normalized attributes from the pattern and anti-pattern. VIKOR operates on non-standard values of the attributes of the decision making alternatives. Three specific rankings are used to indicate the most appropriate decision options. The technique takes the possibility of using a veto from unfavorable attributes and the related sensitivity analysis into account. The technique also ensures that the ultimately recommended decision making alternative or variants show significant advantages over the other decision making alternatives.

There are also other tools that use the idea of aspiration and reference levels. For example, Konarzewska-Gubała (2009) proposed the BIPOLAR technique in this context, combining some features of the reference-level methodology and the ELECTRE family techniques.

### 2.4. Remaining techniques

Based on the works of Trzaskalik (2014) and Greco et al. (2016), three groups of other techniques can be distinguished: interactive, verbal, and those that use decision rules and specific representations of imperfections in any available information. Due to their complexity, the use of any of the above techniques requires computer support.

Interactive techniques have been developed to solve complex and insufficiently defined problems under conditions of imperfect information and, therefore, require the gradual discovery of knowledge about them. Basically, they are used to evaluate and select decision options. For this purpose, they use a multistage interaction with the decision-maker, which includes a repeated repetition of two phases. The first involves updating the information thanks to a dialogue with the decision-maker, and the second involves calculations that use the acquired information. There are several tools that implement such ideas; e.g., STEM-DPR (Nowak, 1992).

Verbal techniques are based on the idea of VDA (verbal-decision analysis). These techniques only use qualitative verbally expressed assessments of decision-making alternatives. Due to its use, it is possible to solve the issues of selecting and grouping decision-making alternatives. To accomplish the first of the above tasks, for example, one can use the ZAPROS LM technique (Russian: Метод ЗАПРОС – ЗАмкнутые

ПРоцедуры у Опорных Ситуаций) by Larichev and Moshkovich (1997) or the second one by the ORCLASS technique (Ashikhmin & Furems, 2005).

Among the techniques that use decision rules and a specific representation of imperfect information, the dominance-based rough set approach (DRSA) by Greco et al. (2002) stands out. It can be used to solve diverse problems: the selection, ranking, and grouping of decision making alternatives. Interesting analysis possibilities are also provided by the family of techniques called stochastic multi-criteria acceptability analysis (SMAA) by Landhelma and Salminen (2010). These involve exploring the space of the weights to determine those preferences that correspond to the specific positions of individual decision making alternatives in their ranking. The approach is applied in several stages; the individual stages serve to gradually expand the available information thanks to more-accurate measurements or determining the preferences of decision-makers, for example. The final decision is only made at the stage when the available information resources allow it.

## 3. APPLICATION OF MADA METHODOLOGY IN MDHSs

Below is a brief review of several dozen cases of applications of the MADA methodology in urban thermal energy, which were identified on the basis of the literature review. For this purpose, the *Scopus* bibliographic database was primarily used (https://www.scopus.com).

### 3.1. Full-preference aggregation technique use

AHP dominates other approaches that implement the idea of a full aggregation of preferences. The technique was also used to consider various contexts of sustainable development. For example, Wang et al. (2019) assessed the effectiveness of private-public partnerships in terms of investments in clean sustainable district heating systems. Laktuka et al. (2021) attempted to assess the degrees of attention of regional and local strategies to increase the efficiency of heating and cooling in the aspect of intensifying sustainable urban development, and Balode et al. (2021) proved the advantage of district heating systems over individual heating systems. Pellegrini et al. (2019) classified potential technical solutions that could facilitate the transformation of district heating systems into sustainable systems.

The AHP technique has been also used to evaluate geothermal district heating systems (Eltez et al., 1999), demand-side investment-management programs (Lee et al., 2007), and the engineering value of various configurations of systems that provide heat and cooling through the use of seawater heat pumps (Shu et al., 2010).

This technique also turned out to be an appropriate tool for supporting the optimization of the locations of heating plants (Geri et al., 2018), the energy-efficiency of a heating system (Skiba et al., 2021), and a system that integrated a heating network with an energy network (Arslan et al., 2021). In the last case, the use of AHP was skilfully combined with the TOPSIS technique.

In addition, this technique proved to be effective in solving the problem of selecting an appropriate heat source for a heating system (Dytczak & Ginda, 2006;

Fang & Wang, 2014). It was also used – together with GIS (geographical information system), a Bayesian network, and data-envelopment analysis (DEA) – to jointly implement a balanced-score chart (BSC) that supported the strategic management of a heating system (Bazil et al., 2021).

In turn, Bilić et al. (2020) used the SAW technique for a multi-attribute assessment of the suitability of geothermal waters in the context of their use, among others, for heating purposes.

### 3.2. Outranking-relationship technique use

The use of outranking-relationship techniques in urban thermal energy is represented by the ELECTRE and PROMETHEE techniques. The first was used by Grujić et al. (2014) to determine appropriate heat sources for Belgrade's district heating system, and Mróz (2008) applied it to plan a district heating system. Ghafghazi et al. (2010) applied it to assess the suitability of heat sources in a scenario-based approach. Fang and Wang (2014) used it – together with AHP – when selecting a proper heat source, and Ziemele et al. (2014a) used it – together with TOPSIS – during a scenario-based optimization of heating-system control.

### 3.3. Aspiration and reference-level-technique use

Among the techniques that use aspiration and reference levels in the context of urban thermal energy, the TOPSIS technique is dominant. At the same time, it is the most frequently used tool. By far, most of the applications of this technique concern the optimization of integrated systems that produce a combined heat and electricity output (Arslan et al., 2021; He et al., 2019; Wu et al., 2022), a subsystem of a heating system (Wu et al., 2020), a network that was powered by heat from two energy sources (Zhao et al., 2021), devices that were intended for heating systems that supplied heat to residential areas (Wu et al., 2021), the share of industrial waste heat and energy that was supplied by heat pumps to a heating system that would result in an effect that was close to carbon neutrality while reducing costs (Yuan et al., 2021).

Further applications of TOPSIS have concerned technological issues; in particular, assessments and selections of heat sources for municipal heating systems. As part of this topic, a multi-scenario assessment was carried out, and selections of technologies and heat sources for a municipal heating system were made (Boran, 2013; Polikarpova et al., 2019), an assessment of technologies used in heating systems was carried out (Streimikiene & Balezentiene, 2014), and an analysis of a cogeneration energy system that supplied a network was carried out, and its appropriate shape was recommended (Cimdina et al., 2014). The technique also supported an analysis of energy-transformation issues; this included determining the structure of a zero-emission heating system in the sense of avoiding the need to acquire greenhouse gas-emission allowances (Ziemele et al., 2016) and determining a target energy source for a heating system that operated within a local government unit (Prodanuks & Blumberga, 2018).

The use of this technique has also facilitated solutions of issues regarding sustainable development in heating systems. For example, Siksnelyte-Butkiene and Streimikiene (2023) assessed selected European countries in terms of sustainable development of the heating industry. For this purpose, multi-scenario analysis was used. On the other way, Prodanuks and Blumberga (2018) drew attention to the fundamental impact of the development of heating systems on the formation and development of urban energy plans, and Laktuka et al. (2021) – additionally supported by the AHP technique – carried out an attempt to assess the degree of attention that was paid in regional and local energy strategies to the potential for intensifying the sustainable development of cities by increasing the efficiency of their heating and cooling. However, Abokersh et al. (2021) addressed the issue of supporting the process of popularizing NZEB (near-zero-energy buildings) using solar district heating systems (SDHSs). Finally, a study determined the appropriate scale of an SDHS and proved its useful role in achieving sustainable development goals thanks to the use of a machine-learning model that integrated multi-criteria optimization with multi-attribute decision analysis. In turn, the additional – parallel – use of the VIKOR technique and several other tools allowed Wen et al. (2021) to prove the environmentally friendly nature of district heating systems as an energy source for Danish households.

In addition to the joint use of the technique that was mentioned with AHP to implement the BSC idea (Bazil et al., 2021), it has also been proven to be useful in other contexts of district-heating-system management. For example, TOPSIS was integrated with PROMETHEE in order to support the search for the optimal control mode of a heating system that supplied new buildings (Ziemele et al., 2014a), and the technique itself was used to support the reduction of pollutant emissions that were generated by a heating company due to the appropriate structuring of the thermal energy tariffs, thus promoting an increase in energy efficiency and the use of renewable energy sources in a heating system (Ziemele et al., 2014b).

### 3.4. Use of other techniques

Among other techniques, the SMAA technique has been used in urban thermal energy. Kontu et al. (2015) applied it to indicate an appropriate heat source for a planned estate of single-family homes, which ultimately turned out to be a heating system that produce heat from biomass in combination with electricity. Kirppu et al. (2018) used it for a multi-attribute assessment of zero-emission (i.e., carbon-neutral) heat-generation technologies. Wang et al. (2018) utilized the technique for an multi-criteria stochastic assessment of heating systems, while Pinto et al. (2019) used it to evaluate carbon-neutral technologies for district heating systems.

From the point of view of the subject matter that is considered in this work, an isolated case of using SMAA to evaluate alternatives of potential investments in an urban heating system (Wang et al., 2017) deserves special attention in the context of practical applications of the MADA methodology.

## 4. CONCLUSIONS

Contemporary decision-making problems in district heating systems are very complex, as their solutions are influenced by many specific factors; e.g., their multi-disciplinary nature, involvement of numerous stakeholders, multi-dimensionality and difficulty in measuring (at least some) assessment criteria, goals, and interactions with the multi-dimensional environment, and uncertainty as to the nature of their conditions in the future. Solving them cannot simply rely only on intuition, as this requires complex analyses. Fortunately, the MADA methodology has provided many different tools to support such analyses.

The literature review on the applications of MADA in urban thermal energy shows that, despite the much-earlier and long-term availability of mature techniques, interest in these applications has been relatively recent in urban thermal energy (only since the turn of the 20th and 21st centuries). Moreover, most of their applications concern the last few years and the following problems: the assessment and optimization of urban heating systems, the selection of the appropriate technology (including sources of heat), and the implementation of sustainable development and energy transformation. Some of the applications have also concerned the management of a district heating system and an enterprise.

In practice, the tools that represent each of the two types of MADA techniques that were distinguished at the beginning of this section were used for this purpose. These tools include TOPSIS (which represents aspiration- and reference-level tools) and AHP (which represents a full aggregation of preferences). Among the other more frequently used techniques, the following stand out: PROMETHEE (in the group of outranking relationship techniques), and SMAA (in the group of the remaining techniques).

Only in one of the applications – regarding the use of the last of the above-mentioned tools – the context of assessing and selecting investments in urban heating systems appeared directly. However, the nature and practice of using other MADA tools suggest the possibility of also using more-intuitive tools from other groups for this purpose, including the AHP, TOPSIS, and PROMETHEE techniques (and especially the underestimated tool – the VIKOR technique – which skillfully complements the methodology of aspiration and reference levels with a type of analysis sensitivity and the concept of veto). In turn, if it is necessary to take non-hierarchical multi-directional connections between various factors that determine the assessments of decision making alternatives into account, it is possible to use an improved variant of the AHP technique (in the form of ANP).

Ultimately, it can be concluded that the MADA methodology still has a lot to offer in the context of supporting the analysis of the complex investment variants that are implemented in urban heating systems – especially since there are also numerous possibilities of combining various tools. For example, if it is necessary to supplement quantitative techniques (such as tools that use aspiration and reference levels or SAW with the possibility of taking factors that are difficult to measure into account – safety, comfort, social mood, etc.), it is worth using the possibility of reliably processing expert opinions by using pair-comparison techniques; e.g., AHP or ANP. It is also worth using a similar option in the case of objectifying the weights that determine the importance of the individual dimensions of investment analysis, which has been provided by several recent works (Arslan et al., 2021; Bazil et al., 2021; Fang & Wang, 2014; Laktuka et al., 2021; Ziemele et al., 2014a). An interesting potential solution that will enrich the analysis of investment variants may also be the use of a specific type of sensitivity analysis thanks to the concurrent independent use of various MADA techniques during the analyses of investment alternatives; e.g., Wen et al. (2021).

It is also worth noting that an undoubted advantage of the MADA methodology with regard to the analysis and selection of investment alternatives in municipal district heating networks may be the wide availability of their computational implementations that were extensively presented by Ishizaka and Nemery (2013) – especially in the case of using more-complex and more-advanced techniques.

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