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Supporting Multi-Attribute, Non-Compensating Selection of the Right Heat Pump Device for a Residential Building, Considering the Limited Availability of the Necessary Resources

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Abstract: Reliable and comprehensive choice of a suitable domestic heat pump for a common dwelling house is discussed in the paper. The application of common and freely available market information about possible heat pump options is considered in this regard. The intangibility, imperfect nature, and overload of available information, as well as a common issue amongst interested homeowners—scarce critical resource availability, e.g., financial means—are also dealt with. A specific, universal multistage decision support procedure is proposed in the paper to help a houseowner to make an informed heat pump choice. At first, a concept of a pairwise comparison and a notion of dominance under imperfect information are utilized to build a kind of option hierarchy. A particular heat pump device is then recommended by means of exploring consecutive option hierarchy levels and an actual houseowner's critical resource capacity in a non-commensurable manner. It seems that this joint application of common imperfect information about available options and critical resource availability, as well as the ideas of option dominance and non-commensurability, make the approach an interesting way for a casual homeowner to make an informed heat pump device choice. A sample analysis is also applied to show the merits and the usefulness of the approach in the paper.

Keywords: decision support; heat pump; dwelling house; limited resource capacity; informed choice; common market information; imperfect information; intangibility; pairwise comparison

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1. Introduction

This study is devoted to the issue of multi-attribute assistance in choosing the right heat pump device for a user of a typical new single-family house. The proposed solution is illustrated by a computational example. At the same time, we take into account the limited availability of resources necessary for both the implementation of such an investment and its subsequent uninterrupted operation. The choice of the pump as a source of thermal energy was dictated by environmental considerations, particularly preventing the emission of air pollutants.

There are many manufacturers and distributors of heat pumps on the heat pump market. The market offer is full of many types of heat pumps [1], each featuring many different devices with different attributes (parameters). Heat pumps are generally selected on the basis of their intended use and appropriate power. Of the other attributes, usually only the investment costs are taken into account, which are the final criterion for the decision to undertake such an investment. In fact, heat pump offers presented by various manufacturers and distributors may differ significantly in terms of other attributes—not only related to technical and easily measurable issues. Such differences should also be taken into account when analyzing the available offers in order to make a really good choice.

The initial research interest in heat pump devices appeared in the first half of the 20th century. Firstly, the possibility of the application of heat pumps for house space heating was discussed by Zehnle [2] and Berry [3]. Secondly, the possible application of heat pump for continuous air-conditioning was provided [4,5]. Thirdly, the utility and practical impacts of heat pump devices were considered [6,7]. Primary attention was initially paid only to ground source heat pumps (GSHPs) [8]. The first review of contemporary heat pump technology was presented by Penrod [9]. Both ground and air were acknowledged to be a possible lower heat source in this regard. However, these were GSHPs that prevailed in heat pump research in the subsequent decades.

Research problems which deal with air source heat pumps (ASHPs) have appeared in the literature since the mid-1980s. The initial research dealt with the comparison of their efficiency against a GSHP device [10]. Actual development of research on ASHPs started at the turn of the century with experimental investigation of ASHPs for cold regions [11], techno-economic ASHP analysis [12], performance ASHP characteristic identification [13], and analysis of the effects of substitute refrigerant application for ASHPs [14]. Several ASHP-related studies have emerged since then. Diverse issues were mainly addressed by the researchers in this regard. The main discussion patterns are presented below.

ASHP performance seemed to be the topic of primary interest among researchers. For example, the authors of [15] conducted a field test investigation of a double-stage coupled heat pump heating system for cold regions. The described system consisted of an ASHP device and a water source heat pump (WSHP). Kelly and Cockroft [16] devoted their research to the performance of an ASHP device during its retrofit application. Cabrol and Rowley [17] confirmed supremacy in the performance of a coupled floor heating–ASHP system in a residential building over an analogous system based on natural gas boiler application as a heat energy source. Wang et al. [18] investigated frost-free ASHP performance in the case of domestic hot water (dhw) preparation. The performance of a two-stage variable-capacity ASHP was also investigated, and simulation results were compared with field test results by Safa et al. [19]. Hakkaki-Fard et al. [20] confirmed ASHP's superiority over GSHP application in terms of performance during a period of investment return for Canadian cold climates. Techno-economic analysis of an ASHP device applied for space heating was dealt with in [21]. Real performance results of ASHP application under the coldest Chinese climate conditions were reported by Zhang et al. [22]. ASHP-based heating, ventilation, and air-conditioning (HVAC) system superiority over a GSHP-based HVAC system was also confirmed in the case of a residential net-zero-energy building [23].

Investigations of ASHP performance have continued. For example, Wang et al. [24] showed the results of extremum seeking ASHP control strategies for a novel transcritical CO_2 heat pump for simultaneous space heating and cooling. The integration of multi-split ASHP devices with different energy accumulators to improve the overall ASHP system performance was also discussed [25]. Model predictive control for the effective operation of a transcritical CO_2 air source heat pump water heater [26] was proposed. A semi-theoretical model for ASHP energy efficiency assessment was introduced by Xu et al. [27]. Cheeser et al. [28] performed an in situ ASHP performance assessment, while Vučković et al. [29] dealt with the comparison of ASHP operation in different real operational conditions by means of using an advanced exergy-based and exergoeconomic approach. The seasonal performance of ASHP devices was investigated by Yang et al. [30]. Xu et al. [31] devoted their efforts to the analysis of the key factors influencing ASHP performance while taking into account real monitoring data. Liu et al. [32] designed and optimized an ASHP-based multisource complementary heating system for the Tibetan area. Short-term dynamic monitoring was applied by Sun et al. [33] to predict seasonal heating performance for an air-to-water ASHP. The performance of an ASHP system for housing stock load applications at low-to-medium and high supply temperatures was analyzed by Abid et al. [34]. Pei et al. [35] investigated the characteristics of a combined air-conditioning system which consisted of ASHP with a heat pump water heater (HPWH). The impact of water volume on an ASHP system's energy-saving potential was analyzed [36]. Liu et al. [37] addressed the performance of a novel dual-temperature ASHP, called NDAHP, which was based on the application of an ejector vapor compression cycle. The actual adequacy of simulation results was verified by experimental data. Mohammadpourkarbasi and Sharples [38] compared different heating alternatives with regard to lifecycle costs and acknowledged the merits of ASHP device application for heating, especially when used together with a solar energy-heated dhw system. Note, however, that they did not expect an immediate rush in using the device because of its considerably long payback time in comparison with alternative ways for heating energy supply.

The domestic context of ASHP performance was also discussed in several publications. For example, the performance of a residential heating system which consisted of a photovoltaic/thermal collector and ASHP device was modeled and simulated for cold Canadian climate conditions [39]. ASHP performance was optimized by means of the application of a generalizable occupant-driven model application for dhw preparation by Kazmi et al. [40]. Residential ASHP performance underwent data-driven analysis by Zendehboudi et al. [41]. Abid et al. [42] considered the impact of heat supply temperature and operating mode of control in a specific domestic ASHP case on retrofit assessment.

Innovative solutions were proposed to enhance the effects of the performance of ASHP devices. For example, Jiang et al. [43] presented a novel non-frosting ASHP system based on the application of glycol, and Jabari et al. [44] proposed and optimized a specific novel advanced adiabatic compressed air energy storage and ASHP-based combined cooling and heating system. Fang et al. [45] and Fang et al. [46] introduced a prototype bed-based ASHP and assessed thermal comfort for inhabitants. An innovative coupling of phase change thermal storage floor and ASHP was proposed and experimentally studied by Heng et al. [47]. Ural et al. [48] applied energy and exergy-based methodology while discussing the performance of a textile-based solar-assisted ASHP.

Since ASHP performance may be considerably hindered by the frosting phenomenon, the reduction in or even elimination of the effect of the phenomenon has been a very popular detailed topic among researchers. For example, an experimental investigation of reverse cycle defrosting techniques was presented in [49], and Minglu et al. [50] discussed the possibility of improving thermal comfort during defrost thanks to the application of a novel reverse-cycle ASHP defrosting technique. The operating performance of a novel reverse-cycle hot gas defrosting method for ASHPs was researched in an experimental setting by Wenju et al. [51], while Dong et al. [52] presented an experimental study of defrosting heat supplies and energy consumption during a reverse cycle defrost operation in a ASHP device. A reverse cycle defrosting performance on a multi-circuit outdoor coil unit in an ASHP was discussed by Qu et al. [53]. Jiang et al. [54] showed and experimentally confirmed the efficiency of a novel defrosting control technique based on the degree of refrigerant superheat, while Zhu et al. [55] proposed a specific temperature–humidity–time defrosting control technique with the use of a frosting map concept. Tang et al. [56] introduced a novel frost prevention technique and experimentally confirmed its efficiency. The energy transfer process in ASHP and the specific effect of metal energy storage during defrosting were investigated [57] to improve defrost efficiency. Chung et al. [58] and Wang et al. [59] dealt with the assessment of proper defrosting time start. A semi-experimental ASHP frosting performance technique was provided by Pu et al. [60]. Li et al. [61] proposed to apply image recognition to frost build-up detection in ASHP devices. The application of a heater-assisted ASHP conditioner was introduced Wang et al. [62] to improve thermal comfort for occupants with frost-retarded heating and heat-uninterrupted defrosting.

There are also several review publications available which dealt with ASHP-based frosting issues. For example, Song et al. [63] reviewed the improvements for ASHP units during frosting and defrosting, and Zhang et al. [64] presented several approaches which might make ASHP operation frostless.

The influence of frosting on the degradation of ASHP performance was also investigated. ASHP performance under a specific effect of a mal-defrost phenomenon was dealt with in [65]. Qu et al. [66] conducted an experimental investigation related to the performance of reverse-cycle defrosting for an ASHP device which used an electronic expansion valve. Song et al. presented the results of an experimental study on even frosting performance for ASHP unit with a multi-circuit outdoor coil [67,68]. On the other hand, Song et al. [69] conducted an experimental investigation with regard to the performance of an ASHP unit with a three-circuit coil for its reverse cycle defrosting termination temperature. Eom et al. [70] utilized a deep learning artificial neural network (ANN) to predict ASHP system performance under frosting conditions. The effect of real temperature on seasonal energy performance under different locations was investigated by Di Schio et al. [71].

A considerable number of publications have dealt with the issues related to the ASHP application potential. For example, Singh et al. [72] identified factors which influenced the uptake of heat pump technology by the UK domestic sector. Probabilistic modeling and assessment of electric ASHPs and GSHPs on low-voltage distribution networks was dealt with by Navarro-Espinosa and Mancarella [73]. Su et al. [74] addressed ASHP device applications for heating in residential buildings and their future outlook in this regard. The applicability of different alternatives for a combined solar ASHP system under different climatic conditions was investigated by Xu et al. [75], while Wang et al. [76] analyzed the effects of the application of a low-temperature ASHP heating system in a cold area. A specific ASHP application-related topic of load matching and energy cost issues in net-zero-energy houses was analyzed by Lim et al. [77]. Tzinnis and Baldini [78] discussed the integration of sorption storage technology with ASHP to foster the integration of solar technology with buildings. Practical recommendations about the suitability of GSHP and ASHP devices were also formulated for several coldest world's cites by Nikitin et al. [79].

There are also some reviews available which discussed peculiar ASHP technology application cases. For example, Kamel et al. [80] dealt with the integration of PV solar systems and heat energy storage with ASHP devices, while Wang et al. [81] and Yang et al. [82] discussed recent advances in ASHP systems assisted by solar thermal, photovoltaic, and photovoltaic/thermal sources. Liu et al. [83] addressed the energy effectiveness of renewable energy technologies, including ASHPs in the context of near-zero-energy houses in different climatic zones, and Carroll et al. [84] dealt with field tests of ASHP devices.

The application of domestic ASHP was also addressed by several reviews. For example, Staffel et al. [85] discussed available domestic heat pump options, Greening and Azpagic [86] showed interest in environmental lifecycle impacts and the potential for domestic heat pump sector in the UK, Kelly et al. [87] coped with the potential of ASHP technology for residential sector to limit the use of solid and liquid fuels, and Poppi et al. [88] presented a techno-economic review on solar heat systems supported by ASHP device application to reduce a gap in residential heating systems-related research.

The available literature and actual market trends show that ASHP devices are becoming more and more acknowledged and popular heat source appliances in the domestic sector. However, despite the considerable number of market offers, the common recommendation of the proper ASHP device for individual investors and homeowners is usually based on a very limited set of technical and economical device attributes, which do not provide adequate measures for a reliable overall device assessment. Moreover, the available ASHP device offers are often incompatible with each other due to differences in presented information. Therefore, individual investors and homeowners are often deprived of an opportunity to make a conscious informed device choice, and they are finally forced to choose a device solely on the basis of the actual offer price which is always given by suppliers.

Therefore, a procedure is proposed in this paper to enable interested individual investors and homeowners to make a reliable and informed multi-attribute choice of an adequate ASHP device. The procedure allows making use of common imperfect and universally available information about possible devices, i.e., diverse market ASHP device offers. Pairwise comparisons are applied in this regard to take the influence of both intangible and tangible device attributes into account. Merit analysis of available offers is conducted independently of the analysis of critical means availability, e.g., financial resources. This is because such an approach is capable of providing a means to improve the final ASHP device choice as it is only possible under the actual availability of critical resources.

Dynamic development of heat pump technology resulted in an air source heat pump (ASHP) application boom in recent years, particularly among dwelling houseowners. Therefore, the popularity of ASHP technology drove us to propose a procedure for the reliable choice of an ASHP device which would be well suited for the purpose of conscious and informed use by a regular homeowner. In practice, such a perspective user is usually confronted with diverse offers. The offers are often inconsistent with each other and incomplete. A critical assessment of the offers is, therefore, necessary. We are aware that there is a possibility to consult details with ASHP device providers. However, even an informed homeowner is not often able to consult their doubts with each provider due to time constraints. Admittedly, there is a possibility of using some kind of consulting service. In addition to being costly, the use of consulting services may bring some danger for a rather unexperienced and not fully aware homeowner. This danger is related to a lack of ability to critically assess information provided by the services due to gaps in the homeowner's knowledge and experience. The perspective ASHP users are finally faced with a multitude of inconsistent and incomplete offers. Nevertheless, the situation of a homeowner interested in the application of a heat pump may be even more disadvantageous. This is because of a lack of adequately attainable and easy-to-use yet reliable and comprehensive heat pump choice support. This is why we propose the adequate supporting procedure in the paper, which is well suited to the limits in market information provided by ASHP suppliers.

Our proposal is devoted to the official local Polish market offer for ASHP devices. We aimed to provide a necessary means for the choice of such a device for a typical new house located in Cracow, Poland. It is assumed that the device should be able to provide heating energy for colder periods, cooling energy for hotter periods, and domestic hot water (dhw) throughout the year in the case of a six-person family. A typical detached single-family house architecture and construction technology are applied. The house area is about 320 m^2. We also expect the homeowner to be able to spend no more than PLN 60,000 (about USD 15,000 as for October 2021) for the device.

2. Methods

2.1. Multi-Attribute Decision Making Support

Due to the ever-increasing complexity of contemporary practical issues, making the right decisions requires methodical support. For this purpose, the multicriteria decision making (MCDM) methodology has been constantly developed. Two separate approaches can be distinguished within it. The first, referred to as multipurpose decision support, i.e., multi-objective decision making (MODM), consists of the specific programming of decisions, i.e., creating the optimal option. In the second approach, called multi-attribute decision analysis (MADA), also known as multicriteria decision analysis (MCDA), a certain, predetermined set of possible options (decision alternatives) is considered. The issue discussed in the paper falls within the MADA methodology, which is reviewed below.

The beginnings of the MADA methodology date back to the 1960s, when a pioneering method of supporting the decision analysis Élimination et Choix Tranduisant la Réalité (ELECTRE) was boldly proposed [89]. Currently, this methodology offers numerous and varied tools to support the decision-making process. Basically, they facilitate a rational evaluation of the available options, described by at least two different attributes, when carrying out various types of tasks. The tasks carried by MADA methodology include the following [90]:

- MADA problem description.
- The choice (indication) of the most suitable option (options) among options available.
- Ranking/ordering of available options from best to worst, or vice versa.
- Grouping (sorting or classification) of available options.

It should be noted that, regardless of the actual basic purpose of the analysis, a specific model is always used to express the relations among problem components: objects, their attributes, the principles of their assessment, etc. Note that, when there is a need for a closer examination of the characteristics of a very original and complex decision-making problem, we may limit ourselves to the sole description and the understanding of the problem. In the case of other types of tasks, the description of a specific decision-making problem is the starting point for building the model. This model is then used to solve the problem. The process of solving of an MADA problem includes the following stages:

- Problem definition.
- The determination of considered options and appropriate criteria for their assessment.
- The choice of the technique for solving the problem, as well as the construction of a detailed problem model.
- A multidimensional assessment of options.
- Provision of a problem solution by means of the recommendation of the best option (or a set of the best options), constructing the ranking of options, or dividing options into several groups.

MADA methods include both specialized techniques for solving specific problems and universal techniques. Depending on the applied rules, they can be divided into three basic groups [91]:

- Full preference aggregation techniques.
- Outranking relation techniques.
- Goal, aspiration, or reference-level techniques.

In addition, there are other, generally less popular, techniques available that do not fit into any of the three groups. Detailed information on them can be found in numerous review publications [92–95]. Due to their outstandingly applicative nature, many interesting details related to the principles of their application can be found in numerous studies dedicated to specific applications [96–107]. In addition to compact publications, the use of the MADA methodology can be found in many scientific articles and conference papers; for example, a query for MADA and MCDA abbreviations in the SCOPUS scientific bibliography database currently generates a list of about 3000 such sources.

The techniques of the full preference aggregation group are derived from the concept of the multi-attribute value (MAVT) and the multi-attribute utility (MAUT) [108]. They mostly use weighted aggregation of partial option ratings, which correspond to particular decision alternative attributes. Popular methods of this group include simple additive weighting (SAW) and simple pairwise comparisons, along with even more complex techniques, e.g., analytic hierarchy process (AHP) [109] and analytic network process (ANP) [110]. It is also worth paying attention to the methods that eliminate some disadvantages of the classic methods of this group, e.g., Measuring Attractiveness by a Categorical-Based Evaluation Technique (MACBETH) [111] and Ratio Estimation in Magnitudes or Deci-Bells to Rate Alternatives Which Are Nondominated (REMBRANDT) [112]. In general, full preference aggregation techniques make it possible to compensate for the worse partial ratings of options with better ratings. Note that such a feature may not be accepted in the decision analysis while searching for the undoubtedly best option.

Outranking relation-based techniques are mainly represented by two families of methods: ELECTRE [113] and Preference Ranking Organization Method for Enriched Evaluation (PROMETHEE) [114]. Currently, several versions of the ELECTRE and PROMETHEE methods are available. They differ in purpose, resulting from gradual improvement. In the ELECTRE methodology, partial binary relations which connect different options are used to build the overall outranking relationships. These relations are then used as part of the so-called exploitation procedure to finally solve the stated problems. The basis for the identification of the outranking relationships in the PROMETHEE methodology is provided by the unitarized difference of option preferences. The unitarized differences result from the absolute difference in the value of the option evaluation criteria. So-called positive (used to express the advantage of a given option) and negative (used to express an advantage of other options over a given option) outranking flows are finally applied to derive the characteristics of relations which connect different options.

Several derivative techniques were also proposed on the basis of ordinary ELECTRE and PROMETHEE concepts [115]. Contrary to the full preference aggregation techniques, the techniques which employ a concept of outranking relationship do not allow for the compensation of worse partial scores of options with better partial scores. As such, the feature is often desirable in decision making.

The techniques belonging to the goal, aspiration, and reference-level group implement diverse ideas:

A. Minimizing the differences between the evaluation of options and the evaluation of certain patterns, e.g., in linear programming-based goal programming [116] for ranking of options and the choice of the best option.
B. The concept of a distance in a multidimensional space of assessment criteria from an option to assumed anti-ideal and ideal option patterns, such as in popular ranking approaches Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [117] and Visekriterijumska Optimizacija i Kompromisno Resenje (VIKOR) [118].
C. Result-to-input ratios, such as data envelopment analysis (DEA) [119], used to identify effective (nondominated) options in terms of productivity.

The decision analysis methodology is complemented by methods that use other, less consistent ideas. In general, they involve the use of specific information representations. Examples of these can be found, for example, in the chapter entitled 'Nonclassical MCDA Approaches' of the book by Greco et al. [92]. The choice of an approach other than the three types of MADA methods mentioned above is often determined by the need to strictly adjust the method of solving a given problem to the specific type of conditions related, e.g., to the available information. Note that, to solve the problem to which this work is devoted, we also used such a specific, strictly dedicated approach.

It is also worth paying attention to the fact that the universal nature of most MADA methods means that they can be used in a number of different ways, e.g., by skillfully combining them to use their full potential in solving various practical problems [120].

2.2. The Choice of Appropriate Approach

A review of the available literature reveals that there are a few publications only which dealt with multidimensional heat pump device choice. There are several more publications available, nevertheless, which dealt with several strictly related issues, particularly the choice and prioritization of a medium or equipment. Some representative publications in this regard are listed in Table 1. It seems that some of them apply employed several MCDA tools, such as PROMETHEE, TOPSIS, and VIKOR. However, it also turned out that specific optimization and operational research tools were utilized in this regard. Linear programming (LP), mixed integer linear programming (MILP), mixed integer nonlinear programming (MINLP), mixed integer quadratic constrained programming (MIQCP), and fuzzy logic, along with specific improvement and innovation tools, e.g., Taguchi techniques, have been utilized to deal with the inherent complexity of modeling and solving of heat pump-related problems. Nevertheless, the complexity and specific assumptions make them rather nonintuitive. Thus, the intention to use them consciously imposes an obligation on their perspective casual user to master knowledge about the tools to be able to exploit their merits. This is why an approach based on an intuitive notion of pairwise comparison and dominance in the Pareto sense is proposed in this paper to deal with the informative and uncompromising choice of a heat pump device for a casual homeowner and other interested parties.

Table 1. A sample of the related literature.

Publication	Details	Technique
Vering et al. [121]	Selection of a refrigerant for a heat pump	PROMETHEE
Wen et al. [122]	The prioritization of diverse residential energy sources	VIKOR and TOPSIS
Rikkas et al. [123]	The optimization of energy supply for a building	LP/MILP
Vering et al. [124]	The identification of the most appropriate working fluid for a heat pump	PROMETHEE
Zhou et al. [125]	Numerical and economic GSHP optimization	Taguchi technique
Hering et al. [126]	Multiple-heat-pump network optimization	MIQCP
Wu et al. [127]	Emission and life cost-oriented optimization of a district for building retrofit purposes	Epsilon-constrained MILP

2.3. The Procedure Supporting the Selection of a Heat Pump

Before starting the selection of a specific pump device, it is necessary to determine a set of factors related to the local conditions in which it will be used. Such factors include technical conditions related to the possibility of using certain types of heat pumps (air, water, or ground), their specific purpose (heat delivery for heating, heat and domestic hot water, or cooling), and the required technical parameters of the pumps (e.g., power supplied by the device). Such a set of factors can, thus, generally be regarded as a preliminary "sieve", making it possible to limit the set of potential pump devices to those that can actually be used in specific circumstances.

A multi-attribute assessment based on other relevant attributes of such devices also fits well when searching for the appropriate heat pump device in given local conditions. However, particular attention should be paid to the limitations in the supply of resources, which determine the final possibility of heat pump purchase and use. They may include the availability of (usually not insignificant) financial resources that are necessary to acquire the device itself, its instrumentation, and other required equipment, as well as the availability of personal abilities, human resources, etc. That is why we finally decided to apply the proprietary adaptation of the idea of a multistage MADA [128], which consisted of the following stages:

1. Initial limitation of the set of all available heat pump devices based on local conditions and technical feasibility.
2. Multidimensional device assessment and ordering of technically feasible heat pump devices in terms of important substantive attributes other than critical resources needed to acquire and use a device.
3. The identification of the best device taking into account critical resource availability.

The ordering of heat pump devices, referred to in the second stage of the analysis, was assumed to be non-compensatory. This is because of a general intention to provide interested people with necessary means for an uncompromising ASHP choice. To implement this, a proven idea, originally presented in [129], was used. Its efficiency was positively verified in the case of the recommendation of the appropriate economic, social, and environmental options for changing dirty heat sources in residential buildings [130]. It is based on the use of pairwise comparisons of technically feasible heat pump devices. The comparisons are made in relation to substantive attributes which have not been utilized for the identification of technically feasible devices. The main reason for using pairwise comparisons is to enable a uniform method of taking into account both measurable (tangible) and immeasurable (intangible) attributes of heat pumps which are used to describe available device offers.

The attributes describing heat pump devices may not only differ in terms of their measurability, but also represent various specific aspects, e.g., time, delivery or execution, or a specific investment. We can also use the principles of the qualitology [131] to divide them into three specific groups:

- The maximums, called stimulants in econometrics, and values in commercial offers (a higher level is better).

- The minimums, called destimulants in econometrics, and shortcomings in commercial offers (a lower level is better).
- The optimums, called nominants in econometrics, and mediums in commercial offers (a given range of levels is best).

Note that individual attributes can differ significantly in terms of the units of measure and the range of values. However, the cross-attribute differences do not matter in our case. This is because simple pairwise assessments propose which of two compared ASHP devices at a time is more preferable than the other, according to a given attribute. Therefore, the application of pairwise comparisons of heat pump devices facilitates the construction of a multilevel structure of domination for the heat pump devices considered. The highest level of the structure is made up of heat pump devices that are nondominated, in the Pareto sense, by other devices. Such devices dominate over those that make up the remaining levels of the hierarchy or are incomparable with other devices. Domination in the Pareto sense means surpassing other heat pump devices in terms of at least one of the remaining substantive attributes, while remaining equivalent in the case of other attributes. Subsequent, lower levels of the hierarchy are occupied by heat pump devices that are dominated by heat pumps from higher levels of the hierarchy. As a consequence of the application of such a principle, the lowest hierarchy level is occupied by heat pump devices which are dominated by devices from higher hierarchy levels. Note that the dominance hierarchy can be clearly represented in the form of a directed hierarchical graph expressing the well-known idea of a Hasse diagram [132].

The age-old, but still popular [133] technique, named Interpretative structural modeling (ISM) [134], can be used to construct a dominance hierarchy in a stepwise manner. It consists of using comparisons of options, i.e., devices of heat pumps in our case, in order to identify binary relations connecting individual devices. These relationships comprise the foundation for constructing a square matrix **A** (Equation (1)), composed of the number of rows and the number of columns corresponding to the number of options n. The fact that the i-th successive option dominates over the j-th successive option ($I, j = 1, 2, \ldots, n$) corresponds to the value of the matrix element located at the junction of the j-th row and i-th column of the matrix equal to 1, while a value equal to 0 means that there is no such relation between these options.

$$\mathbf{A} = [\mathrm{a}_{ij}]. \tag{1}$$

The square unit matrix **I** of the same size is then added to matrix **A** to obtain matrix **B**.

$$\mathbf{B} = (\mathbf{A} + \mathbf{I}). \tag{2}$$

Finally, **B** undergoes the process of raising it to powers, which are consecutive natural numbers, starting with the power of 2. As a result, we obtain a series of exponentiation results: $\mathbf{B}^2, \mathbf{B}^3, \ldots, \mathbf{B}^k, \mathbf{B}^{k+1}$. This process finishes when the location of all zero elements in two successive exponentiation results (power exponents: k, $k + 1$) of the matrix **B**, i.e., in matrices $\mathbf{B}^k$ and $\mathbf{B}^{k+1}$, does not change. Then, a matrix **D** (Equation (3)) is constructed on the basis of matrix $\mathbf{B}^k$. Zero components in matrix **D** appear in the same places as in the case of matrix $\mathbf{B}^k$, and nonzero components in $\mathbf{B}^k$ are replaced with those in **D**.

$$\forall_{i=1,\,2\,\ldots n}\ \forall_{j=1,\,2\,\ldots n}\ d_{ij} = \left\{ 1 \leftrightarrow b_{ij}^{(k)} \neq 0 \,\middle|\, 0 \leftrightarrow b_{ij}^{(k)} = 0 \right\}, \tag{3}$$

where $b_{ij}^{(k)}$ denotes a component of the i-th subsequent row and the j-th subsequent column in the result of the operation $\mathbf{B}^k$.

Matrix **D** presents interesting features. Unitary components of the matrix ($d_{ij} = 1$), which appear in the i-th subsequent row indicate ASHP alternatives which are preceded by the i-th subsequent option in dominance order. Such alternatives may be defined, therefore, as descendants of the i-th subsequent alternative. On the other hand, unitary components which appear in the j-th subsequent column are related to alternatives which are antecedents of the i-th subsequent option. This is the information about sets of descendants $\Gamma^-(i)$ and sets of antecedents $\Gamma^+(i)$ for the subsequent (i = 1, 2, . . . , n) option that provides a bare foundation for the process of heat pump device domination hierarchy construction. The construction starts from the uppermost hierarchy level and ends at the bottommost hierarchy level. At the same time, a universal rule is applied, according to which each of the currently considered options goes to the currently considered hierarchy level, for which the set of descendants is the same as the intersection of the sets of its antecedents and descendants. In relation to the i-th option, this principle is presented as follows:

$$\Gamma^-(i) \equiv \Gamma^-(i) \cap \Gamma^+(i). \tag{4}$$

After identifying the options for a given hierarchy level, they are removed from the sets of the antecedents and descendants of the remaining options. The composition of the next, lower, level of the dominance hierarchy is then set. In this way, at individual stages of building the structure of domination, only those options that have not yet been placed on any of the previously considered levels of the hierarchy are taken into account. The process of the composition of individual levels of the dominance hierarchy ends when there are no options left. Thus, from a formal point of view, a set of all options $\{o_i\}$ is subject to a gradual reduction in the process of constructing the hierarchy of domination until it becomes an empty set.

The essential elements of the procedure responsible for deriving the hierarchy of domination for options, i.e., heat pump device alternatives, are as follows:

1. Determination of the characteristics of option attributes and their states for individual options.
2. The creation of a rectangular decision matrix **X** to describe attributes of considered options. The matrix consists of n rows which are devoted to subsequent options (I = 1, 2, . . . , n) and m columns which deal with subsequent substantive attributes (j = 1, 2, . . . , m). Matrix component x_{ij} contains information about a state (a level) of the j-th subsequent attribute in the case of the i-th subsequent option.
3. Unifying the character of option attributes—the transformation of the decision matrix into a form **X*** which is based on a uniform nature of all attributes. This can be achieved by means of adequate transformation of all attributes that are minimums or optimums into maximums. For example, the application of zero-based unitarization [135] may help in this regard.
4. The identification of direct option dominance cases thanks to the application of $n(n-1)/2$ pairwise option comparisons and the construction of direct dominance matrix **A** (Equation (1)).
5. The identification of indirect option dominance cases, i.e., the dominance through other options. The derivation of a series of results of raising **B** matrix (Equation (2)) to subsequent powers and the construction of domination matrix **D** (Equation (3)) to express final dominance hierarchy for heat pump device alternatives.

The final dominance hierarchy is then used in the next stage of the analysis to identify the most appropriate heat pump device alternative. For this purpose, consecutive dominance hierarchy levels are exploited, from the highest level downward, to identify the devices which are feasible according to the availability of necessary critical resources. If the available amounts of critical resources allow for the practical use of more than one of the devices from a given hierarchy level, then different additional criteria can be used to identify the most appropriate among them. Note that resource efficiency in the context of selected substantive attributes or savings in the use of necessary resources and, as a last resort (in the case of the lowest level of consumption of necessary resources by more than one option), a MADA method or even heuristics [136] may be applied for this purpose.

However, in this study, the application of a specific complementary approach is proposed in this regard. This is because the approach makes it possible to take the imperfect characteristics of available information about offers into account. The attributes which appear in the description of the substantial majority of all considered offers, e.g., 80% of all offers, at least, are used with this regard. It is also assumed that a higher actual share of such an attribute increases its credibility. Note that such concept of credibility is in line with the 100% credibility of substantial attributes which appear in all offers. Auxiliary attributes can be then applied, starting from the most credible one to the least credible one, to compare the feasible device at a given dominance hierarchy level until only one (or very few) of them remains. Note that any suitable decision analysis technique may be used to indicate the most beneficial option in the case that more than one heat pump device remains after the application of all auxiliary attributes.

The overall procedure for the recommendation of a heat pump device is illustrated by the flowchart given in Figure 1, which also provides general the idea about the usage of both substantial and auxiliary information while searching for the most appropriate device. Note that actual stages of the procedure are expressed by bolded boxes, while the information input and output for each stage is expressed by dotted and dashed boxes, respectively.

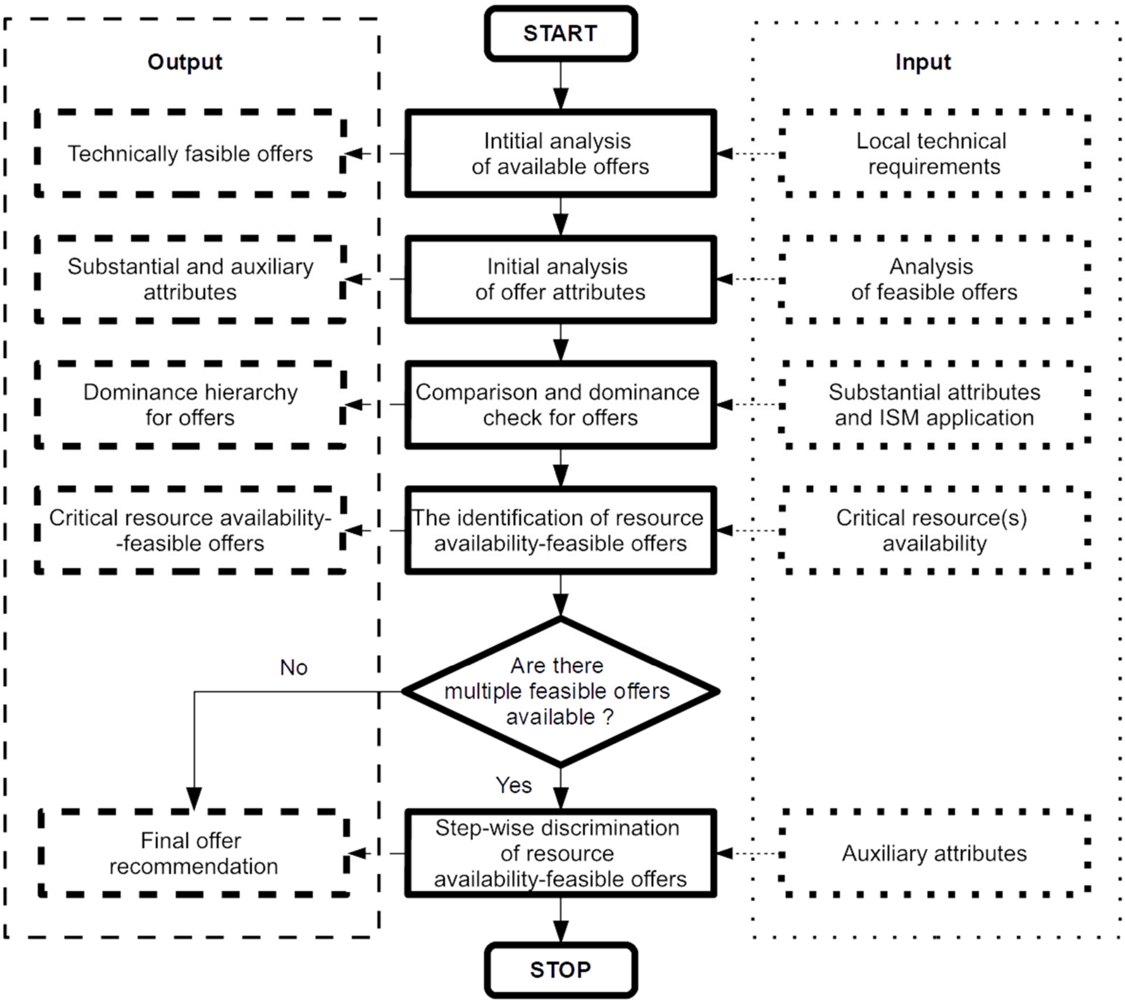

Figure 1. Proposed procedure scheme.

Figure 1 makes it evident that local technical requirements are needed to supply the initial analysis of available offers to identify technically feasible offers. Identified feasible offers then undergo a detailed investigation. This investigation results in their substantial and auxiliary offer attributes. A hierarchy of auxiliary attributes according to their share in initially identified offers is also derived. The next stage deals with the application of identified substantial offer attributes to compare individual feasible offers and ISM to derive complete dominance hierarchy for offers. Then, the availability of critical resources is utilized to indicate technically feasible offers that are applicable in terms of such resources.

The highest possible dominance hierarchy level that contains applicable offers is applied in this regard. In cases where a single feasible offer is identified, the offer is then registered and recommended, and the procedure stops. Otherwise, the attributes form successive levels of a hierarchy of auxiliary attributes, which are utilized until a single offer or a few feasible offers are identified. The identified offer(s) are finally recommended, and the procedure stops.

It is also worth paying attention to the benefits of separating the substantive analysis of offers from the verification of the practical possibility of their use, in the context of the limited availability of necessary resources. Firstly, this allows for the indication of an appropriate offer based on the current availability of critical resources. Secondly, in the case of an insufficient supply of the critical resources, significant information is obtained about their deficit. Such information may turn out to be particularly helpful in the context of possible acquisition of a necessary amount of critical resources in order to enable the choice and use of a sufficiently good heat pump device, positioned at a sufficiently high domination hierarchy level.

2.4. A Sample Analysis

2.4.1. Basic Requirements

A casual contemporary and well-insulated two-story house without the basement, but with a well0isolated attic and ground floor, is assumed. The house is located in Cracow, Poland and is intended for a family that consists of six members. The house with regard to the heated zone is 320 m^2. Traditional structural solutions, i.e., external walls made of porous ceramics and ribbed ceramic floors, are also considered.

Lastly, the applied ASHP device should cover the actual need for heating energy above all. This is why heating power plays a fundamental role in the choice of a heat pump device. The actual need for heating power stems from the structural and geometric house properties, as well as from specific inhabitant needs. It turns out that the application of traditional structural and geometric solutions, presented above, results in a rather mediocre requirement for heating energy. Therefore, in this study, a rate of 35 W/m^2 is assumed in this regard. Thus, about 11.2 kW of heating power is required to cover the needs for heating power in the considered case. Casual heating power rate is also assumed for domestic hot water (dhw) at 0.3 kW per person. Therefore, covering the overall need for heating energy requires the application of an ASHP of nominal heating power equal to 13 kW or more. It is assumed that providing the device with such a nominal heating power level would also provide sufficient cooling energy for the house.

2.4.2. Utilized ASHP Offers

During the initial selection of options (heat pump devices), we took into account the current state of their technology [1]. We obtained information about them from an analysis of the current market offers. As the issue discussed in the paper concerns Poland, only ASHP offers from the domestic market were applied. At the same time, we collected all the information about offered devices, including technical, economic, and environmental details. It is obvious that, in the case of a different investment location, the corresponding, locally available offers should be considered.

A comprehensive study was undertaken to indicate perspective ASHP devices, which covered hundreds of offers available on the Internet. At first, more than 50 perspective ASHP devices were identified on the basis of a required power level of 13 kW. A closer look at them revealed that over 20 devices did not fit the stated requirement. This was because of insufficient capabilities, overwhelming power reserves, or even scarce data listings. Therefore, only 30 ASHP device devices qualified for the detailed analysis. Their characteristics are presented in Table A1 in the Appendix A.

2.4.3. Substantial Attributes and Required Resources

The attributes should enable both a proper evaluation of offers and a determination of the resources necessary for the effective implementation and subsequent reliable operation of the ASHP devices.

Substantive attributes for ASHPs were established on the basis of the information gathered as a result of the analysis of the current market offers. These attributes ought to facilitate the discrimination of available offers. This is why, according to the analysis of differences in domestic heat pump offers, we identified a number of attributes responsible for the diversification of the substantive assessment of these devices.

Reading the offers revealed numerous substantial ASHP device attributes, which allowed assigning them to 17 groups:

1. Brand.
2. Model.
3. Nominal power (kW).
4. Seasonal energy efficiency scores SCOP (-), SSEff. (%), and annual energy consumption (kWh/year).
5. For heating: power output (kW), external input energy demand (kW), and coefficient of performance—COP (-); for different external air temperature (OAT) levels: 15 °C, 7 ° C, 2 °C, and −7 °C.
6. For cooling: power output (kW), external input energy demand (kW), and energy efficiency ratio EER (-); for different combinations of external air temperature (OAT) and leaving water temperature LWT (°C) levels, e.g., 35 °C and 18 °C, and 35 °C and 7 °C, respectively.
7. Applied refrigerant brand and amount (kg).
8. Heat pump operational temperature range for heating and for cooling function (°C).
9. Water temperature range in indoor plant part for heating and for cooling function (°C).
10. Domestic hot water temperature range (°C).
11. Noise intensity (dB).
12. Mass of outdoor and indoor ASHP device parts (kg).
13. Hot water tank volume (if used as standard component of ASHP device set) (l).
14. Energy efficiency class for heating (and for domestic hot water production by means of a standard dhw tank together with water consumption profile).
15. Length and height difference limits for tubes (m).
16. Power supply: voltage (V), current (A), and number of current phases.
17. Number and power (kW) of additional heaters.

The ASHP market offers available on the Internet differed substantially in terms of the provided data. However, some of data appeared more frequently in the descriptions of the 30 initially qualified devices. It appeared that the following nine attributes appeared in the case of offers pertaining to all devices:

1. Nominal power.
2. Power output, required power supply, and COP indicator during heating at an outdoor temperature level of 7 °C.
3. Power output, required power supply, and EER indicator for cooling function at an outdoor temperature level of 35 °C and leaving water temperature of 18 °C.
4. Maximum provided temperature for domestic hot water.
5. Hot tank volume (if applicable).

There were also six attributes whose contribution to ASHP device offers hit a level of 80% or more:

1. Mass of basic device components (the contribution equal to 90%).
2. Energy efficiency classes (87%).
3. Noise level (87%).
4. Lower (83%) and upper (80%) outdoor temperature limits for heating function.
5. Amount and type of refrigerant (80%).

Two attributes with a complete contribution to the offers were finally abandoned. Nominal power was excluded because power output was found to be a better indicator of actual heat pump capability. The domestic hot water tank volume was relevant in specific ASHP device cases only; accordingly, it was applied as a rather auxiliary attribute when coping with such specific devices. The remaining seven substantial attributes of complete contribution to offers were finally treated as fundamental criteria for the identification of direct dominance cases.

The mass of basic device components was considered rather irrelevant. Thus, only the remaining five attributes with a partial contribution to offers were considered auxiliary attributes for a final discrimination of the dominating ASHP alternatives. To appreciate their share in offers, they were applied in order from the most frequently appearing one to the least frequently appearing one. Despite the same share level, energy efficiency classes preceded the noise level in the order due to a merit advantage. It should also be noted that the type and amount of applied refrigerant may be considered in environmental terms. The global warming potential (GWP) ratio may be used in this regard. There were two distinct refrigerants applied among the considered offers. The one that prevailed was R410A (GWP = 2088/kg), along with a second, more environmentally friendly one, i.e., R32 (GWP A4 = 657/kg). The final environmental outcome in the case of a given refrigerant amount (mass) results from the multiplication of the amount (mass) of applied refrigerant by the GWP value. Thus, the environmental outcome was finally utilized to express refrigerant quality. Note that the energy efficiency classes and upper outdoor temperature limits were treated as stimulants, while the remaining auxiliary attributes are considered as destimulants.

Information about some devices with regard to auxiliary attributes may also be missing. In order to reduce the degree of uncertainty and facilitate fair comparisons of the AHSP device offers, it was also assumed that the lack of a specified auxiliary attribute was equivalent to its least favorable level. The levels of the considered substantial and auxiliary ASHP device attributes are given in Table A2. Note that missing attribute levels are expressed by a question mark, while nonapplicable cases (dhw tank option) are expressed by a hyphen.

Advanced technological solutions may be very expensive. Heat pumps are no exception. Therefore, especially in the context of the average user, the investment and exploitation costs determine the crucial importance of the necessary financial resources to make the final decision on the use of a specific heat pump offer. At this stage of the device selection procedure, the parameters of the commercial offer of heat pumps may also play an important role, e.g., the waiting time for bringing the device or the scope of additional support for the investor during the heat pump device implementation and subsequent operation of the device. In addition, the application of other specific—also intangible—resources can be taken into account. Such a specific, intangible critical resource could be, for example, the investor's maturity and their readiness to take full advantage of the possibilities offered by the concrete implementation of heat pump technology. When using such attributes and evaluating them in terms of individual offers, the universal idea of comparing them in pairs may again prove to be useful.

Ultimately, for the purposes of an exemplary application of the proposed procedure, only one type of critical resource was utilized, i.e., the necessary financial resources to implement the investment.

2.5. Software Support

A freely available, and cross-platform FLOSS software was used to support the analysis of current ASHP device offers to facilitate software acquisition for an interested user. The R Project for Statistical Computing (available at: https://www.r-project.com (accessed on 10 June 2020)), Python 3 programming language tools (available at: https://www.python.org (accessed on 10 June 2022)), Graphviz tools (available at https://graphviz.org (accessed on 10 June 2022)), and the Apache OpenOffice Calc application (available at:

https://www.openoffice.org (accessed on 10 June 2022)) under GNU Linux OS (https://www.linux.org (accessed on 10 June 2022)) were applied in this regard.

Software tools were only supplied with data resulting from the current commonly available commercial ASHP device offers. This was because such an approach to data acquisition served well for taking into account the casual homeowner's point of view with regard to limited information about the available options. A universal data form was applied for data storage, i.e., a comma-separated ASCII (CSV) file. Information about the serious limitation of necessary resources (PLN 600,000) was also considered.

Note that the provided data were processed interactively in a rather manual manner. This was due to both instructional reasons and the intention to model a casual homeowner's perspective.

3. Results

3.1. Domination Hierarchy

To facilitate the identification of nondominated ASHP device offers, in the direct sense, all substantial attributes were normalized. Linear zero-based unitarization [128] was applied in this regard. Note that almost all substantial attributes were stimulants. Energy inputs for heating and cooling comprised notable exceptions in this regard. The normalized attribute levels are presented in columns 1–7 of Table A3.

It turned out that the set of directly dominating ASHP device offers consisted of nine items, numbered 1, 11, 20, 21, 47, 48, 53, 54, and 55. However, offer number 48, which dominated over offer number 3, was dominated by three other offers, namely, offers 47, 54, and 55. The Hasse diagram in Figure 2 presents the structure of domination for the abovementioned offers. Note that the majority of offers (7, 8 10, 12, 16–19, 22, 23, 26, 27, 29, and 32) were incomparable with other offers. As such, they were finally placed at the highest level of the dominance hierarchy. As a result, the complete dominance hierarchy consisted of three distinct levels, as presented in Table 2.

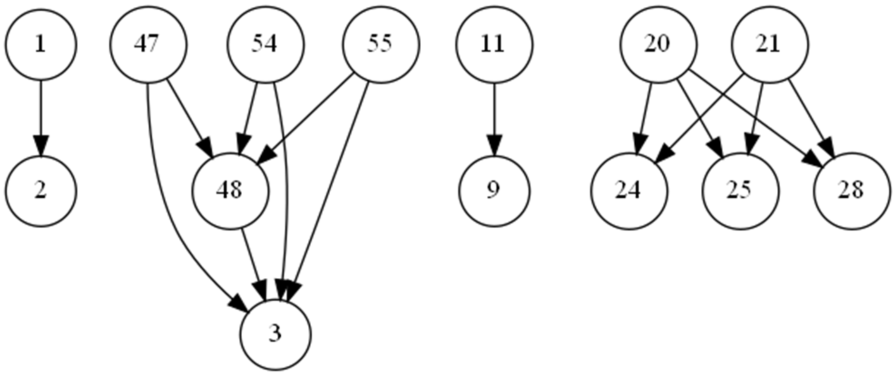

Figure 2. Structure of dominance for offers.

Table 2. Complete dominance hierarchy levels.

Level	Offers
I	1, 7, 8, 10, 11, 12, 16–19, 22, 23, 26, 27, 29, 32
II	2, 9, 24, 25, 28, 32, 48
III	3

3.2. Identification of the Best Offers

At first, all nondominated ASHP device offers were considered. These offers occupied the top dominance hierarchy level. It is evident from Figure 2 and Table 2 that there were 22 nondominated offers. Therefore, their auxiliary attributes were used to discriminate them.

At first, the energy class attribute was applied. The application of the attribute resulted in the indication of 10 A+++ class offers, numbered 1, 8, 10, 11, 20–22, 47, 54, and

55. Note that four offers (17–19 and 32) were excluded from further analysis due to a lack of information about energy class.

Thus, the educed set of offers consisted of multiple offers. Thus, the application of the next auxiliary attribute—noise level—was suitable. Note that a lack of information about noise level resulted in three ASHP device offers being abandoned from the reduced set (8, 10, and 11). Only one offer (i.e., LG R32 monoblock), among the remaining perspective offers, provided the lowest noise level. The cost was both affordable and very competitive compared with the assumed cost limit of PLN 60,000, as it was equal to PLN 22,219. This offer became the natural ASHP recommendation, and the use of the remaining auxiliary attributes became unnecessary. Moreover, the selected offer also scored well in the case of the lower and upper outdoor temperature limit, in addition to using a more environmentally friendly refrigerant (R32).

Note that the recommended option does not include a dhw tank, which usually improves the comfort level of the heat pump device. This is why the application of a dhw tank is also worth considering. A look at the dominance hierarchy (Tables 2 and A2) confirmed that only two ASHP device offered such a setup among the nondominated options with the highest energy efficiency classes of A+++/A+. These were options 10 (monoblok Viessmann Vitocal 222-A mono 221.D13) and 11 (Viessmann Split Vitocal 222-S 221.C13 + dhw). The offers did not differ in any of the remaining auxiliary attributes, and both had a pretty large dhw tank volume. Accordingly, the cost criterion was finally utilized to discriminate them. The costs of both devices proved to be affordable and competitive as they were equal to PLN 47,452 and PLN 44,393 for offers 10 and 11, respectively. The cheaper one was finally recommended for final use.

4. Discussion

The presented analysis showed that the main challenge in the application of the proposed procedure resulted from two reasons. The first reason dealt with a need to unify the available information, while the second one pertained to the construction of the ASHP dominance hierarchy. This was especially true in the case of the numerous considered device offers. However, once the complete dominance hierarchy was defined, the subsequent steps pertained to easy pairwise comparisons of normalized assessments. Moreover, the application of the pairwise comparison technique facilitated the processing of qualitative ordered attributes.

The results of the sample application of the proposed procedure confirmed its usability and efficiency. This is because it took only two additional pairwise comparison-based steps (related to two distinct auxiliary attributes) to identify the most appropriate ASHP device. It was also proven that the selection of a more comfortable device including an additional dhw tank would also take two pairwise comparison-based steps (related to a single auxiliary attribute and price information).

We are aware, however, that the number of required steps depends on the actual number of device offers, as well as the available amounts of critical resources. The presented analysis was nevertheless based on data resulting from a review of actual offers. This is why a similar efficiency of the procedure is expected when assessing common device offers in the future.

Altogether, the proposed procedure can seemingly provide a casual user with an effective mechanism for comprehensive and uncompromising multidimensional and informed assessment of available device offers. Moreover, it seems to be able to reasonably exploit the credibility of information provided by casual ASHP device offers. The application of the common concept of pairwise comparisons and the stepwise nature of the procedure also aligns with the mental effort limitations of casual people preparing decisions with widespread and long-lasting consequences for both them and different stakeholders. This is because the procedure is flexible enough to allow the influence of diverse attributes to be considered in a unified way. For example, economic issues (price, energy output, required energy input, and energy efficiency attributes), comfort issues (dhw capacity, noise level, and operational temperature range), and environmental issues (harmful green gas emissions) can be simply addressed in this regard.

It seems, therefore, that the merits of the proposed procedure make it worthy of interest for casual homeowners and other parties interested in a reliable selection of an appropriate ASHP device in an informed manner.

5. Conclusions

The reliable and responsible operation of residential building equipment, such as heat pumps, in technical, economic, and environmental terms, makes their proper selection a real challenge. Moreover, the issues pertaining to the intangibility, imperfection, and overload of available information, homeowner's expectations, and possible scarcity of needed critical resources make this challenge even more complex. Therefore, the need for the application of a custom decision support tool, such as the one proposed in the paper, to cope with the challenges instead of a standard decision support tool becomes evident.

The sample application of the proposed procedure for informative selection of an appropriate ASHP device fully revealed the following main advantages:

1. Flexibility, consisting of the possibility of its strict adaptation to the needs related to various local conditions.
2. The non-compensatory nature of the Pareto domination idea, which prevents undesirable compromises and allows for an uncompromising multi-attribute evaluation of available ASHP device offers.
3. The simplicity of considering both tangible and intangible device attributes in available offers, thanks to the application of universal and easily implementable pairwise comparisons.
4. The possibility to take into account the actual limited availability of critical resources, e.g., financial sources, necessary for the reliable implementation and operation of an ASHP device. Note that the procedure may also comprise an interesting tool for providing its user with information about the scale of possible insufficiency of critical resources.

The proposed procedure is based on some tedious numerical tasks which are required to comprehensively assess available ASHP device offers. It makes sense, therefore, to provide common houseowners with a complete and user-friendly software solution that would be capable of processing user-provided data and providing analysis results automatically. The application of free, widely available FLOSS tools, in particular, seems to be a vital option in this regard. This is because their application would result in free and unlimited accessibility on various portable hardware and software platforms, including PCs, notebooks, tablets, web services, and even individual smartphones. However, the successful use of such a possibility would depend on free access to reliable, unbiased, and actual information about existing offers. This is why support in this regard from both ASHP device providers and governmental and self-governmental institutions is welcome.

The availability of common tools for data processing would result in further procedure development opportunities. Potential future improvements to the procedure could also deal with taking the imperfections in available information more fully into account. For example, the proposed procedure may be coupled—at the stage of designing and construction—with the forecasting of changes in the demand for critical resources necessary to implement an outstanding heat pump device in order to determine the right moment of acquisition. Another improvement could deal with the incorporation of a sensitivity analysis of the results to changes in individual substantive ASHP offer attributes. Other possible enhancements could deal with the incorporation of a benefits, costs, opportunities, and threats analysis, e.g., SWOT, into the procedure, while also taking the opinions of a team of experts in a MADA framework into account.

However, the integration of other tools into the procedure does not comprise the only possible improvement option. This is because the universality of the procedure makes it also applicable in the case of selecting other advanced energy supply-related technology devices.

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Abbreviations

ASCII	American Standard Code for Information Interchange
AHP	Analytic hierarchy process
ANN	Artificial neural network
ANP	Analytic network process
ASHP	Air source heat pump
COP	Coefficient of performance
DEA	Data envelopment analysis
dhw	Domestic hot water
EER	Energy efficiency ratio
ELECTRE	Élimination et Choix Tranduisant la Réalité
FLOSS	Free and Libre Open-Source Software
GSHP	Ground source heat pump
GWP	Global warming potential
HPWH	Heat pump water heater
HVAC	Heating, ventilation and air-conditioning
ISM	Interpretative structural modeling
LP	Linear programming
LWT	Leaving water temperature
MACBETH	Measuring Attractiveness by a Categorical-Based Evaluation Technique
MADA	Multi-attribute decision analysis
MCDA	Multicriteria decision analysis
MCDM	Multicriteria decision making
MILP	Mixed linear programming
MINLP	Mixed integer nonlinear programming
MIQCP	Mixed integer quadratic constrained programming
MODM	Multi-objective decision making
NDAHP	Novel dual ASHP
OAT	External air temperature
PROMETHEE	Preference Ranking Organization Method for Enriched Evaluation
REMBRANDT	Ratio Estimation in Magnitudes or Deci-Bells to Rate Alternatives Which Are Nondominated
SAW	Simple additive weighting
SCOP	Seasonal coefficient of performance
SSEff.	Seasonal energy efficiency score
SWOT	Strengths, weaknesses, opportunities, and threats analysis
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UK	The United Kingdom and Northern Ireland
VIKOR	Visekriterijumska Optimizacija i Kompromisno Resenje
WSHP	Water source heat pump

Appendix A

Table A1. Final candidate ASHP devices.

No.	Brand	Name	Type	dhw Tank	Nominal Power (kW)
1	LG	R32 Monobloc	Mono	No	14
2	LG	R410A Split	Split	No	14
3	LG	R410A Split IWT	Split	Yes	14
7	Viessmann	Split Vitocal 101-s 101.A14	Split	No	14
8	Viessmann	Vitocal 200-A mono 201 A13	Mono	No	13
9	Viessmann	Split Vitocal 200-S 201.D13	Split	No	13
10	Viessmann	Vitocal 222-A mono 221.D13	Mono	Yes	13
11	Viessmann	Split Vitocal 222-S 221.C13 + dhw	Split	Yes	13
12	Viessmann	Vitocal 300-A mono 301.B14	Mono	No	14
16	Vaillant	Split aroTHERM VWL 155/2A	Split	No	15
17	Hestor	Lzti—LZTi/SW6	Mono	No	15
18	Hestor	Split WZT—WZT/SW6 14M	Split	No	14
19	Hestor	Split WZT—WZT/SW6 14Tt	Split	No	14
20	Panasonic	AllInOne Aquarea HP—KIT-ADC16HE5 + dhw	Split	Yes	16
21	Panasonic	AllInOne Aquarea HP—KIT-ADC16HE8 + dhw	Split	Yes	16
22	Panasonic	AllInOne Aquarea T-CAP generacji H—KIT-A XC16HE8 + dhw	Split	Yes	16
23	Panasonic	AllInOne Aquarea T-CAP generacji H—KIT-AQC16HE + dhw	Split	Yes	16
24	Panasonic	Split Aquarea HP generacji H SDC—KIT-WC16H6E5	Split	No	16
25	Panasonic	Split Aquarea HP generacji H SDC—KIT-WC16H9E8	Split	No	16
26	Panasonic	Split Aquarea T-CAP generacji H SXC—KIT-WXC16H9E8	Split	No	16
27	Panasonic	Split Aquarea T-CAP generacji H SQC—KIT-WQC16H9E8	Split	No	16
28	Panasonic	Mono Aquarea HP generacji H MDC—WH-MDC16H6E5	Mono	No	16
29	Panasonic	Mono Aquarea HP generacji H MXC—WH-MXC16H9E8	Mono	No	16
32	Haier	Monoblock AU162FYCRA(HW)	Mono	No	16
47	Inventor	ATS 14T/HU160T9	Split	No	14
48	Inventor	ATMH14T9	Mono	No	14
52	Daikin	Altherma 3—16S18D6V(G)/D9W(G) + 14DV	Split	Yes	14
53	Daikin	Altherma 3—16D6V/D9W + 14DV	Split	Yes	14
54	Sevra	SEV-HPS1-14/O + SEV-MHPS3-16/I	Split	No	14
55	Sevra	SEV-HPS3-14/O + SEV-MHPS3-16/I	Split	No	14

Table A2. Substantial and auxiliary attributes of considered ASHP offers.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13a	13b
1	14	3.11	4.50	14	3.26	4.3	80	-	A+++	63	−25	48	R32	?
2	14	3.18	4.41	12	3.08	3.9	80	-	A+++	66	−20	48	R410A	?
3	14	3.43	4.08	11	3.53	3.12	60	200	A+++/A	66	−20	48	R410A	?
7	15	3.19	4.70	9.5	2.57	3.7	60	-	A++	64	?	?	R410A	5
8	14.2	2.84	5.00	9	2.20	4.1	60	-	A+++	?	−20	?	R410A	2.4
9	13.7	2.80	4.90	11.5	2.95	3.9	60	-	A+++	?	?	?	R410A	3.6
10	14.2	2.84	5.00	11.5	2.95	3.9	60	220	A+++/A+	?	?	?	R410A	3.6
11	13.7	2.74	5.00	11.5	2.95	3.9	60	220	A+++/A+	?	?	?	R410A	3.6
12	13.9	2.78	5,00	12	4.80	2.5	60	-	A++	54	?	?	R410A	4.75
16	14.6	3.40	4.50	13.7	4.40	3.2	63	-	A++	66	−20	46	R410A	4.4

Table A2. *Cont.*

No.	1	2	3	4	5	6	7	8	9	10	11	12	13a	13b
17	15	3.40	4.40	14.5	3.71	3.9	65	-	?	67	−20	?	?	?
18	13.9	3.30	4.20	15.4	4.10	3.8	65	-	?	66	−20	?	?	?
19	13.9	3.20	4.30	15.5	4.00	3.9	65	-	?	66	−20	?	?	?
20	16	3.74	4.28	12.2	2.96	4.12	65	185	A+++/A	72	−20	35	R410A	2.55
21	16	3.74	4.28	12.2	2.96	4.12	65	185	A+++/A	72	−20	35	R410A	2.55
22	16	3.74	4.28	12.2	3.50	3.49	60	185	A+++/A	68	−28	35	R410A	2.99
23	16	3.74	4.28	12.2	3.50	3.49	60	185	A++/A	68	−28	35	R410A	2.99
24	16	3.74	4.28	12.2	2.96	4.12	60	-	A+++	72	−20	35	R410A	2.55
25	16	3.74	4.28	12.2	2.96	4.12	60	-	A+++	72	−20	35	R410A	2.55
26	16	3.74	4.28	12.2	3.50	3.49	60	-	A++	72	−28	35	R410A	2.9
27	16	3.74	4.28	12.2	3.50	3.49	60	-	A++	68	−28	35	R410A	2.99
28	16	3.74	4.28	12.2	2.96	4.12	60	-	A+++	72	−20	35	R410A	2.1
29	16	3.74	4.28	12.2	3.50	3.49	60	-	A++	72	−20	35	R410A	2.35
32	16	3.86	4.15	16	3.64	4.4	60	-	?	67	−20	46	R32	2.6
47	14.5	3.09	4.7	13.5	3.75	3.6	60	-	A+++	65	−25	43	R32	1.65
48	14.5	3.15	4.6	13.5	3.75	3.6	60	-	A+++	69	−25	43	R32	1.75
52	14.5	2.91	4.99	11.1	2.72	4.09	70	180	A+++/A	68	−28	43	R32	3.5
53	14.5	2.91	4.99	11.1	2.72	4.09	75	180	A++	68	−28	43	R32	3.5
54	14.5	3.09	4.70	13.5	3.75	3.6	60	-	A+++	65	−25	43	R32	1.84
55	14.5	3.09	4.70	13.5	3.75	3.6	60	-	A+++	65	−25	43	R32	1.84

Legend: columns 1–3—output power (kW), input power (kW), and COP (-), respectively, for heating at OAT 7 °C; columns 4–6—output power (kW), input power (kW), and EER (-), respectively, for cooling at OAT 35 °C and LWT at 18 °C; column 7—maximum dhw temperature (°C); column 8—dhw tank volume (L) (optional); column 9—energy effectiveness class (heating/dhw); column 10—outdoor noise level (dB); column 11—the lower outdoor air temperature limit for heating (°C); column 12—the upper outdoor temperature limit for cooling (°C); columns 13a and 13b—refrigerant type and mass (kg).

Table A3. Relative dimensionless attribute levels for considered ASHP offers.

No.	1	2	3	4	5	6	7	8	10	11	12	13
1	0.130	0.670	0.457	0.714	0.409	0.947	1	-	0.5	−0.625	1	?
2	0.130	0.607	0.359	0.429	0.340	0.736	1	-	0.333	0	1	?
3	0.130	0.384	0	0.286	0.512	0.326	0	0.5	0.333	0	1	?
7	0.565	0.597	0.674	0.071	0.143	0.632	0	-	0.444	?	?	0
8	0.217	0.911	1	0	0	0.842	0	-	?	0	?	0.582
9	0	0.950	0.891	0.357	0.289	0.737	0	-	?	?	?	0.313
10	0.217	0.911	1	0.357	0.289	0.737	0	1	?	?	?	0.313
11	0	1	1	0.357	0.289	0.737	0	1	?	?	?	0.313
12	0.087	0.964	1	0.429	1	0	0	-	1	?	?	0.056
16	0.391	0.411	0.457	0.671	0.846	0.368	0.15	-	0.333	0	0.847	0.134
17	0.565	0.411	0.348	0.786	0.582	0.737	0.25	-	0.278	0	?	?
18	0.087	0.5	0.130	0.914	0.731	0.684	0.25	-	0.333	0	?	?
19	0.087	0.589	0.239	0.929	0.693	0.736	0.25	-	0.333	0	?	?
20	1	0.109	0.217	0.457	0.294	0.853	0.25	0.125	0	0	0	0.549
21	1	0.109	0.217	0.457	0.294	0.853	0.25	0.125	0	0	0	0.549
22	1	0.109	0.217	0.457	0.499	0.521	0	0.125	0.222	1	0	0.450
23	1	0.109	0.217	0.457	0.499	0.521	0	0.125	0.222	1	0	0.450
24	1	0.109	0.217	0.457	0.294	0.853	0	-	0	0	0	0.549
25	1	0.109	0.217	0.457	0.294	0.853	0	-	0	0	0	0.549
26	1	0.109	0.217	0.457	0.499	0.521	0	-	0	1	0	0.470
27	1	0.109	0.217	0.457	0.499	0.521	0	-	0.222	1	0	0.450
28	1	0.109	0.217	0.457	0.294	0.853	0	-	0	0	0	0.649
29	1	0.109	0.217	0.457	0.499	0.521	0	-	0	0	0	0.949
32	1	0	0.076	1	0.555	1	0	-	0.278	0	0.847	0.931

Table A3. *Cont.*

No.	1	2	3	4	5	6	7	8	10	11	12	13
47	0.348	0.688	0.674	0.643	0.597	0.579	0	-	0.389	0.625	0.615	1
48	0.348	0.634	0.565	0.643	0.597	0.579	0	-	0.167	0.625	0.615	0.993
52	0.348	0.848	0.989	0.3	0.202	0.837	0.5	0	0.222	1	0.615	0.866
53	0.348	0.848	0.989	0.3	0.202	0.837	0.75	0	0.222	−1	0.615	0.866
54	0.348	0.688	0.674	0.643	0.597	0.579	0	-	0.389	0.625	0.615	0.986
55	0.348	0.688	0.674	0.643	0.597	0.579	0	-	0.389	0.625	0.615	0.986

Legend: columns 1–3—output power (kW), input power (kW), and COP (-), respectively, for heating at OAT 7 °C; columns 4–6—output power (kW), input power (kW), and EER (-), respectively, for cooling at OAT 35 °C and LWT at 18 °C; column 7—maximum dhw temperature (°C); column 8—dhw tank volume (L) (optional); column 10—outdoor noise level (dB); column 11—the lower outdoor air temperature limit for heating (°C); column 12—the upper outdoor temperature limit for cooling (°C); column 13—GWP AR4-related refrigerant environmental influence.

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