Pol. J. Environ. Stud. Vol. 24, No. 3 (2015), 1327-1338

Original Research

Developing an Environmentally Sound Selection Method for Heating Appliances Using Ecolabeling, an Analytic Hierarchy Process, and Cost-Benefit Analysis: a Heat Pump Case Study

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Received: 5 November 2013
Accepted: 5 December 2014

Abstract

This article presents an assessment of heating appliances prepared on the basis of the multi-criteria evaluation method known as the analytic hierarchy process (AHP). The authors propose a new way of designing the hierarchy of criteria utilizing the concept of sustainable development and the criteria originating from ecolabeling programs. An evaluation of real heat pumps is presented as a case study.

The cost-benefit analysis (CBA) of the same heat pumps is also conducted using the AHP method to calculate the integrated benefit of each heat pump while the cost was calculated using the Net Present Value indicator. Both methods of analysis yielded very similar results.

Keywords: multi-criteria analysis, AHP, ecolabeling, heat pumps, HIPRE, Cost-Benefit Analysis

Introduction

Any decision maker, deliberately or not, always applies a cost-benefit method when trying to find the best solution that meets the selected criterion, or accepts the fact that there are many criteria and looks for a compromise solution.

When applying the multi-criteria method, the decision maker has to select the method of analysis and then develop the evaluation criteria. There are many multi-criteria decision analyses (MCDA) and extensive literature reviewing its application [1-7]. The application of MCDA in environmental projects is numerous because the projects require consideration of trade-offs between socio-political, environmental, and economic impacts, and are often complicated by various stakeholder views. The methods become more and more popular, and the total number of papers that mention one of the MCDA methods increased from single digit numbers in the early 1990s to hundreds toward the late 2000s [2]. One of the most popular methods of MCDA is the analytic hierarchy process (AHP). Measuring by the number of papers published, AHP dominates at 48% (in 312 articles analyzed by the authors, 150 used AHP as a method of analysis) [2]. It is the most popular among Asian, American, and European researchers in all application areas (with the exception of air quality) and its popularity in comparison with other MCDA methods has increased over time [2].

AHP, developed by T.L. Saaty [8, 9], is a decision-making method for prioritizing alternatives when multiple criteria must be considered. This approach allows the decision maker to structure problems in the form of a

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hierarchy or a set of integrated levels, such as the goal, the criteria, and the alternatives. The primary advantage of the AHP is its use of pairwise comparisons to obtain a ratio scale of measurement. Ratio scales are a natural means of comparison among alternatives and enable the measurement of both tangible and intangible factors.

Since its introduction, AHP has been widely used in all areas of decision making, among others banks, manufacturing systems, site selection, strategy selection, supplier selection, staff recruitment, project selection, and customer requirement rating [10, 11]. Recently, it has been observed that the focus has been confined to the application of the integrated AHPs rather than the stand-alone AHP. The five tools that commonly combined with the AHP include mathematical programming, quality function deployment (QFD), meta-heuristics, SWOT analysis, and data envelopment analysis (DEA) [12]. AHP is also being combined with other environmental tools such as life-cycle analysis and environmental performance indicators to create a new tool for measuring a firm's environmental performance [13].

The article presents the application of the AHP method for heat pump evaluation when ecolabeling program criteria are used in analysis [14, 15]. Integrating ecolabeling criteria into the AHP process is a concept similar to developing integrated AHP or combining AHP with other tools of environmental assessment [16]. The obtained results are compared with the results from cost-benefit analysis.

Our article presents the application of all three stages of the AHP method for heat pump selection. The first stage, design of the evaluation criteria hierarchy, is carried out following the concept of sustainable development, and the criteria of the European Union ecolabeling program. The second stage of analysis assigns the weights of different criteria; this part is done based on the authors' knowledge and experience. The last stage of the AHP method – the evaluation of the analyzed heat pumps combined with the sensitivity analysis of the assumed weights – is also presented and discussed.

Brief Description of the Analytic Hierarchy Process

Psychological fundamentals of the AHP method are as follows:

- Humans prefer to compare dimensionless ratios (not differentiate), and are able to compare up to seven objects simultaneously
- Humans see the world as a hierarchy of goals with relationships
- Human reactions to impulses are more logarithmic than linear
- All judgments are based on preferences

Based on these fundamentals, the AHP selection method was created. The method is executed in four stages:

- Developing the criteria of evaluation organized in a hierarchical order
- Assigning the weights for each criteria by a pair-wise comparison
- Evaluation of alternative solutions using the developed criteria by a pair-wise comparison or using the directly obtained evaluation data
- Calculating the final score of each alternative as a sum of products of weights and alternatives performance in each evaluating category [17].

The used criteria can be both descriptive (e.g. design) or measurable (e.g. price). Sometimes a decision-maker wants the criteria to reach the maximum value (efficiency) while sometimes the minimal value of the criterion is the best (price).

One of the shortcomings of the AHP method is the lack of scientific background that would assist in developing the hierarchy of evaluation criteria, and therefore different evaluation hierarchies may lead to different evaluation results. Additionally, sometimes criteria can be selected in such a way that identical specific performance of alternatives is evaluated several times by different criteria. On the top of it, the decision-maker very often lacks specific technical knowledge and has to rely on the information provided by the producer's representative, which is naturally biased. To avoid all these problems and errors a new method of building the hierarchy of criteria is proposed. This method constructs the hierarchy of evaluation criteria based on the principle of sustainable development, and measures the environmental performance with criteria developed for the ecolabeling programs.

Ecolabeling as a Basis for Criteria Selection

The idea of ecolabeling [14, 15] originates from the assumption that consumers are looking for environmentally friendly products. On the other hand, producers knowing consumer preferences are ready to deliver such products if quality is objectively confirmed. To allow such an objective quality check, the independent certifying organizations set up very specific criteria, unique for specific groups of products. The products can voluntarily apply for an ecolabel presenting their products for certification. If the products meet the criteria and the producer pays a fee, they are allowed to display the ecolabel sign on the product for a certain period of time. The certifying organization undertakes the responsibility to start a campaign supporting the product. Both sides hope for favorable consumer response. Fig. 1 presents four European ecolabels.

Ecolabeling criteria do not include the economic aspects of product usage, but since these features are critical for consumers the economic criteria have to be included in the decision process. Because economic criteria tend to dominate the whole analytical process, they are introduced into the decision process in a very careful way. Hass [18] proposes analyzing the products' benefits without the economic criteria and then incorporate them separately into the analysis.

Heat Pump Ecolabeling Criteria

The EU Commission decision issued on 9 November 2007 with later amendments [19] specifies the ecological criteria for the European ecolabel program for heat pumps powered by gas, electricity, and heat (max. power 100 kW). According to European Community Regulation No. 1980/2000, to obtain the ecolabel a heat pump must meet all environmental criteria set out in the annex to this decision.

The criteria's objective is to limit the environmental impact of the production, operation, and subsequent decommissioning of heat pumps. The criteria include:

– Efficiency of heating and/or cooling of buildings
– Reduction of environmental impact during heating and/or cooling of buildings
– Reduction or prevention of risks to the environment/human health due to the use of hazardous substances
– Proper transfer of information to customers and fitters on efficient operation of the heat pump

There are nine important elements identified in the ecolabeling document, which decide whether or not the ecolabel is granted. The list of those criteria with their brief descriptions is presented underneath.

Coefficient of Performance (COP)

The coefficient is a ratio of generated heating power Q_k, to input power L (electricity or gas) for a particular source and output temperature:

$$COP = {}^{Q_k}\!/\!{}_{L} \qquad (1)$$

The minimal efficiency of an electrically powered heat pump working in a heating mode in a brine/water system must not be lower than 4.3 (internal unit input/output temperatures -30ºC/35ºC) or 3.50 (internal unit input/output temperatures -40ºC/45ºC).

Primary Energy Ratio (PER)

Additionally, the primary energy ratio PER for a brine/water system has to exceed 1.72 (internal unit input/output temperatures -30ºC/35ºC) or 1.40 (internal unit input/output temperatures -40ºC/45ºC), while for a combi unit (with a cooling function) the minimal value of a PER ratio should be 1.2. Both PER and COP ratios are closely related and for an electrically powered heat pump this relationship is described by the formula:

$$PER = COP \times 0.4 \qquad (2)$$

The coefficient value 0.4 is the average European efficiency of electricity generation, including grid losses. In the case of heat pumps powered by gas or heat the coefficient's value is 0.91, which is the European average for gas with distribution losses. Due to the fact that both PER and COP are linearly related, only one (COP) was included in the analysis.

Global Warming Potential (GWP)

The global warming potential coefficient (GWP) was introduced to describe the impact of refrigerant on a global climate. In the case of heat pumps, GWP shows how much the used refrigerant increases global warming if compared to carbon dioxide. The GWP for carbon dioxide is assumed to be 1 and the lifespan of the analysis is 100 years. A high value of the GWP means that the refrigerant absorbs a lot of infrared radiation and will remain in the atmosphere for a long time. According to the EU commission (decision 2007/742/WE [19]) the refrigerant's GWP cannot exceed 2,000 in a 100-year lifespan.

Noise

Following the ecolabeling requirements for heat pumps, a noise level has to be measured according to the standard ENV-12 102, and the results, in dB(A), have to be presented in the product information document.

Heavy Metals and Flame Retardants

Cadmium, lead, mercury, chromium (VI) or flame retardants polybrominated biphenyl (PBB) or polybrominated diphenyl ether (PBDE) cannot be used in heat pump units or heat pump systems. The acceptable limits of these substances are precisely set in the commission document 2005/618/WE. The concentration levels of these substances have to be certified.

Personnel Training

Heat pump manufacturers are responsible for personnel training in the European Union countries where the pumps are sold. The training should focus on proper pump sizing and installation as well as provide assistance while filling up the documents. The heat pump manufacturer's declaration about the training and its place is required.

Documents

Heat pump manufacturers have to deliver a complete user's manual with the equipment. The manual has to provide information on installation, maintenance, and operation of the heat pump. All these documents have to comply with the standard EN 378:2000 and all later amendments.

Spare Parts

The heat pump manufacturer guarantees that the spare parts will be available for 10 years, starting from the date of purchase. The manufacturer should also specify how this requirement is going to be met.

Fig. 1. Examples of ecolabels in the EU.

Information Sheet

The heat pump manufacturer guarantees that a blank information sheet is available at the location where the heat pump is sold. This is to guarantee the minimal level of consumer assistance. Fitters should have access to a completed "information sheet" for fitters. Additionally, manufacturers should provide fitters with special tools, computer software, and assistance to allow them to calculate the following working parameters of the heat pump installation: seasonal energy efficiency ratio (EER), seasonal coefficient of performance (COP), or yearly carbon dioxide emission.

Comparative Analysis of Heat Pumps

Multi-Criteria Analysis of Heat Pumps AHP-HIPRE (Analytic Hierarchy Process-HIerarchical PREference)

The goal of analysis was to prepare a rank list of the evaluated heat pumps using the selected criteria. The AHP method combined with ecolabeling criteria listed in EU decision 2007/742/WE [19] and free software HIPRE [20] were used. A detailed description of the applied method is presented in the article focusing on power equipment [21-23].

Construction of the Objective Hierarchy

Ecolabeling criteria were only used as a basis for selection of the final objective hierarchy. To help

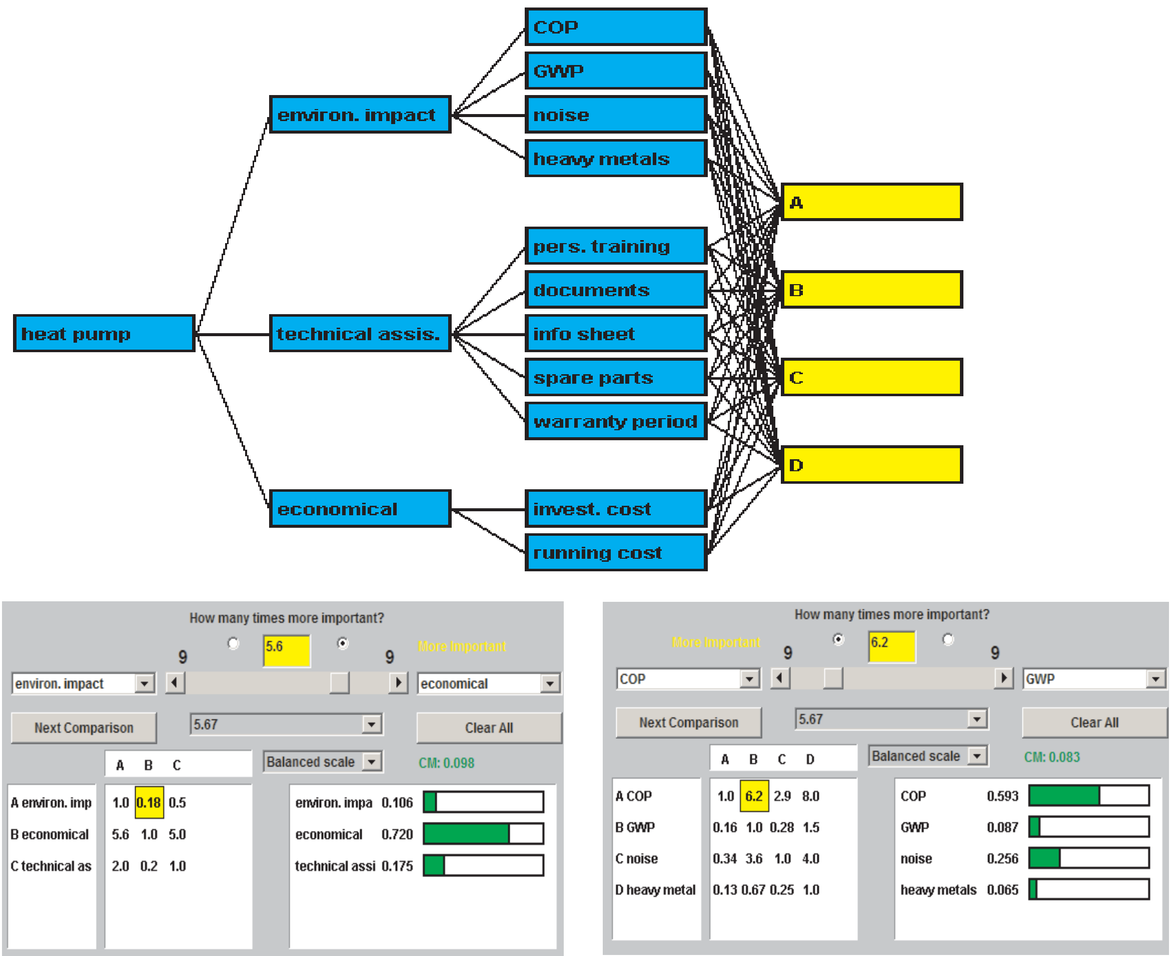


Fig. 2. Objective hierarchy for heat pump analysis and exemplary calculation of weights.

determine the weights of the final subcriteria they were grouped into three categories/objectives. These categories were selected according to the sustainable development requirements. The final goal of the selection was divided into three categories: "impact on natural environment," user friendliness called "technical assistance" and "economical." .Introduction of the economical criterion, next to others, follows the concept of sustainable development, but can lead to serious distortion in weights assignment and, further on, to false results. Because the analysis is usually carried out by professionals or by the heat pump users, the authors assumed that the risk of such a problem is minimal.

Fig. 2 presents the created objective hierarchy and examples of weight calculation.

The criterion "environmental impact" was divided into very specific subcriteria taken from the ecolabeling procedure. The impact on global warming can be measured by GWP or by TEWI, which measures not only the impact of the refrigerant when released into the atmosphere, but also the impact of the unit during its many years of operation. Generally, TEWI is more accurate, but in this case efficiencies of heat pumps have already been measured by economical criteria. To avoid the case that the same parameter is measured by two different criteria, the authors decided to use GWP. GWP and TEWI offer the same results, assuming that all examined heat pumps have the same amount of refrigerants and the same level of refrigerant recovery; the present system of refrigerant collection makes such assumptions justified.

Decision 2007/742/WE [19] also sets a few additional (not environmental) objectives to ensure the supplier's dependability, such as: access to technical "documents" and "personnel training." These criteria were grouped into the objective called "technical assistance." The Decision also talks about the 10-year period for "spare parts" availability. This criterion as well as the "warranty period" was also included in the objective hierarchy.

Economic performance can be measured by a whole range of indicators. At present, the most popular one is an index called net present value (NPV), which measures simultaneously running and investment costs. Often these two costs are covered by two different subjects. Additionally, purchasing costs may occur when the investor is short of money having many other expenses. Because of these reasons the authors decided to use two subcriteria: "running cost" and "investment cost" instead of using one NPV index.

Evaluation of Heat Pumps Using the Selected Criteria

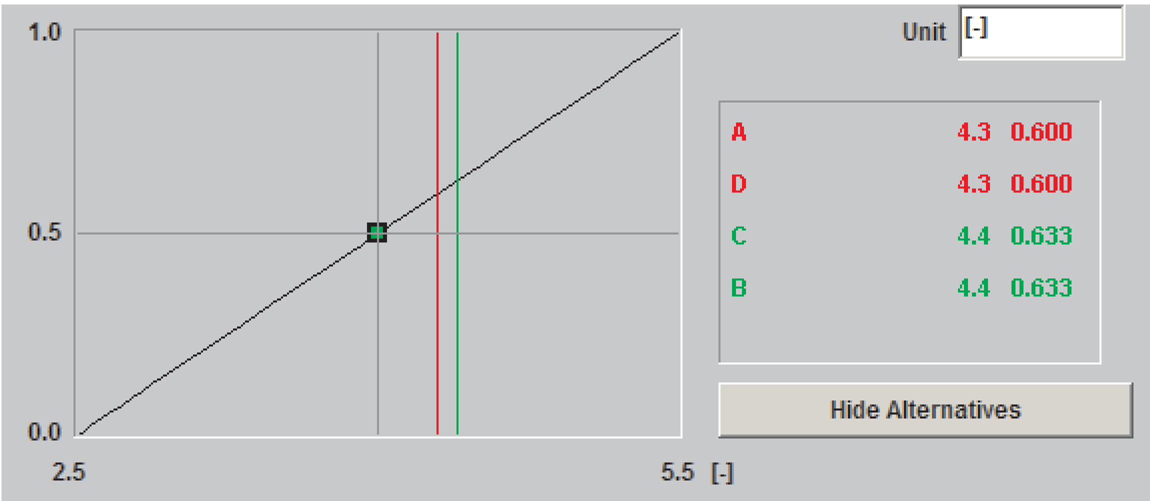
The analysis comprised heat pumps used for heating a single family house, with a water storage tank and power of approx. 10 kW with no cooling capacity. Four manufactured heat pumps were selected and marked A, B, C, and D. Information about heat pumps performance was delivered by the manufacturers' representatives.

Before the final evaluation of the heat pumps it is necessary to make some additional assumptions concerning the units and acceptable levels of selected criteria. Some categories ("heavy metals and flame retardants," "personnel training," "documents," and "information sheet") are binary. If the requirements are met, a value of 1 is assigned and if not, 0. Because EU Decision 2007/742/WE [19] specifies only the minimal and maximal values for GWP and COP, it was necessary to specify the accep-table range for each category. Additionally, it was necessary to decide if the relationship between the subjective level of acceptance for each parameter is linear with absolute value of the heat pump's performance in this category.

The performance of the heat pumps and the acceptable range for each category are presented in Table 1.

Table 1. Heat pump parameters and the acceptable range of values.

Criteria	C	A	D	B	Min rating	Max rating	Unit
Spare parts	10	20	20	10	0	20	[years]
Global Warming Potential (GWP)	1610	1890	1610	1610	0	2000	[-]
Coefficient of Performance (COP)	4.4	4.3	4.3	4.4	2.5	5.5	[-]
Personnel training	1	1	0	0	0	1	Yes/No (1/0)
Information sweet	1	1	1	1	0	1	Yes/No (1/0)
Noise	51	46	47	47	20	60	db(A)
Heavy metals and flame retardants	0	0	1	0	0	1	Yes/No (1/0)
Documents	1	1	1	1	0	1	Yes/No (1/0)
Warranty period	3	2	2	2	2	3	[years]
Investment cost	6068	5228	8210	5659	2380	9523	[€]
Running cost	13885	9309	9309	13885	7142	14285	[€/15 years]



COP

Fig. 3. Linear standardization function for the COP parameter.

COP

The Commission's Decision 2007/742/WE [19] specifies the minimal value of the COP for electric brine/water heat pumps. Because this parameter is of great importance in the "environmental impact" category, the authors decided not to evaluate it in a binary scale. In such a case, all the pumps with COP higher than the minimal value would have the value 1, without differentiating among the different heat pumps. Additionally, it was assumed that the acceptable level of the COP is below 4.3. This assumption was made to differentiate among the heat pumps, which have the COP equaling exactly 4.3.

The minimal value of COP was calculated using the economic efficiency coefficient W_o [24]:

$$W_o = \frac{COP \times K_n}{K_{el}} \tag{3}$$

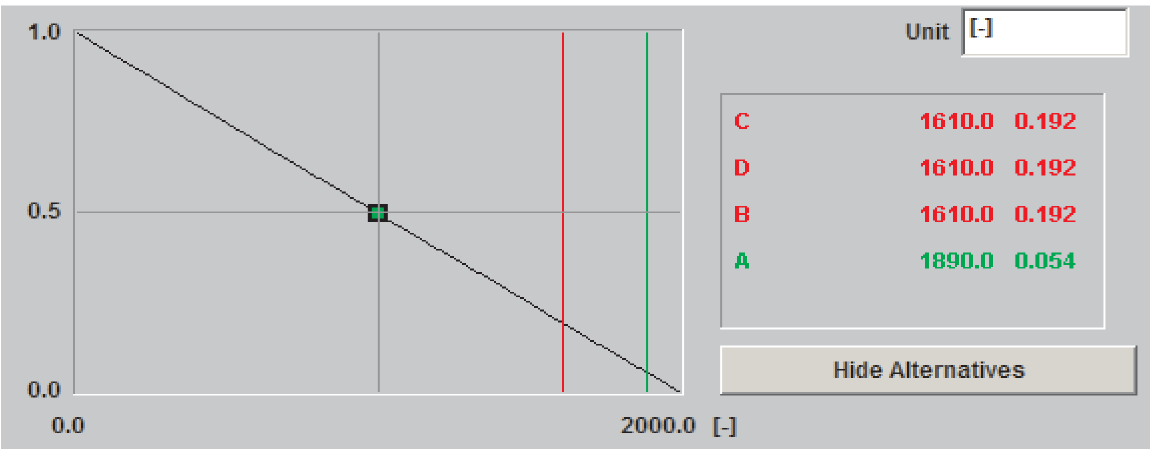
…where: K_n is cost of heat energy from natural gas or heating oil, assumed to be 0.06 [€/kWh] (a gas-fuelled condensing boiler) [24], K_{el} is cost of heat energy from the electrically powered heat pump, assumed to be 0.14 [€/kWh] [24].

Assuming that the economic efficiency coefficient W_o should be higher than 1 (a heat pump is more efficient than traditional heat energy production methods), authors set it at the level of 1.05, the minimal COP value was calculated as follows:

$$COP = \frac{W_o \times K_{el}}{K_n} = \frac{1.05 \times 0.14}{0.06} = 2.5 \tag{4}$$

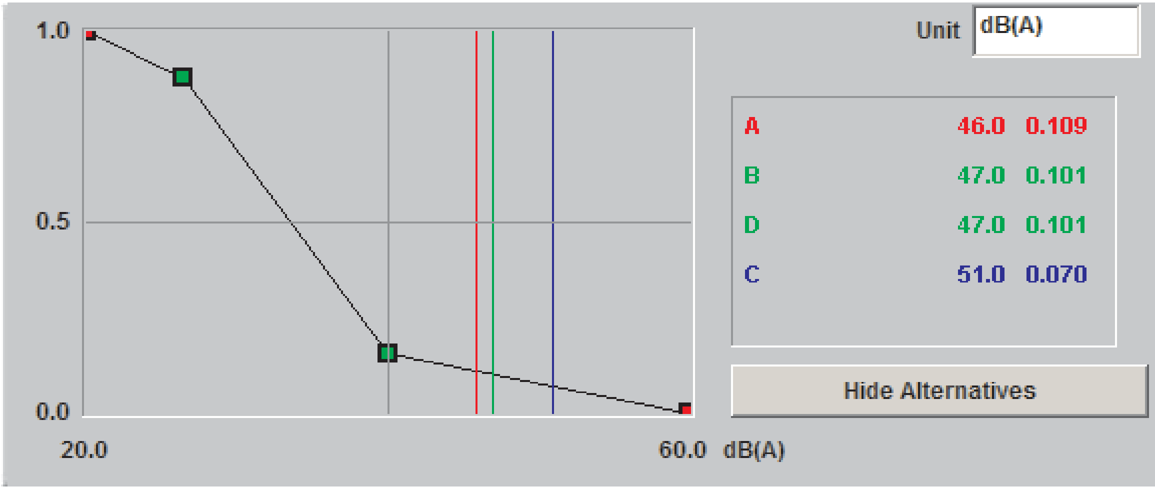
The upper COP limit was assumed to be 5.5 – the value suggested by heat pump manufacturers.

The studied heat pumps had COP coefficients ranging from 4.3 to 4.4, therefore there was little difference



GWP

Fig. 4. Linear standardization function for the GWP.



NOISE

Fig. 5. Nonlinear noise standardization function.

between the best and the worst heat pump if measured by the standardized parameter (0.6 and 0.633). The COP parameter standardization function is presented in Fig. 3.

GWP

Opposite to the COP, smaller values of the GWP indicate better performance. Ecolabels set the highest acceptable value at GWP = 2000 while the lowest value is, naturally, 0. The standardization function shows a linear character (Fig. 4).

Noise

The Commission's Decision 2007/742/WE [19] does not set the highest acceptable noise level, which can be generated by the heat pumps. Because the noise ranging from 35 to 70 dB(A) has a negative impact on the human nervous system while below 35 dB(A) is harmless, it was decided to use an audibility threshold value of 20 dB(A) as the minimal value. The maximum value was set up at 60 dB(A), or the noise of a conversation.

A noise scale is logarithmic, which is why it was decided that the standardization function should follow an inverted logarithmic function (Fig. 5).

Heavy Metals, Personnel Training, Documents, and Information Sheet

These criteria have been evaluated in a binary system; if a heat pump meets the criteria it receives 1 and if not, 0. The exemplary standardization function for a "heavy metals and flame retardants" criterion is presented in Fig. 6.

Spare Parts and Warranty Period

The Commission's Decision 2007/742/WE [19] obliges the manufacturers to provide the user with spare parts for 10-year performance, beginning from the purchase date. All four heat pumps meet this condition,

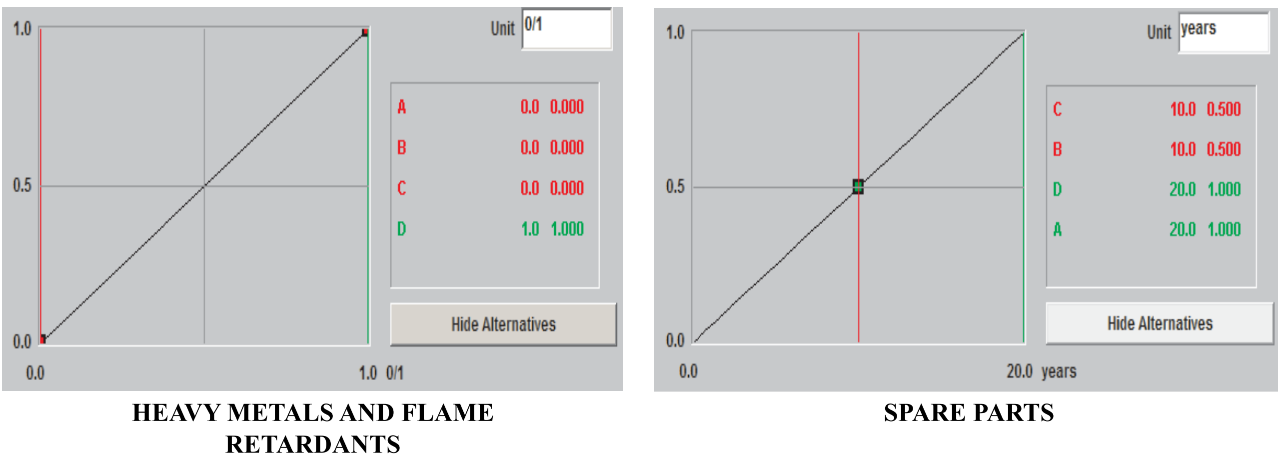


Fig. 6. Linear standardization function for "heavy metals and flame retardants" and for "spare parts."

Table 2. Weights and partial results from the first level of analysis and final results.

Level I°	Weights at the level I°	Results at the level I°			
		A	B	C	D
Environmental impact	0.106	0.055	0.058	0.057	0.063
Economical	0.720	0.450	0.302	0.271	0.225
Technical assistance	0.175	0.132	0.069	0.153	0.090
	Final results	0.638	0.429	0.481	0.379

Table 3. Weights and results at the second level of analysis.

Criteria at level II°	Weights at level II°	Results at level II°			
		A	B	C	D
COP	0.593	0.825	0.847	0.847	0.825
GWP	0.087	0.054	0.192	0.192	0.192
Noise	0.256	0.109	0.101	0.070	0.101
Heavy metals and flame retardants	0.065	0	0	0	1
Personnel training	0.240	1	0	1	0
Documents	0.225	1	1	1	1
Information sheet	0.047	1	1	1	1
Spare parts	0.246	1	0.5	0.5	1
Warranty period	0.241	0	0	1	0
Investment cost	0.750	0.601	0.541	0.484	0.185
Running cost	0.250	0.697	0.056	0.056	0.697

and some manufacturers extend this period up to 20 years.

In the case of "spare parts" the authors decided to use instead of a binary function, a linear function from 0 to 20 years. If there are not spare parts available the function takes 0, and if spare parts are available for 20 years the function takes 1 (Fig. 6).

The parameter "warranty period" was standardized in the same way as "spare parts." In the case of the "warranty period" parameter the lower value is two years and the upper value is three.

Analysis of the AHP-HIPRE Results

The results of the AHP-HIPRE analysis are presented in Tables 2 and 3. The final result for each heat pump comprises a sum of partial results (Table 3), multiplied by relative weights at levels I° and II°. The final results also have been presented in a graphical form by HIPRE software in Figs. 7 and 8.

The analysis indicates that heat pump A is the best choice. (Fig. 7). Remaining heat pumps received similar scores; if compared with heat pump A they were lower by 1/3. The second was heat pump C, and then pumps B and D.

The high score of heat pump A is a result of superior economic performance, mainly a low "investment cost." The final score of heat pump A is also improved by a high score in the category "technical assistance," mainly "personnel training" and "spare parts." Heat pump C was equally well evaluated in the category "technical assistance" and had an extremely long "warranty period" (Fig. 8). Mainly due to this long "warranty period" heat pump C is second in the ratings. A low evaluation score for heat pump D results from a high "investment cost."

Sensitivity Analysis

Sensitivity analysis tries to assess the impact of the weight change of different categories on the final score. Only the weights of the categories from level I° were assessed. Since level II° is the final level of hierarchy, a sensitivity analysis at this stage would only indicate how much the pump performance in each category must change to change the final pumps' ratings.

Fig. 9 presents the impact of the "environmental impact" weight on the final score of the evaluated heat pumps. The present weight, 0.106, is marked in the picture. At this weight heat pump A received the best total score of 0.638, 1/3 better than the other heat pumps. If the weight for environmental impact was larger than 0.8, heat pump D would get the highest score, but all four heat pumps would end up having a very similar final result. If the weight got higher than 0.91 heat pump A would turn out to be the worst solution.

Fig. 10 presents the sensitivity analysis for the "technical assistance" criterion. The present value of this weight is 0.175. If the weight of this criterion is larger than 0.64 the top two heat pumps would swap their ratings.

Fig. 11 presents sensitivity analysis for the "economic" criterion. The present weight of this criterion is 0.72, making heat pump A the best choice. If the weight increases, the ratings of the heat pumps do not change. The weight has to drop to 0.24 to change the best solution. Since the difference between the present weight value (0.72) and the breaking point (0.24) is so significant, one can say that the final solution is rather insensitive to this weight's change. The ratings of the remaining two pumps stay significantly lower for any weight value of "economic" criterion.

Cost-Benefit Analysis

Another way to compare the costs and performance of the analyzed heat pumps is to use cost-benefit analysis (CBA) [25]. This can be done by separate calculations of the benefits of each heat pump, and then by graphical comparison with the calculated costs.

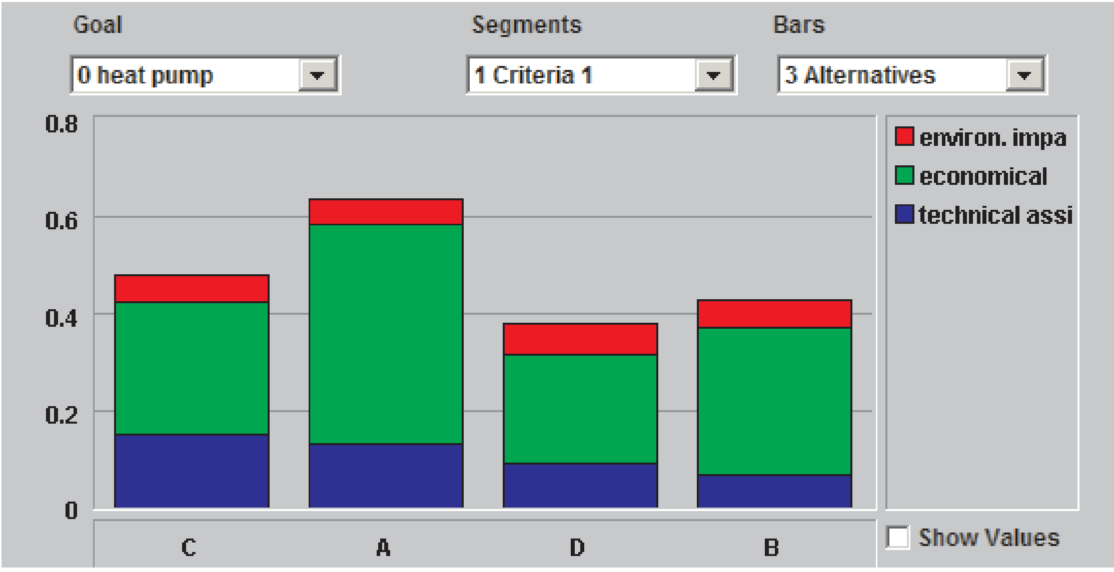


Fig. 7. Comparison of heat pump performance at the I° level of evaluation.

The cost of each heat pump was calculated as NPV. The costs include the investment cost (Table 1) and running costs for the entire 15-year period. The NPV was calculated using nominal prices, with the assumption that the energy cost increases 6% per year and the discount rate is 8%.

The benefits for each heat pump were calculated using the AHP method. This time the economic criteria were removed from the criteria hierarchy. All other criteria and performance parameters remained the same as in previous analysis. The CBA results are presented in Fig. 12.

The graph clearly indicates that heat pump A is the best solution. The pump shows the highest benefit-to-costs ratio graphically displayed as the slope of the ray from the origin to the point representing each heat pump. The slope is the highest for heat pump A, which means the highest unit benefit. Heat pump C offers slightly higher benefits, but at significantly higher costs. Heat pumps C, D, and B cost almost the same, but differ substantially in delivered benefits.

The CBA results are the same as calculated using the multi-criteria analysis. Because in the CBA method all the benefits are aggregated and it makes detailed analysis more difficult. On the other hand, the CBA results are self-explanatory and almost intuitive.

Conclusions

Our article presents the application of AHP-HIPRE – a multi-criteria method and ecolabeling criteria to compare four actual heat pumps. As required by the AHP method, the hierarchy of criteria was built and the weights of each criterion were estimated. Creation of the hierarchy of criteria is a very subjective process and requires a lot

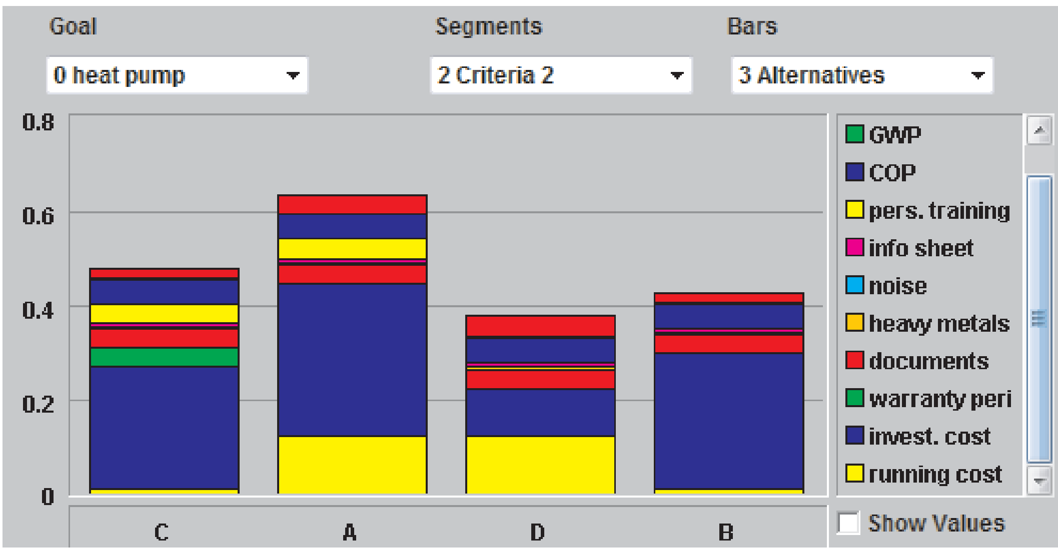


Fig. 8. Comparison of heat pump performance at the II° level of evaluation.

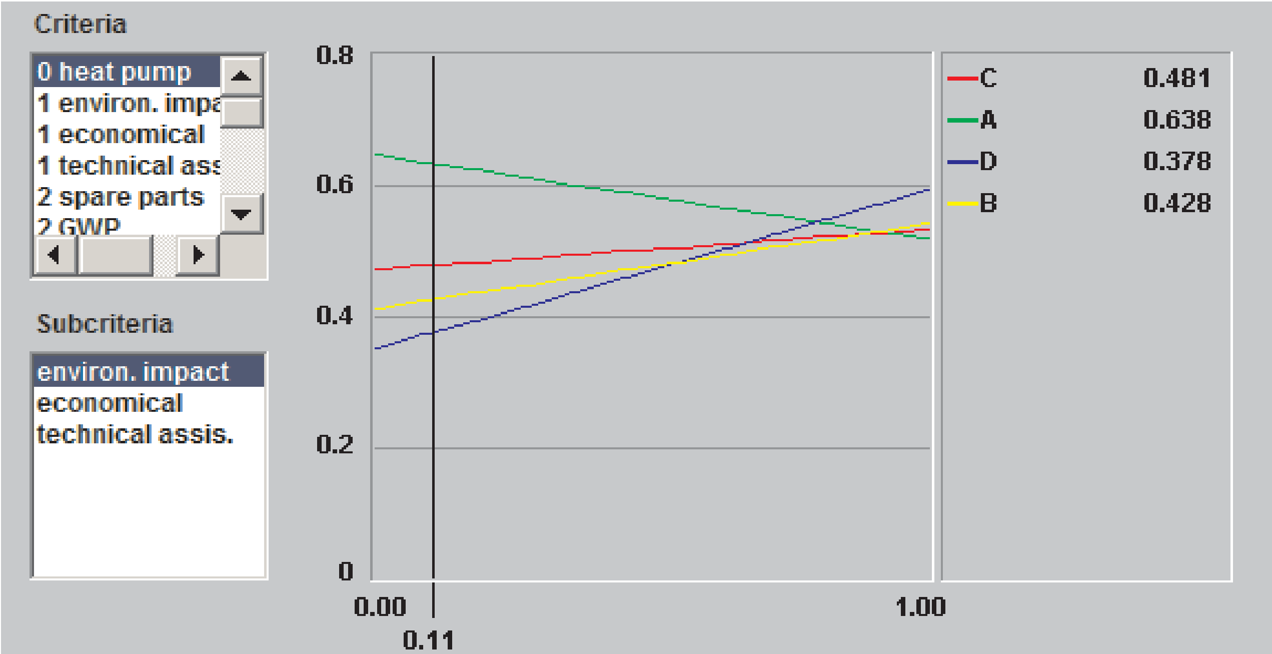


Fig. 9. Sensitivity analysis: "environmental impact" criterion.

of technical expertise. Implementation of the ecolabeling program's criteria into the criteria hierarchy used for heat pump evaluation can be a helpful procedure. The criteria were selected using the European Union Decision 2007/742/WE [19] on ecolabeling. Some other criteria were added, such as "warranty period," "investment cost," and "running cost." HIPRE, a free software available online [20], was used for analysis.

Generally, the AHP method and the use of ecolabeling criteria turned out to be a useful tool in heat pump comparison. In the analyzed case the AHP method allowed the selection of the best solution, which turned out to be insensitive to the weight value changes.

The CBA, for the same set of heat pumps, was also conducted, giving the same final results. The AHP method, being more difficult in application, seems to deliver more

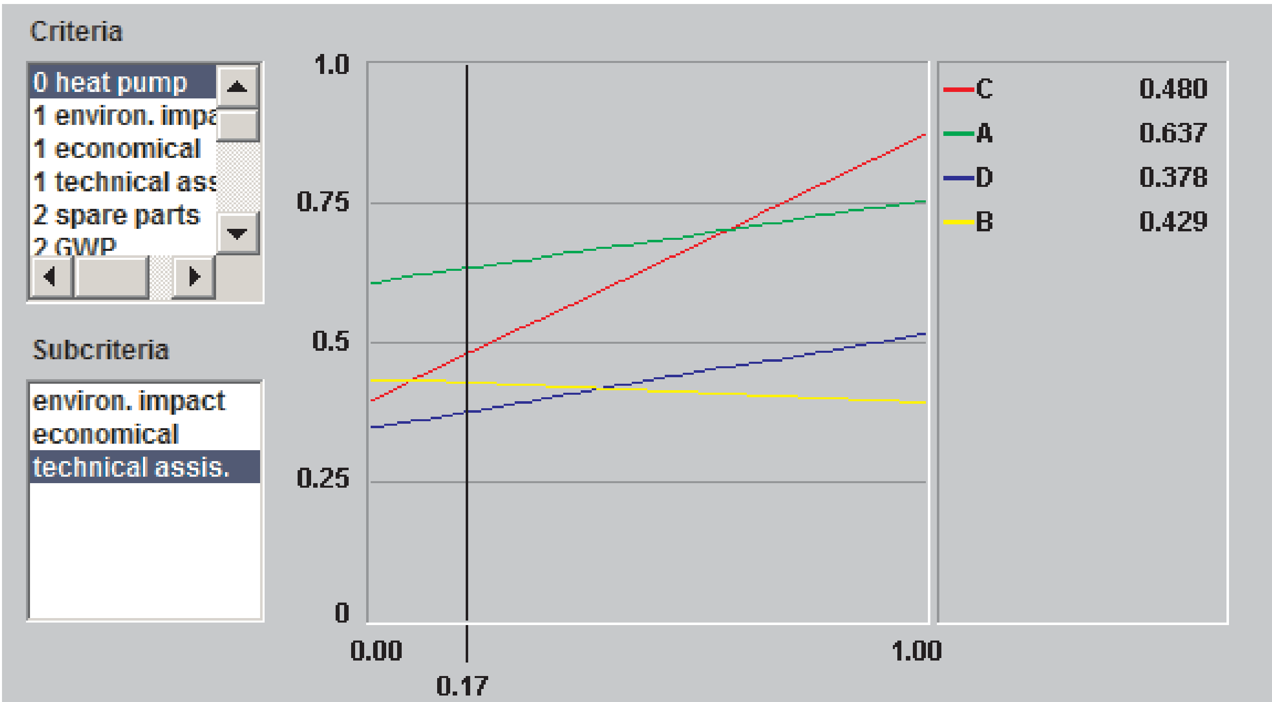


Fig. 10. Sensitivity analysis: "technical assistance" criterion.

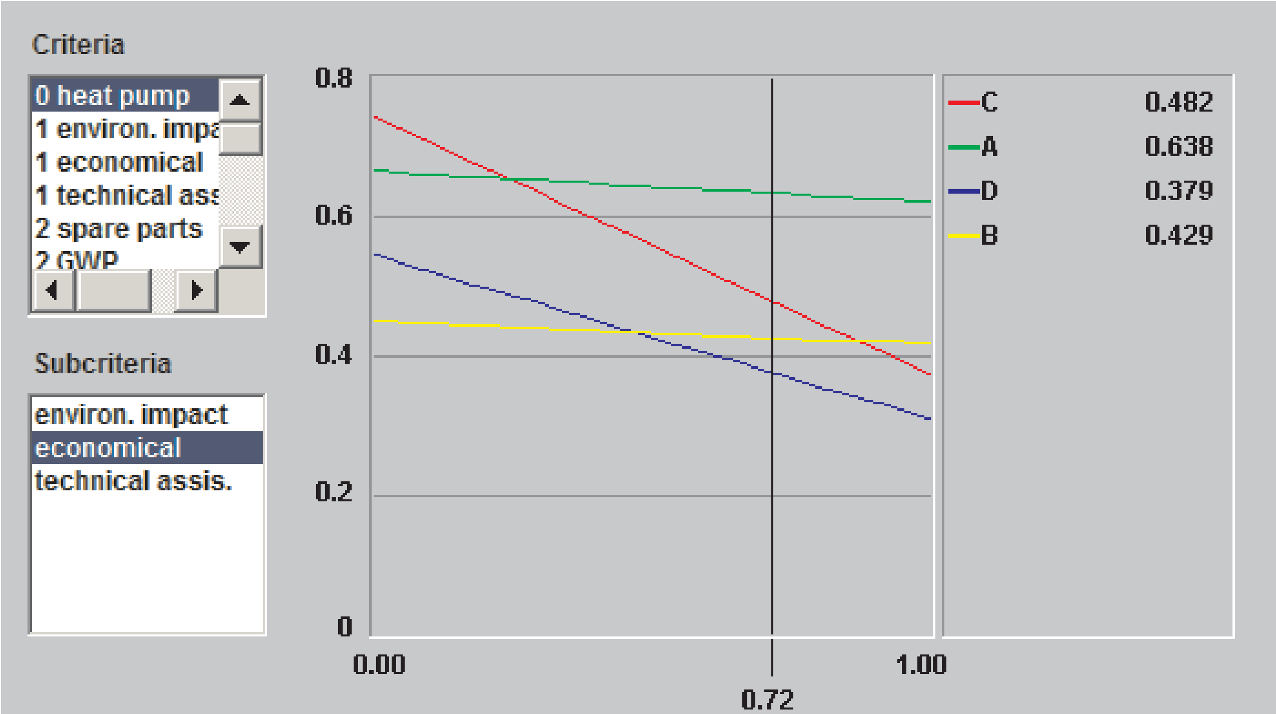


Fig. 11. Sensitivity analysis: "economic" criterion.

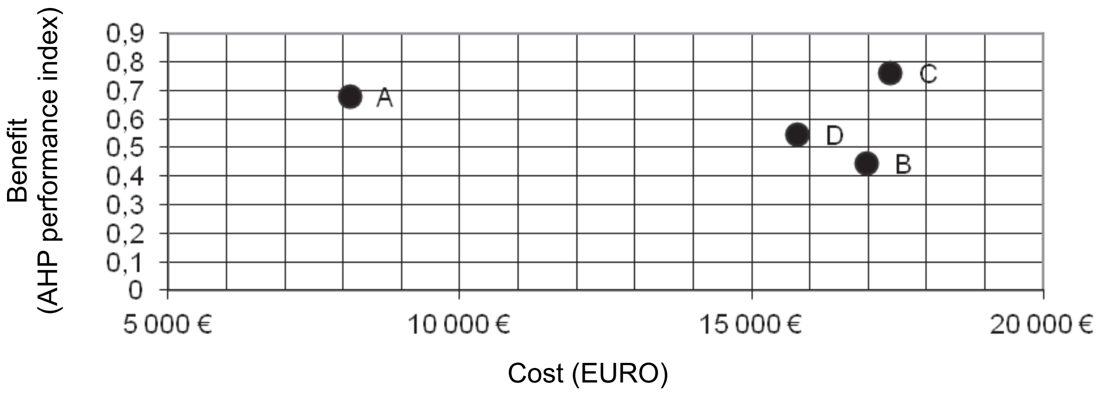


Fig. 12. CBA for the analyzed heat pumps.

information to the decision makers and allow for a more complex analysis.

Another problem appears when introducing the cost factor into the analysis. All the analyzed heat pumps deliver similar quality service, but often at very different cost. The article highlights the economic criteria introduced once as part of the hierarchy structure and also as a separate group of criteria in the CBA.

References

1. MENDOZA G.A., MARTINS H. Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. Forest. Ecol. Manage. **230**, 1, **2006**.
2. HUANG I.B., KEISLER J., LINKOV I. Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. Sci. Total. Environ. **409**, 3578, **2011**.
3. DRUŻYŃSKA E. Multi-criteria Decision Support Methods in Water Management. Doctoral Disertation. Krakow University of Technology, **1997** [In Polish].
4. BUCHHOLZ T., RAMETSTEINER E., VOLK T.A., LUZADIS V.A. Multi Criteria Analysis for bioenergy systems assessments. Energ. Policy **37**, 484, **2009**.
5. SCOTT J.A., HO W., DEY P. K. A review of multi-criteria decision-making methods for bioenergy systems. Energy **42**, 146, **2012**.
6. ZOPOUNDIS C., PARDALOS P.M. Handbook of multicriteria analysis. Springer-Verlag Berlin, Heidelberg, **2012.**
7. TRIANTAPHYLLOU E. Multi-Criteria Decision Making Methods: A Comparative Study. Kluwer Academic Publishers, Dordrecht, The Netherlands, **2010.**
8. SAATY R.W. The Analytic Hierarchy Process-What It Is

And How It Is Used Mat/d Modelling, **9** (3-5), 161, **1987**.

9. SAATY T.L. Decision making with the analytic hierarchy process. Int. J. Services Sciences, **1**, No. 1, **2008**.
10. ISHIZAKA A., LABIB A. Review of the main developments in the analytic hierarchy process. Expert Syst. Appl. **38**, 14336, **2011**.
11. VAIDYA O. S., KUMAR S. Analytic hierarchy process: An overview of applications Eur. J. Oper. Res. **169**, 1, **2006**.
12. HO W. Integrated analytic hierarchy process and its applications – A literature review. Eur. J. Oper. Res. **186**, 211, **2008**.
13. HERMANN B.G., KROEZE C., JAWJIT W. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. Journal of Cleaner Production **15**, 1787, **2007**.
14. The EU Ecolabel (http://ec.europa.eu/environment/ecolabel/).
15. Polish Center of Research and Certification (http://www.pcbc.gov.pl/ecolabel/index.php), [In Polish].
16. AL-YAHYAI S., CHARABI Y., GASTLI A., AL-BADI A. Wind farm land suitability indexing using multi-criteria analysis. Renew. Energ. **44**, 80, **2012**.
17. REVELLE C., McGARITY A.E. Design and Operation of Civil and Environmental Engineering Systems. John Wiley & Sons, Inc. N. York, **1997**.
18. AHP tutorial (http://www.boku.ac.at/mi/ahp/ahptutorial.pdf).
19. COMMISSION DECISION of 9 November **2007** establishing the ecological criteria for the award of the Community eco-label to electrically driven, gas driven or gas absorption heat pumps (2007/742/WE), with later amendments (2011/740/UE).
20. HIPRE software (http://www.hipre.hut.fi) - Global Decision Support.
21. STYPKA T., FLAGA-MARYANCZYK A. Multi-criteria evaluation of power equipment using the AHP-HIPRE method and eco-labeling criteria. Chłodnictwo, **1-2**, (2012), 24, Sigma-Not Sp. z o.o., **2012** [In Polish].
22. STYPKA T., FLAGA-MARYANCZYK A., SCHNOTALE J. Design of the heat pump evaluation criteria hierarchy using the AHP-HIPRE method and eco-labeling criteria. Chłodnictwo, **3**, (2012), 26, Sigma-Not Sp. z o.o., **2012** [In Polish].
23. FLAGA-MARYANCZYK A., STYPKA T., SCHNOTALE J. Heat pump evaluation using the AHP-HIPRE method and eco-labeling criteria. Chłodnictwo, **4**, (2012), 26, Sigma-Not Sp. z o.o., **2012** [In Polish].
24. Economic efficiency of heat pumps (http://www.ogrzewnictwo.pl/artykuly/de-dietrich-oplacalnosc-zastosowania-pompy-ciepla-typu-alezio-ii), [In Polish].
25. BEHRENS W., HAWRANEK P.M. Manual for the Preparation of Industrial Feasibility Studies. United Nations, **1991**.