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Application of the AHP Method in Environmental Engineering: Three Case Studies

Tomasz Stypka, Agnieszka Flaga-Maryańczyk and
Jacek Schnotale

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Abstract

The chapter presents the application of the Analytic Hierarchy Process (AHP) method in the field of environmental management. The work shows how to use the results of environmental engineering tools or models as an input for the AHP method. Three case studies are presented: selection of the best municipal solid waste disposal system, assessment of the tap and bottled water consumption on the environment, and selection of the heat pump for the individual home. In the first case study, the AHP analysis was required to assess the environmental impact of waste disposal system. This was done by the use of Integrated Waste Management model (IWM-1), which delivered results aggregated, at the next step, into Life Cycle Analysis (LCA) categories. The obtained results were used in the AHP analysis to choose the best scheme for the waste disposal system. In the second case study, the AHP method was used to evaluate different patterns of water drinking. Obtained results help decision makers in assessing regional and individual environmental impact if the drinking pattern changes. Selected evaluation criteria were solid waste stream, energy consumption, carbon dioxide emission, and Eco-indicator 99 H/A points. The third case study presents the method of heat pump selection. The environmental performance criteria were developed using the criteria of the ecolabeling program. All three case studies are based on real data.

Keywords: AHP, MSWM model, sustainable development, ecolabeling, heat pumps

1. Introduction

The Analytic Hierarchy Process (AHP) method turns up to be a useful and dominant method for solving the whole spectrum of multicriteria problems [1]. It is the most popular among

European, Asian, and American researchers in all environmental areas with the exception of air quality and its popularity is growing in time [1]. At present, it is often integrated with other tools of decision making such as Quality Function Development (QFD), meta-heuristics, SWOT analysis, mathematical programming, and Data Envelopment Analysis (DEA) [2].

The full potential of the AHP in solving the environmental problems can be unveiled when the method is combined with the environmental tools. The environmental tools are used to develop and measure many criteria of the analyzed systems performance which are used as an input for the AHP analysis. Such tools can also help in the proper designing of the criteria hierarchy. The presented case studies show such an integrated approach where environmental tools—ecolabeling programs, Life Cycle Analysis (LCA) software or Eco-indicator 99 H/A points—are used to measure the environmental impact and deliver input information for the AHP analysis. These tools can also help build the proper structure of the hierarchy of criteria.

The first case study shows how the AHP method can be combined with the LCA waste disposal model to help select the best municipal solid waste system. Two systems, one based on incineration and the other based on landfilling, are compared. Because one of the evaluation criteria is an environmental performance, the professional solid waste management tool called Integrated Waste Management model (IWM-1) was used to calculate this environmental impact. Because the IWM-1 results are too detailed for the AHP, they, in the next step, had to be integrated into Life Cycle Analysis (LCA) impact categories. For the final integration, the AHP method was applied. The Web-HIPRE software (http://hipre.aalto.fi/) was used to conduct the analysis. Finally, the presented sensitivity analysis showed the confidence of the obtained results and pointed out the most important assumptions of the whole analysis.

The second case study shows how the AHP method combined with eco-indicators can be used to help develop municipal policy toward drinking tap and bottled water. So popular bottled water is expensive for individuals and causes problems for the environment and waste disposal communities. The goal of the project is to measure this burden to help municipality develop rational policy in this area. The impacts of drinking tap water and bottled water are estimated using criteria such as waste stream reaching landfills, energy consumption, carbon dioxide emission, and Eco-indicator 99 H/A points. The developed criteria are integrated using the AHP method, which allowed developing graphs that can be used by the decision makers to estimate results and to make appropriate proposals on policy actions toward bottled water drinkers.

The third case study shows how to select the heat pump for a house. Generally, the selection is conducted by professionals with limited attention to the personal needs of the user, or it is made by the user with limited attention to technical details. The presented AHP method combined with the ecolabeling program solves this problem. It can be used by a non-profes-sional to help professionally select a heat pump. The critical problem of proper criteria selection was solved with the help of the "Nordic Swan" ecolabeling program. Because sometimes costs are separated from the criteria hierarchy, the option with the Cost-Benefit Analysis (CBA) of the same heat pumps is also conducted. In this case, the AHP method is used to calculate the integrated benefit of each heat pump while the cost was calculated using the Net Present Value (NPV) indicator.

All three case studies are described in more details in Refs. [3–5].

2. Comparative analysis of municipal solid waste systems: Cracow case study

There is a need to develop, master, and implement a simple, but reliable tool that would help the decision makers select the Municipal Solid Waste Management (MSWM) system. There are number of mathematical municipal solid waste models that might be used to solve the problem, where the objective function is the cost of waste disposal. The environmental elements (the recycling schemes) have appeared in the models beginning in the 1980s [6, 7]. Also there is a group of models, which include the environmental factors in the form of constrains of the economic models [8]. Some of the models are based on the concept of Life Cycle Analysis (LCA) while other focus only on different environmental elements such as traffic or noise [8] or CO_2 emissions from waste delivering vehicles [9]. The review of different models can be found in Refs. [10–12], but so far no model fits fully the decision makers' expectations.

Probably the group of models which, in the best way, reflects the idea of sustainable development is a group of Life Cycle Analysis (LCA) models. The examples of such models are the US-EPA [13], WISARD [14], MIMES/Waste [15], ORWARE [16], ISWM tool Canada, LCA-IWM [17] and Integrated Waste Model (IWM) [14]. IWM (Integrated Waste Model) was first published in 1995 as an IWM-1 (in form of an Excel spreadsheet). IWM-2 was developed to improve certain aspects of IWM-1 and to make the model more global by including new set of data. IWM-1 was rather a European development [18]. IWM-2 was published in more user-friendly SQL-Database environment, which unfortunately is less transparent hence less useful for in-depth analysis. The authors chose IWM-1 model considering it to be transparent, flexible and simple.

The results of IWM-1 model are numerous and detailed, which makes them not convenient for the inexperienced decision makers, who are interested in the clear and simple answer which MSWM system is the best. To help with this issue, the authors integrated IWM-1 results using the LCA impact categories and later, implementing simple, but sound multiobjective AHP method. Described methodology allowed to compare two MSWM systems for the city of Cracow, Poland (population: 742,000).

2.1. Description of the compared MSWM systems

The authors compared two MSWM systems. The real system applied in Cracow, Poland, in year 2001, based on the landfill as the main option of waste disposal (called "system A"), and the hypothetical system based on the assumption that the waste recycling is improved and the main way of rest-waste disposal is incineration. This was the planned system for Cracow at that time. In the analysis, this system is called "system B." The case study is based on real data. The information regarding waste and systems' description was cited after Kopacz [19].

The key data for the MSWM analysis are the amount and composition of waste. Waste input data, the same for system A and system B, divided into categories required by the IWM-1 model presents (**Table 1**).

Amount (t/year)	Household waste composition (wt.%)								
	Paper	**Glass**	**Metal**		**Plastic**		**Textiles**	**Organics**	**Other**
169,346	19.9	7.8	2.9		14.4		6.1	36.2	12.7
			Ferrous	Non-Fe	Film	Rigid			
			65	35	44	56			

Amount (t/year)	Commercial waste composition (wt.%)								
	Paper	**Glass**	**Metal**		**Plastic**		**Textiles**	**Organics**	**Other**
107,806	45.0	5.0	4.1		12.0		1.0	30.0	2.9
			Ferrous	Non-Fe	Film	Rigid			
			60	40	80	20			

Table 1. Composition of different parts of Municipal Solid Waste in analyzed Cracow case.

In system A, landfilling is the main disposal method and there are also 150 recycling material banks for metal, polyethylene terephthalate (PET) bottles, paper and glass. Additionally to the system of recycling banks, there is a system of "bring and earn" collection points and the composting facility with the throughput of 6000 tons per year. A number of charity organizations run the system of collection points for the textile waste.

In system B, the annual throughput of 200,000 tons of waste is assumed for the incinerator. The incinerator generates only electricity with the 20% efficiency. Contrary to the real Cracow plans, the waste heat recovery is not modeled because IWM-1 model does not have such an option. This blurs the final results, but in reality the incinerator generates the heat for the municipal district heating system, substituting the waste heat from the power plants. If the city decides to utilize the heat from the incinerator, the power plants have the problem of "what to do" with their by-product, hence the environmental benefits of incinerator's waste heat utilization are problematic. Additionally, in system B, the number of collection banks is increased up to 450, and thanks to the increase of public awareness, the amount of recyclables collected in each bank is increased by 25%. System B assumes the development of the recycling program. Material Recovery Facility ready to handle 20,000 tons of recyclables along with two composting facilities for 6000 and 9000 tons of green waste is commissioned. Also, in some parts of the town, the "wet" and "dry" waste collection systems are introduced.

As a result of those changes, the amount and quality of waste disposed at the landfill change significantly. The exact results, for both systems, calculated using IWM-1 model are presented in **Table 2**. In system B, the amount of waste disposed at the landfill is reduced by five times (from 247 ktons in system A to 49 ktons in system B). Also in system B, the diversion from

landfill is eight times higher than in system A, and the amount of recyclables is increased more than twice. The economic and environmental results of the two systems are also very different.

Final solid waste	System A	System B
Non-hazardous (kt)	246.98	48.67
Hazardous (kt)	0.39	6.57
Total weight (kt)	247.37	55.24
Total volume (m³)	160,590	44,410
Materials recovery rate		
Average	17%	36%
Paper	25%	54%
Glass	6%	20%
Metal Fe	40%	56%
Metal non-Fe	15%	21%
Plastic film	4%	5%
Plastic rigid	1%	22%
Textiles	6%	11%
Organic recovery rate	1%	4%
Overall recovery rate	10%	22%
Diversion from landfill	10%	80%
Secondary materials (kt/year)		
Paper	20.77	44.09
Glass	1.12	3.66
Metal Fe	2.36	3.25
Metal non-Fe	0.53	0.74
Plastic film	0.92	1.10
Plastic rigid	0.14	3.65
Textiles	0.71	1.25
Compost	1.02	3.58
Total	27.56	61.33

Table 2. Streams of waste and recovered materials for analyzed scenarios.

2.2. Integration method of the IWM-1 results

The IWM-1 model delivers results estimating the air emissions of 22 compounds and emission of 23 compounds into water. Additionally, the basic statistical and economical data about the

systems' performance are also presented. This is a lot of detailed information not useful for the decision makers and has to be combined before implementation. The proposed integration method is based on impact assessment of LCA. To calculate these indicators, the authors used the methodology described in detail in Refs. [20–22]. The general assumption was to estimate the maximum possible number of LCA categories, which could be calculated based on the IWM-1 results. **Table 3** presents the list of the selected categories.

Impact categories	Characterization factor	Unit
Baseline categories		
Depletion of abiotic resources	Abiotic depletion potential (ADP)	kg (antimony eq.)
Climate change	Global warming potential (GWP 100)	kg (carbon dioxide eq.)
Human toxicity	Human toxicity potential (HTP 100)	kg (1,4-dichlorobenzene eq.)
Ecotoxicity: fresh water aquatic ecotoxicity	Freshwater aquatic ecotoxicity potential (FAETP 100)	kg (1,4-dichlorobenzene eq.)
Ecotoxicity: terrestrial ecotoxicity	Terrestrial ecotoxicity potential (TETP 100)	kg (1,4-dichlorobenzene eq.)
Photo-oxidant formation	Photochemical ozone creation potential (POCP)	kg (ethylene eq.)
Acidification	Acidification potential (AP)	kg (SO_2 eq.)
Eutrophication	Eutrophication potential (EP)	kg (PO_4^{3-} eq.)
Stratospheric ozone depletion	Ozone depletion potential (ODP steady state)	kg (CFC-11 eq.)
Land competition	Land use	m^2 year
Other impact categories		
Odor malodorous air	Reciprocal of odor threshold value (1/OTV)	m^3 (air)

Table 3. Selected categories of the life cycle impact assessment.

Indicators for the different impact categories were selected based on the literature [23]. Unfortunately, not all recommended impact categories can be directly calculated from the IWM-1 result table. The obtained results are presented in **Table 4**. More detailed environmental analysis of the results can be found in reference [3].

The results show that, based on landfilling, system A is superior when the following criteria were analyzed: abiotic depletion, human toxicity, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, acidification and eutrophication. The second scenario, system B, with advanced waste sorting and incineration, turned out to be better in categories of energy consumption, climate change, photochemical smog creation and odor creation.

		System A	System B
Energy balance	GJ th	−102,500	−702,530
Depletion of abiotic resources	kg (antimony eq.)	−8.77E + 00	1.12E + 02
Climate change	kg CO_2 eq.	2.68E + 08	2.11E + 08
Human toxicity	kg (1,4-dichlorobenzene eq.)	3.67E + 05	3.49E + 08
Fresh water aquatic ecotoxicity	kg (1,4-dichlorobenzene eq.)	−7.19E + 04	−3.01E + 05
Terrestrial ecotoxicity	kg (1,4-dichlorobenzene eq.)	−1.89E + 02	3.65E + 05
Photo-oxidant formation	kg (ethylene eq.)	6.19E + 04	−2.51E + 04
Acidification	kg (SO_2 eq.)	4.81E + 04	2.21E + 05
Eutrophication	kg (PO_4^{3-} eq.)	1.36E + 04	1.34E + 03
Odor malodorous air	m^3	1.07E + 13	−9.83E + 11
Land competition	m^2 yr	7.49E + 05	2.07E + 05
Cost	1000 euro	20586.23	37298.27

Table 4. Results of the Integrated Waste Management model (IWM-1) analysis.

The obtained aggregated results still do not give a straight answer about the superiority of one specific system. There are many categories, measured by different units, and the analyzed systems fulfill various criteria in varying degree. Some of the categories are measured using the same units, but even in this case, the comparison between the different categories is impossible. For example, human toxicity, freshwater aquatic ecotoxicity and terrestrial ecotoxicity are all measured by 1,4-dichlorobenzene eq. in 100 years perspective. Even in this case, comparison among these categories is possible only when using the impact ratios.

The final evaluation of the analyzed scenarios was made using the AHP method.

2.3. Multicriteria analysis of the Cracow MSW systems

The authors used Analytic Hierarchy Process (AHP) as a method of further analysis with software prepared by Helsinki University of Technology [24]. Prepared hierarchy of criteria and assigned ratings are presented in **Figure 1**. Criteria were developed based on IWM-1 analysis and the ratings were assigned arbitrarily by the authors based on their experience. The goal of the model was to find the most sustainable solution and the selected hierarchy of criteria reflected this approach. The authors represented the whole spectrum of expertise in environmental engineering, environmental management and waste handling. The final ratings were reached at some point in the joined discussion.

Figure 2 presents the final results of the analysis. The graph shows that system B is better evaluated than system A. The overall score of system A is 0.362 and system B is 0.638. This means that system B is almost two times better than system A and, in other words, meets all the expectations in 64%. System B is superior to system A, thanks to significantly better environmental performance. The more detailed comparison of the environmental performance

of the two MSW systems is presented in **Figure 3**. System B is more friendly toward all three components of the environment: water, soil and air. It is superior to system A in all subcategories of air and water criteria. The environmental superiority of system B in subcategory "soil protection" is not so dominant. System B is better only in "land use" sub-criterion, but because this sub-criterion is so important, the total evaluation of system B in subcategory of "soil protection" is better than the performance of system A.
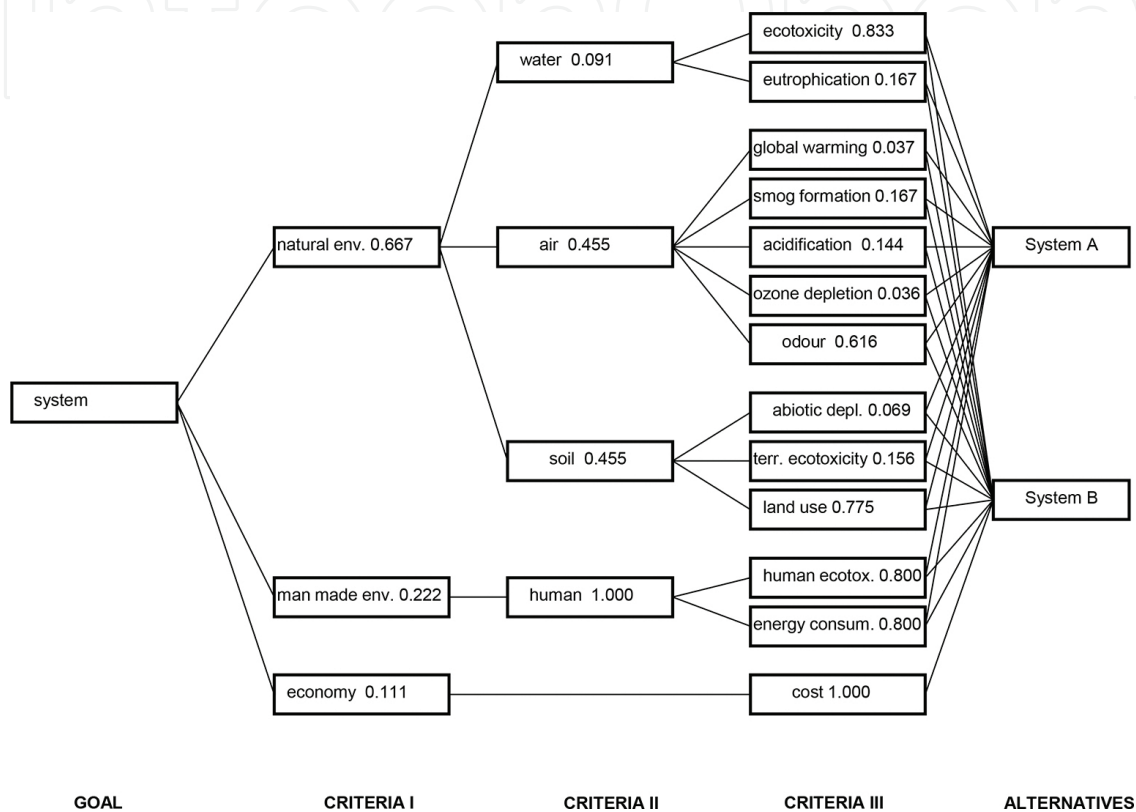
Figure 1. Objective hierarchy and ratings for the Cracow analysis.
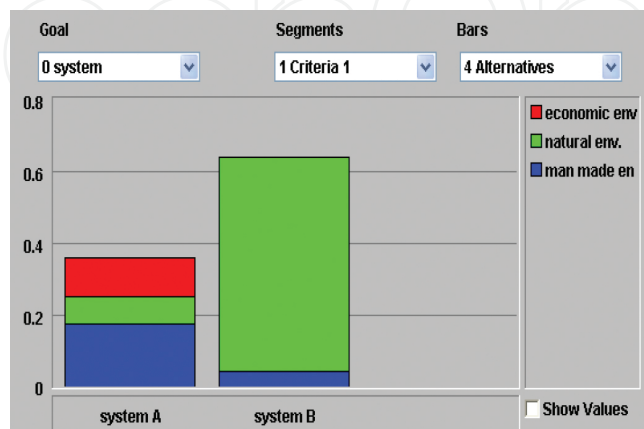
Figure 2. Results of the AHP analysis for the two Cracow MSWM scenarios (criteria 1).
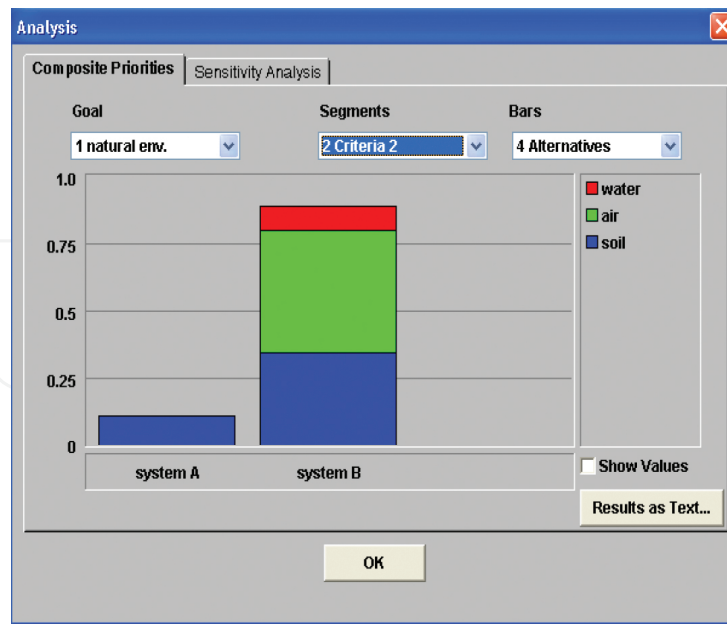
Figure 3. Results of the AHP analysis for the two Cracow MSWM scenarios (criteria 2).

A more detailed analysis of the obtained results allow to draw conclusion about how much the environmental performance of system B is increased by substituting the landfilling with the incineration and extension of the waste collection system. Also, the local and global environmental impacts can be distinguished [3].

The AHP analysis gives very clear answer that system B is superior to system A. Such a simple answer is expected by the decision makers, but the AHP analysis combined with the IWM-1 model also gives more detailed results justifying its overall score which can be useful in further analysis.

2.4. Sensitivity analysis and conclusions

The sensitivity analysis is trying to give answer to the question: how much the obtained results change if there is a change in the input values? The final outcome of the AHP analysis depends on the assumed hierarchy of goals, on the assigned relative weights of the goals and on the performance of the analyzed alternatives, but the performance of the analyzed systems has far more limited impact on the final result. If only two options are compared, it is important if the performance in each category is superior, but not the level of this superiority.

The reason why system B performs better than system A is its significantly better performance in the category "impact on the natural environment." The performance in the AHP analysis is a product of relative weight of the category and estimated physical performance. The relative weight of this category was assumed to be equal to 0.67, but the sensitivity analysis indicates that if this weight is 0.48, both analyzed scenarios will be estimated as equally good (**Figure 4**). If the weight for the natural environment equals 0.48, the other two weights should be in the same proportion to each other, and have the values 0.347 for the impact on the manmade environment and 0.173 for the economic performance. Also, the analysis shows that if the

importance of the economic criterion increases from the present ratio 0.11 to 0.30, this will result in making the two analyzed systems equally good (**Figure 5**). The threefold increase of the economic criterion weight is not likely, but possible. The increased rating of the "manmade environment" from the present 0.22 to 0.47 will result in equalizing of the two systems performance. To change the ranks of analyzed scenarios, the weights have to change significantly. It is up to the decision makers to decide whether such a significant change of weights is possible.
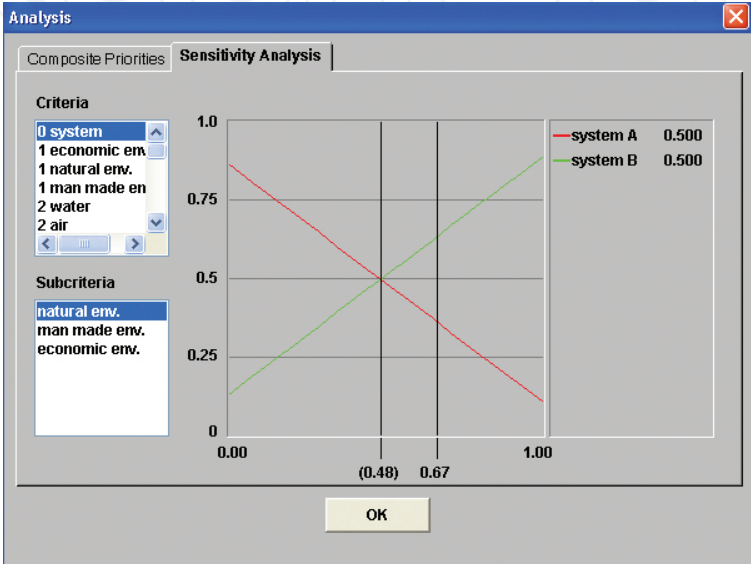
Figure 4. Sensitivity analysis: the relative weight of the category "impact on the natural environment."
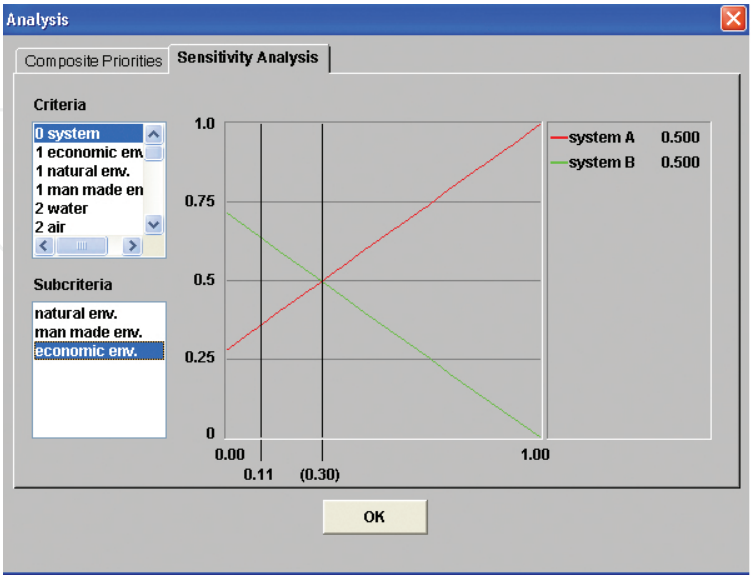

Figure 5. Sensitivity analysis: the relative weight of the category "economic performance."

Changing the weights of all components of the environment (water, air and soil) will change the final evaluation score, but will not change the rating of the systems' impact on the natural environment since all ratings' impact on the natural environment of the system B is better than those of the system A.

No change of water or air criteria ratings can change the two systems' performance in the subcategory "impact on water" and "impact on air" (**Figure 6**). In subcategory "impact on soil," changing the ratings of all subcategories can result in the switch of superiority of the two systems in the category "impact on soil," but the changes have to be substantial (**Figure 7**).
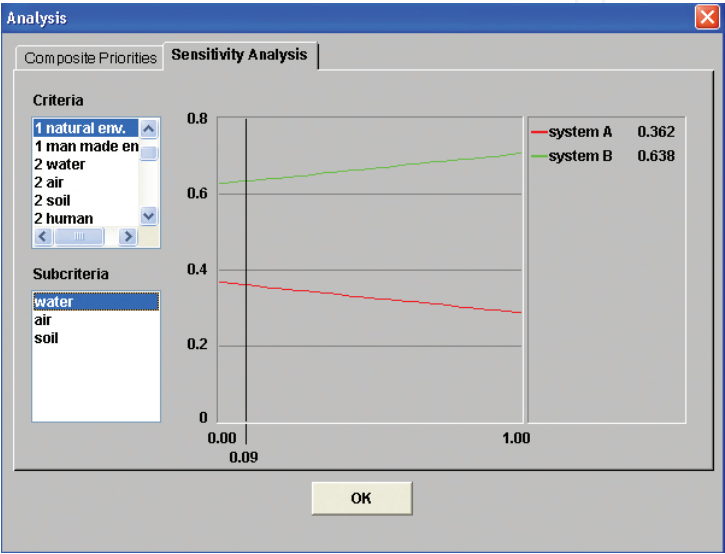

Figure 6. Sensitivity analysis: the relative weight of the subcategory "impact on water."
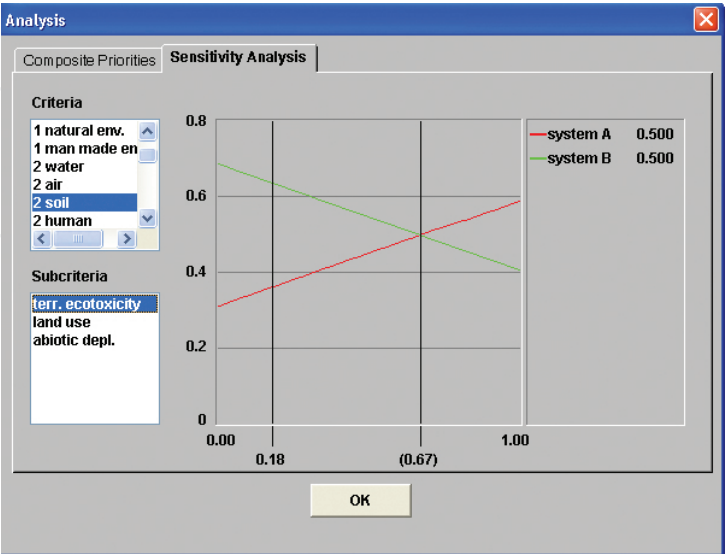

Figure 7. Sensitivity analysis: the relative weight of the subcategory "impact on soil."

Generally, the sensitivity analysis shows that the biggest impact on the final score have the weights assigned at the top level of hierarchy (natural environment, manmade environment, economic impact) and the weights assigned to category "impact on soil."

The AHP method combined with the IWM-1 model allowed the broad and thorough comparison of two different waste disposal systems. In this case, the system based on incineration looks like a better solution and shows superior environmental performance. This good environmental performance is the result of "avoided emissions," thanks to material and energy recovery. The economic performance of the traditional landfilling system is better than the performance of system based on incineration. The overall evaluation shows that the city should build the incinerator and implement advanced recycling programs. These conclusions are in tune with the common trends and regulations. Thanks to the integration of the AHP and IWM-1, the obtained results are clear and detailed simultaneously. This is a quality very much sought by the decision makers.

3. Drinking water consumption in Cracow: an assessment from sustainable development perspective

In this case, the AHP method is used to assess, from a sustainable development perspective, the current consumption model for drinking water in Cracow. It assesses the economic consequences for the average city resident who decides to drink bottled water. The total energy demand for the production, distribution and consumption of bottled water is estimated and is compared to the household energy consumption.

The healthy lifestyle trends and the lack of trust in the quality of tap water result in mass consumption of bottled water. The problem is particularly significant in rich cities, which are visited by large numbers of tourists and also in academic cities, populated by young people who are trend setters, like Cracow. Such a behavior also has consequences from the sustainable development perspective.

The general goal of this case study is to develop a tool for the municipal decision makers to measure the efficiency of policy toward bottled water drinkers.

The environmental impact for the current water consumption model in Cracow is estimated by summing the waste reaching landfills, energy consumption, carbon dioxide emission, and Eco-indicator 99 H/A points. These estimates were calculated based on the data in the reviewed literature revised for the actual quantities of consumed bottled water and bottle recycling levels in Cracow. The potential environmental savings for the city related to an annual reduction of one liter of bottled water consumed by an average resident is also calculated. The different water consumption scenarios are assessed using the AHP to see how compliant they are with sustainable development.

The concept of sustainable development can be considered on three levels: ecological, social and economic. However, a problem arises with how to measure sustainable development for such an activity when the negative effects on an economic and ecological level are partially

compensated for on a social level. Russel [25] suggests that energy-intensity and material-intensity of comparable products or processes serve as sustainability indicators. Life-cycle assessment (LCA) is a tool which enables an assessment of material and energy intensity of tap and bottled water preparation as well as an assessment of the impact on an ecological level. In this case, the authors tried to quantify how much bottled water is drunk in Cracow and then using American and Swiss LCA analysis, assess the actual environmental costs of such consumption for the city and its residents. Thanks to LCA, it is also possible to estimate how the environment and economy will change if an average resident reduces his/her consumption of bottled water by one liter annually. A total assessment method is also presented from the perspective of sustainable development for each of the water consumption scenarios. For the total assessment, the multicriteria AHP was used.

3.1. Economic consequences for the present water consumption model

An average Polish citizen drinks 72.4 liters of bottled mineral water annually [26]. Since most people who drink bottled water have a secondary or university education and reside in cities [27], it can be assumed that a resident in Cracow annually drinks 80 liters of bottled water.

A survey of water prices carried out in one of the supermarkets in Cracow showed that bottled water is about 500 times more expensive than tap water. Considering that a person should drink 1.5 liters of water daily, a resident of Cracow drinks approximately 548 liters of water annually, of which bottled water amounts to at least 80 liters (15%). Consequently, a resident of Cracow pays between 53 zloty and 24.22 zloty annually for bottled water whilst the remaining 85% of water drunk costs just 1.60 zloty.

3.2. The effect of bottled water consumption on the natural environment

One of the main burdens on the natural environment associated with the consumption of bottled water is its energy-intensity and the waste produced. Currently 95% of the bottled water sold in the USA and over 90% in Poland is in bottles manufactured from PET [28].

Energy is required for PET and bottle manufacture, water treatment, transportation of bottled water, chilling the water, and maintaining it at low temperature. The energy demand for bottle production depends on bottle size. For a one liter bottle weighing 38 grams, about 4 MJ of energy is required [28]. The energy required for the treatment of drinking water depends on the technology and the degree of pollution. For example, ultraviolet disinfection requires only 10 kWh/million liters, but the energy required for reverse osmosis can reach up to 1600 kWh/million liters or more as in the case of sea water desalination [29].

The transportation's energy demand depends on two factors: distance and means of transport. The vehicles used in Poland have a medium energy demand between 3.5 and 6.8 J/(kg km) [29]. **Table 5** shows the total estimated energy demand for bottled water [28].

In this analysis, the energy requirements for the long-distance transportation of water through the pipeline or from deep boreholes have not been taken into account. It is assumed that water is first treated and then poured into plastic PET bottles, capped, labeled, and packed in a

bottling plant. Then it is distributed into shops and chilled before consumption. Based on these assumptions, the total energy required for bottled water varies between 5.6 and 10.2 MJ/liter. For comparison, tap water requires on average 0.005 MJ/liter for treatment and distribution [29]. This means consumption of bottled water is between one and two thousand times more energy intensive compared to that of tap water.

Stage	Energy demand (MJ$_{th}$)	Percentage
Manufacture of plastic PET bottle	4	39–71%
Water treatment	0.0001–0.02	0–0.3%
Bottling and labeling	0.01	0–0.1%
Transport—dependent on distance and type	1.4–5.8	25–57%
Chilling	0.2–0.4	3–9%
Total	5.6–10.2	100%

Table 5. Total energy demand for the production and consumption of one liter of bottled water.

3.3. Waste

It is estimated that between 100,000 and 150,000 tons of PET packaging is manufactured in Poland annually [28]. Some of it is recycled, but most ends up in a landfill. According to the estimates of Organizacja Odzysku REKOPOL (Warszawa) (REKOPOL Recovery Organisation S.A. Warsaw) currently about 40,000 tons of PET waste is collected annually [30]. Other sources estimate that 28% of plastic PET bottles are recycled in Poland [31]. In 2010, 73% of packaging waste was recycled in some form in Cracow [32]. Based on these data, one can assume that the average resident of Cracow, drinking 80 liters of bottled water in 1.5 liter bottles annually, uses 53 bottles of which 39 bottles are recycled whilst the remaining 14 end up in a landfill occupying 0.019 m^3 (density of compressed plastic PET bottles is 44 kg/m^3 [33] and an average bottle weighs 60 grams). For the whole of Cracow, this means 14,000 m^3 of waste being sent to landfill annually.

3.4. Adapting LCA analysis for the consumption of bottled water in Cracow

To more accurately assess the effect of drinking water consumption on the environment in Cracow, two reports on a similar subject were studied: an LCA report on drinking water systems in the state of Oregon, USA [34] and a similar report for the water supply for Swiss regions [35]. In the reports, various drinking water supply scenarios were analyzed ranging from unboiled tap water to bottled water transported over long distances. Taken into account were various types of packaging (tap water, bidons, bottles), transportation (different sizes of vehicles, shipping), consumption (boiled, unboiled, chilled) and packaging waste disposal policy. Forty-eight different scenarios were analyzed in the American report and 19 in the Swiss report. It was eventually decided that the conditions in Cracow were best reflected by the scenarios in the Swiss report.

Scenario		Unit indicators		Data for Cracow	
		Energy consumption	Greenhouse gas emissions	Energy consumption	Greenhouse gas emissions
Description	Abbreviation	$\frac{MJ_{eq.}}{l_{water}}$	$\frac{kg\ CO_{2\ eq.}}{l_{water}}$	$\frac{GJ_{eq.}}{year}$	$\frac{kg\ CO_{2\ eq.}}{year}$
Water from a municipal water supply network, unchilled	Kr.4	0.014	4.06E–04	5631	168
Water from a water supply network, boiled in an electric kettle	Kr.6	1.07	1.65E–02	442,991	6831
Bottled water, transported 50 km, still, unchilled, plastic PET bottle	But.4	4.35	1.78E–01	1,800,944	73,694
Bottled water, transported 200 km, carbonated, unchilled, plastic PET bottle	But.5	4.38	1.98E–01	1,813,365	81,974
Bottled water, transported 1000 km, still, unchilled, plastic PET bottle	But.9	8.34	4.25E–01	3,452,845	175,954

Table 6. Energy consumption and greenhouse gas (GHG) emissions for different water consumption scenarios for Cracow.

This report envisages nine tap water supply scenarios, out of which four assume water consumed directly from the tap, without chilling or carbonation. The differences between these scenarios are related to the source of the water and consequently to its treatment. The scenarios cover water from abstraction intakes typical for Switzerland (Kr.1), Europe (Kr.2), Swiss rural

areas (Kr.3) and Swiss urban areas (Kr.4). In Cracow, each abstraction intake uses different water treatment technology [36]. They all have coagulation, sedimentation and disinfection stages. Since surface water is the source for both Zurich and Cracow, i.e., water having similar parameters, it can be assumed that the water treatment processes have a similar burden on the natural environment in both cities. As for bottled water, the Swiss report assumes 10 scenarios depending on the location where the water is produced (Switzerland, Europe), vehicle transportation distance (from 50 to 1000 km), the distribution method to the households (from 0 to 10 km by delivery van), the type of water (carbonated, still), drinking temperature (chilled, not chilled), packaging (1.5 liter PET, 18.9 liter demijohn for recycling, 1 liter glass bottle for recycling). The But.5 scenario seems to be a good choice for the water consumption model for Cracow. Based on unit indicators estimated in the Swiss report and assuming that 756,186 residents drink 1.5 liters of water daily, the annual consumption of primary energy and greenhouse gas emissions has been estimated (see **Table 6**).
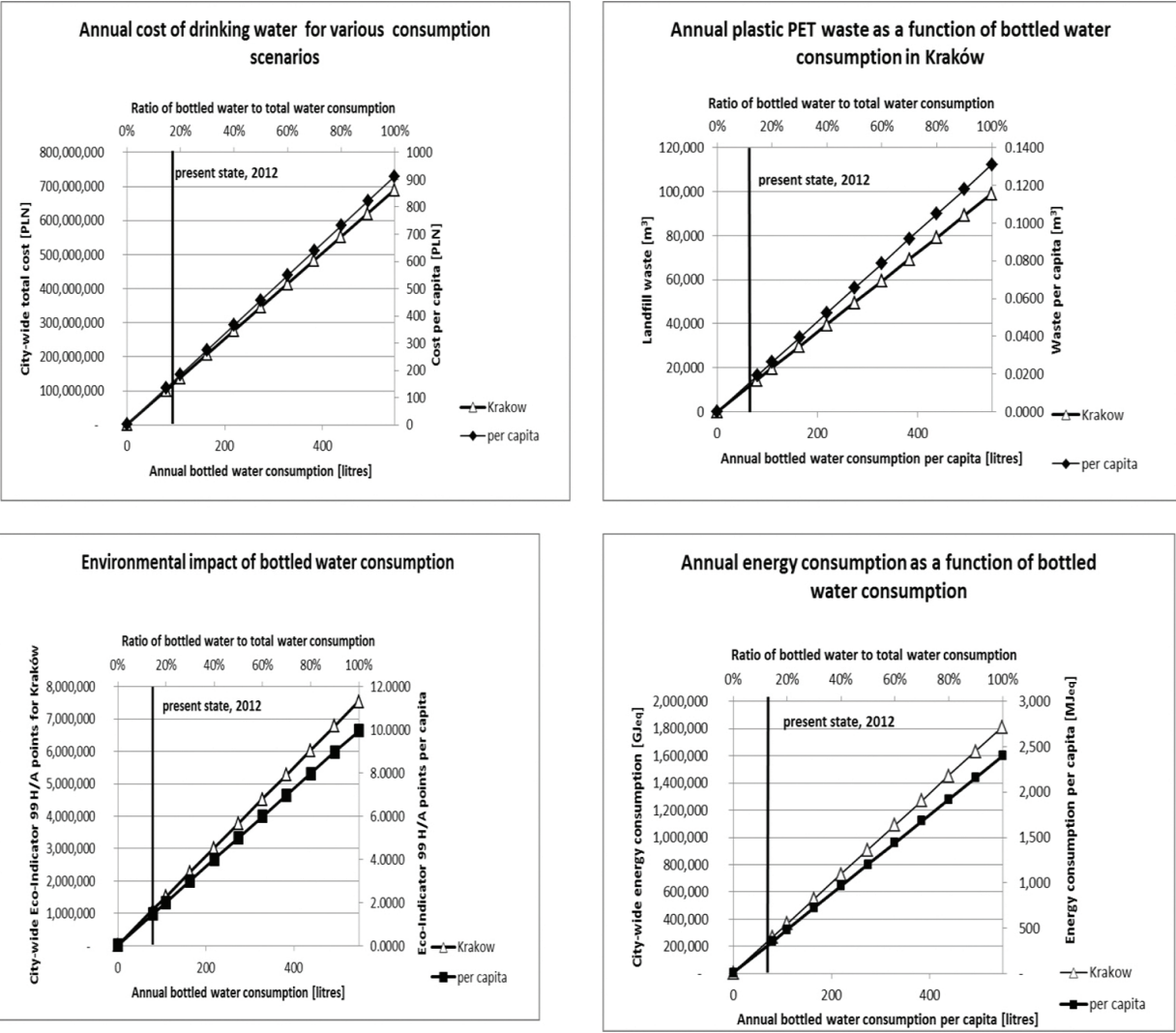

Figure 8. Economic and environmental impact for different drinking water consumption scenarios in Cracow.

Table 6 shows that the environmental impact depends on the water consumption scenario.

In reality, water consumption in Cracow is a mixture of scenarios. About 15% of water (80 liters annually) is drunk as bottled water, which approximately corresponds to scenario But. 5, whilst the remainder is drunk as tap water which corresponds to scenario Kr.4 or Kr.6. Using scenarios Kr.4 and But.5 as the base, the impacts of the intermediate scenarios on the environment were estimated. The results are shown in **Figure 8**.

Figure 8 shows the environmental impact of different bottled water scenarios. If the bottled water consumption increases, all the environmental impact parameters increase very sharply. These charts can be helpful in estimating the expected impacts when changes to the water consumption model are made. The impact of reducing consumption of bottled water by one liter on the global environment and the city was also estimated. These estimates are both city-wide and for one resident. The results are shown in **Table 7**.

Table 7 shows, for example, that the municipal policy which reduces the bottled water consumption by one litter per person results in 3202 GJ energy savings and saves 181 m^3 of the landfill's space. The impact on the environment is measured using Eco-indicator 99 H/A points. Eco-indicator 99 H/A points are used primarily to compare different scenarios and 1000 points have been defined as the annual environmental load of an average European citizen. It is estimated that the impact on the environment is 3.93×10^{-5} points when consuming 1 liter of tap water. However, for bottled water it is 463 times greater at 1.82×10^{-2} points.

	Reduction in bottled water consumption	Energy consumption	CO$_2$ emission	Cost	Volume of waste	Environmental impact
	Liters	MJ eq	kg CO$_2$ eq.	PLN	m^3	Eco-indicator 99 H/A points
For 1 resident	1	4.366	0.198	1.66	0.0002	0.0182
For Cracow	756,183	3,301,797	149,417	1,257,711	181	13,733

Table 7. Environmental impact of a one liter reduction in the consumption of bottled water.

3.5. Evaluation of the water consumption model in Cracow from a sustainable development perspective

The evaluation of individual water consumption models, from a sustainable development perspective, requires an analysis of these models with consideration to their effect on society, the natural environment and economic impact [37, 38]. The next stage is to work out the individual criteria and select the comparison method. The AHP is one of the universal comparison methods which can be used to compare products or processes from a sustainable development perspective [39].
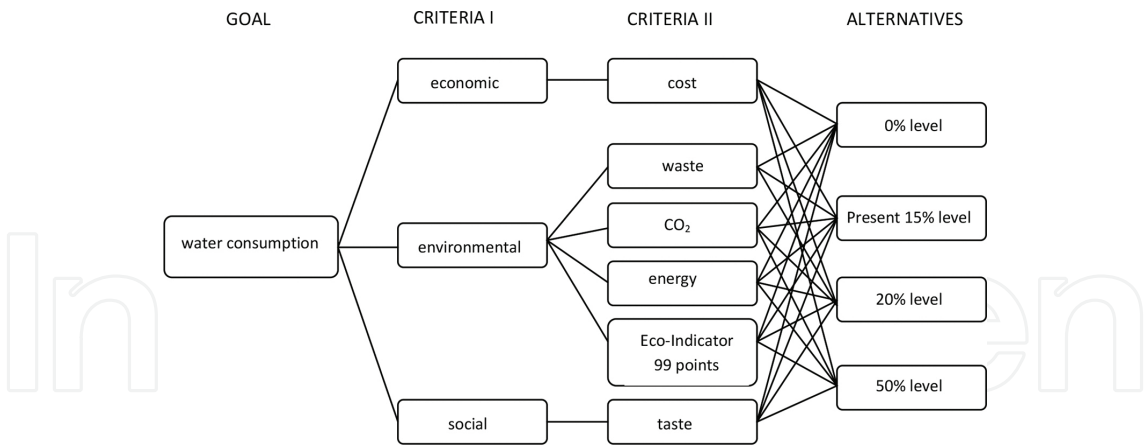
Figure 9. Hierarchical tree of criteria for AHP analysis.

In the case of water consumption in Cracow, four potential scenarios were considered by the authors of the report [4], each differing in the percentage of bottled water of the total water consumed. Scenarios where bottled water constituted, 0%, 15%, 20% and 50% of the water drunk were analyzed. On the basis of the available criteria, a hierarchical tree of criteria (**Figure 9**) was constructed and using the described method earlier, the degree of compliance with individual criteria for each scenario was evaluated (**Table 8**). Minimum and maximum values in each category were assigned to the scenario where bottled water consumption was 0 and 100%, respectively. As a social criterion, the taste of water was assigned between 0 and 10 points. The same satisfaction level from drinking water was assigned to all scenarios since in reality both professionals and amateurs find it difficult to distinguish the source the water originates from [28]. The authors of the article assigned the weightings to individual criterion in accordance with the AHP procedure, comparing individual criteria pair-wise. The process of assigning was the result of experts' discussion. The Web-HIPRE application supplied by the Helsinki University of Technology was used for analyses [24].

Criteria	Unit	Scenarios analyzed (% of bottled water consumed)				Minimum	Maximum
		0%	15%	20%	50%		
Energy consumption	MJ eq/capita	7.45	356.00	485.57	1 202.75	7.45	2398.05
GHG emissions	kg CO_2/capita	0.22	16.03	21.86	54.31	0.22	108.41
Waste	m³/capita	0.00	0.02	0.03	0.07	0.00	0.13
Cost	PLN/capita	1.88	134.94	184.00	457.19	1.88	912.50
Environmental impact	Eco-indicator 99 H/A points	0.02	1.47	2.01	4.99	0.02	9.96
Taste	points	5.00	5.00	5.00	5.00	0.00	10.00

Table 8. Degree of compliance for individual criterion for various water consumption scenarios.

Table 9 and **Figure 10** show the results for the AHP analysis.

Criteria	Weightings for level ll criteria	Analyzed scenarios (% of bottled water consumed)			
		0%	15%	20%	50%
Waste	0.22	1	0.854	0.800	0.500
CO_2 emissions	0.09	1	0.854	0.799	0.500
Energy consumption	0.08	1	0.854	0.800	0.500
Environmental impact	0.62	1	0.854	0.800	0.500
Criteria	**Weightings for level I criteria**				
Economic	0.250	0.250	0.213	0.200	0.120
Environmental	0.655	0.655	0.559	0.524	0.327
Social	0.095	0.048	0.048	0.048	0.048
Total		**0.953**	**0.820**	**0.772**	**0.495**

Table 9. AHP scores for the drinking water problem in Cracow according to sustainable development criteria.
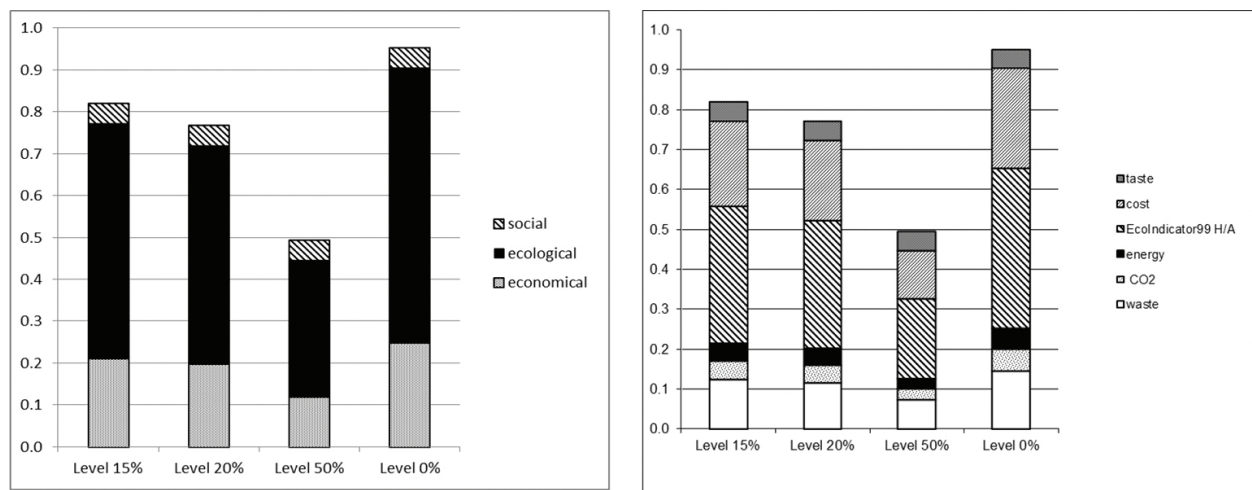

Figure 10. AHP scores for the drinking water problem in Cracow according to sustainable development criteria.

In accordance with the accepted procedure, the scenario which assumes drinking only unboiled tap water has an overall score of 0.953 where the maximum score is 1. This is almost a perfect solution. However, the scenario where 50% of water drunk comes from plastic PET bottles scores 0.495. A sensitivity analysis shows that when the weightings are changed, the overall score for the individual scenarios also changes, but their relative ranking remains unchanged [4]. The current water consumption scenario for Cracow has an overall score of 0.820 and is 14% worse than the best scenario from the sustainable development perspective.

The environmental impact, particularly when measured using Eco-indicator 99 H/A points is the most important criterion for Level I.

It is obvious that drinking safe tap water and not bottled water is superior to the person's economy and to the environment. The conducted AHP analysis shows measurably the size of this superiority. It also shows how much progress can be achieved in the city if tap water drinking becomes more common. This is particularly important in town such as Cracow which plans to organize big social events such as the World Youth Day in 2016 or the Olympic Games in the future. Thanks to the AHP, the impact of water drinking pattern is precisely measured in all selected criteria. This allows individuals and decision makers to compare the results of very different municipal policies. For example, the energy savings obtained, thanks to municipal program of building insulation, can be compared with the results of the bottled water consumption reduction program. The results of the conducted analysis can be used by the decision makers to estimate results and to make appropriate proposals on policy actions toward bottled water drinkers.

4. Developing environmentally sound selection method for heating appliances using ecolabeling and Analytic Hierarchy Process

This case study presents an assessment of heating appliances prepared on the basis of the AHP multicriteria evaluation method. The main problem with appliances' selection is that the consumers do not know which parameters of the equipment are important and, on the other hand, the professionals do not know the individual preferences of the consumers. The authors propose to design the hierarchy of criteria utilizing the concept of sustainable development and the criteria originating from ecolabeling programs [40, 41]. Integrating ecolabeling criteria into the AHP process is a similar concept as developing integrated AHP or combining AHP with other tools of environmental assessment [42].

The case study presents application of all three stages of AHP method for the real 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.

4.1. Ecolabeling as a basis for a criteria selection

The idea of ecolabeling [40, 41] originates from the assumption that consumers are looking for environment-friendly products. On the other hand, producers knowing the consumers' preferences are ready to deliver such products if products' quality is objectively confirmed. To allow such objective quality check, the independent certifying organizations set up very specific criteria, unique for specific groups of products. The producers can voluntarily apply

for an ecolabel presenting their products for certification. If the products meet the criteria, and the producer pays the fee, he is 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 ways, there is a hope for the favorable consumers' response.

The example of four European ecolabels is given in **Figure 11**.

Figure 11. Examples of European ecolabels.

Ecolabeling criteria do not include the economical aspects of product's usage; however, since these features are critical for the consumers, the economical criteria have to be included into the decision process. Because economical criteria tend to dominate the whole analytical process, they are introduced into the decision process in a very careful way. Haas [43] proposes to analyze the products' benefits without the economic criteria and then include them into the analysis, separately.

4.2. Heat pumps ecolabeling criteria

The EU Commission decision issued on November 9, 2007, with the later amendments [44] specifies the ecological criteria for the European ecolabel program for heat pumps powered by gas, electricity and heat (max. power 100 kW). According to the 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 the environmental impact during heating and/or cooling of buildings

- reduction or prevention of the 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 an ecolabel is granted to a heat pump. The list of those criteria with their brief descriptions is presented in the following section.

4.2.1. Coefficient of performance (COP)

The coefficient of performance (COP) is a ratio of generated heating power Q_k, to input power L (electricity or gas) for a particular source and output temperature. 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 = 30°C/35°C) or 3.50 (internal unit input/output temperatures = 40°C/45°C).

4.2.2. 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 = 30°C/35°C) or 1.40 (internal unit input/output temperatures = 40°C/45°C), while for a combi unit (with a cooling function), the minimal value of a PER ratio should be 1.2.

Due to the fact that both PER and COP are linearly related, only one (COP) was included into the AHP analysis.

4.2.3. Global warming potential (GWP)

The global warming potential (GWP) coefficient was introduced to describe the impact of refrigerant on a global climate. In case of heat pumps, GWP coefficient shows how much the used refrigerant increases the global warming, if compared to carbon dioxide. The GWP coefficient for carbon dioxide is assumed 1 and the lifespan of the analysis is 100 years. According to the EU commission (decision 2007/742/WE [42]), the refrigerants' GWP coefficient cannot exceed 2000 in a 100 years lifespan.

4.2.4. 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.

4.2.5. 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.

4.2.6. 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 to provide assistance during filling up the documents. The heat pump manufacturer's declaration about the training and its place is required.

4.2.7. 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.

4.2.8. 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.

4.2.9. 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's assistance. Fitters should have an access to a filled up "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.

4.3. Construction of the objective hierarchy

Ecolabeling criteria were only used as a basis for selection of the final objective hierarchy. To help 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" criterion. 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 problem is minimal.

If one does not want to include the economic criteria into the AHP analysis directly, there is an option to make the AHP analysis without the economic criterion and to include it separately later in form of the cost-benefit analysis. This option is also presented at the end of this case study.
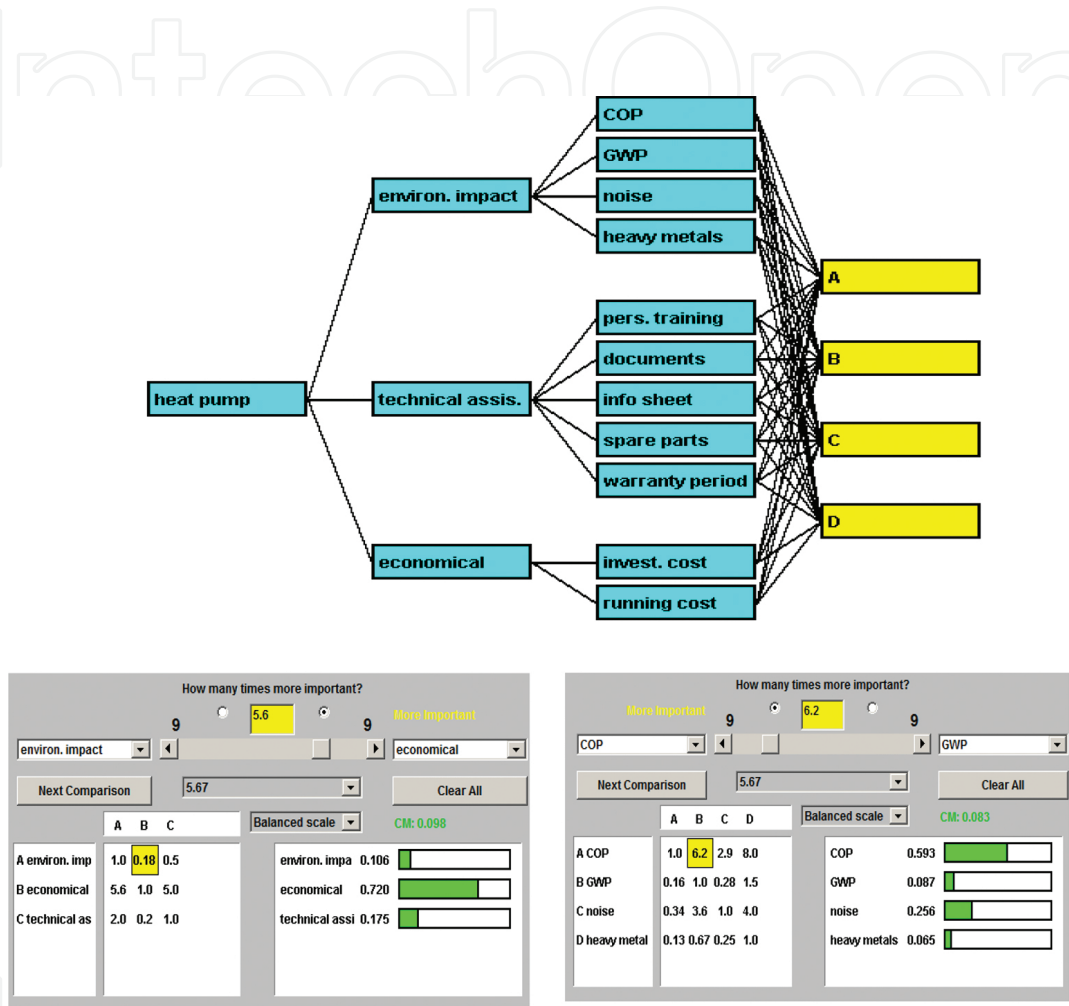

Figure 12. Objective hierarchy for heat pumps analysis and exemplary calculation of weights.

Figure 12 presents the objective hierarchy and examples of weights calculation created by the authors. The hierarchy and weights were developed by the authors and the group of students who participated in the research pretending to be a potential heat pump user. The final weights used in the analysis were the result of the whole group discussion.

4.4. Evaluation of heat pumps with the selected criteria

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

The performance of the heat pumps and the acceptable range for each category are presented in **Table 10**.

Criteria	Heat pump				Min. rating	Max. rating	Unit
	C	A	D	B			
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 sheet	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	Euro
Running cost	13,885	9309	9309	13,885	7142	14,285	Euro/15 years

Table 10. Heat pump parameters and the acceptable range of values.

4.5. Analysis of the AHP-HIPRE results

The results of the AHP-HIPRE analysis are presented in **Tables 11** and **12**. The final result for each heat pump consists of sum of partial results, presented in **Table 12**, multiplied by relative weights at levels I and II. The final results have also been presented in a graphical form by HIPRE software in **Figures 13** and **14**.

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 11. Weights, partial results from the first level of analysis and the final results.

The analysis indicates that the heat pump A is the best choice (**Figure 13**). Remaining heat pumps received similar scores; if compared with the heat pump A, they were lower by one-third. The second was the heat pump C, and then heat pumps B and D.

Criteria at level II°	Weights at level II°	Results at level II°			
		A	B	C	D
Coefficient of performance	0.593	0.825	0.847	0.847	0.825
Global Warming Potential	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

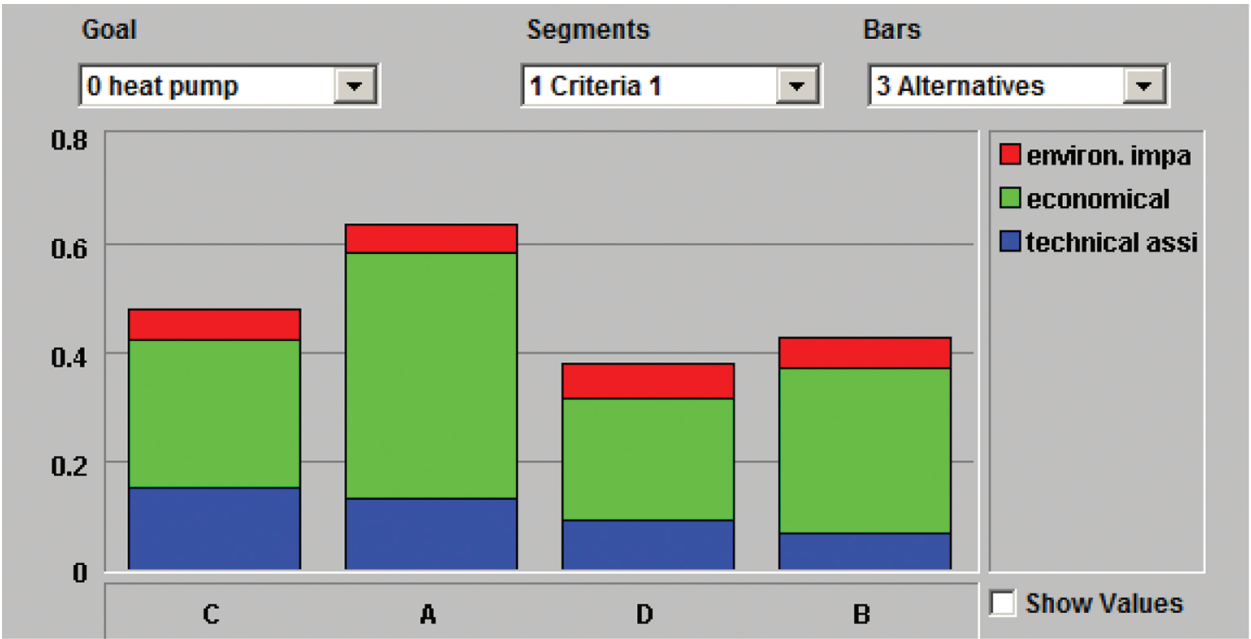**Table 12.** Weights and results at the second level of analysis.

Figure 13. Comparison of the heat pumps performance at level I of evaluation.

The high score of the heat pump A is a result of a superior economic performance, mainly a low "investment cost." The final score of the heat pump A is also improved by a high score in the category "technical assistance," mainly "personnel training" and "spare parts." The heat pump C was equally well evaluated in the category "technical assistance" and had an extremely long "warranty period" (**Figure 14**). Mainly due to this long "warranty period," the

heat pump C is the second in the ratings. A low evaluation score of the heat pump D results from a high "investment cost."
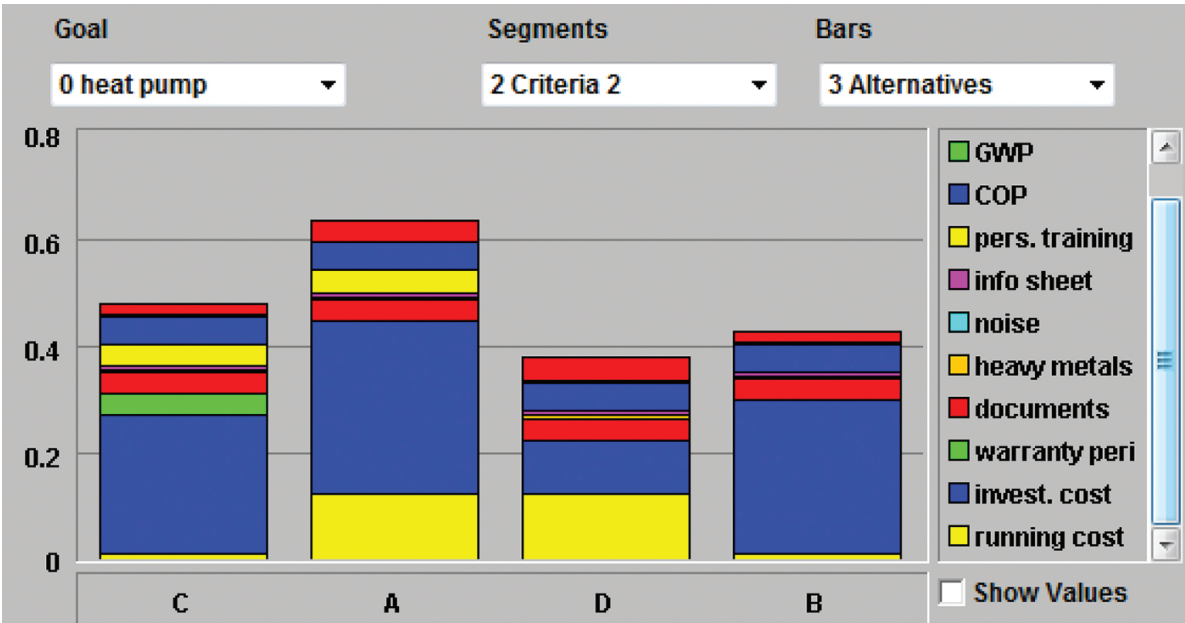

Figure 14. Comparison of the heat pumps performance at level II of evaluation.

4.6. Cost-Benefit Analysis

Another way to compare the costs and performance of the analyzed heat pumps is to use the Cost-Benefit Analysis (CBA) [45]. This can be done by separate calculations of the benefits of each heat pump, and then by graphical comparison with the calculated costs.

The cost of each heat pump was calculated as an Net Present Value (NPV) indicator. The costs include the investment cost (**Table 10**) and running costs for the entire 15-year long period. The NPV was calculated using the 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 a previous analysis. The CBA results are presented in **Figure 15**.

The graph clearly indicates that the heat pump A as 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 the heat pump A, which means the highest value (unit benefit). The heat pump C offers slightly higher benefits, but at significantly higher costs. The cost of heat pumps C, D and B is almost the same, but substantially differ in delivered benefits.

The results of the Cost-Benefit Analysis (CBA) are the same as calculated using the multicriteria AHP analysis. The CBA results are self-explanatory and almost intuitive, but because in the CBA method all the benefits are aggregated into one parameter called "benefit," the detailed analysis of the results is more difficult.

Combining the professional knowledge of the people who set the ecolabeling standards with the potential of AHP method allows the lay person understand the detailed and professional analysis of different appliances.
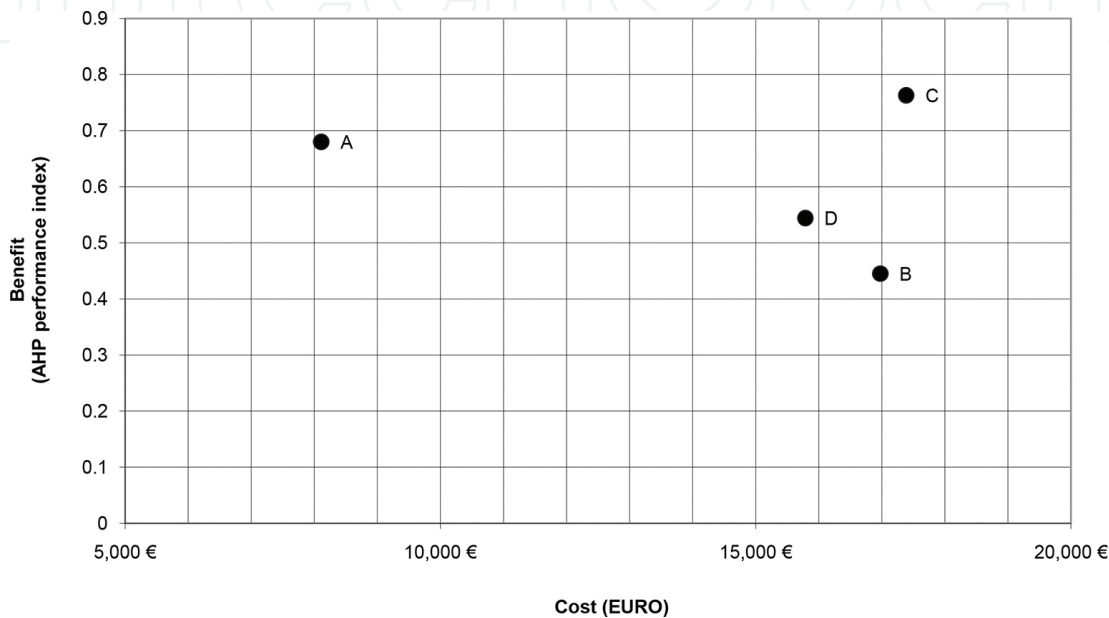

Figure 15. CBA for the analyzed heat pumps.

5. Conclusions

The AHP method is very useful in solving the whole spectrum of real environmental problems and can help choosing more sustainable solutions. The reliability of the obtained results can be increased if during the construction of goal hierarchy or collection of data, special engineering tools are also applied. Such approach can help ease most of the criticisms that there is no theoretical basis for constructing the AHP criteria hierarchy or, that there is no objective criteria which can help in the process of weights assignment. Three presented case studies show how this integration can be carried out.

In the first case study, the two-stage data collection and aggregation is carried out. First, the IWM-1 model was used to calculate the emissions to air, water and soil from each analyzed system. Second, these emissions were aggregated into LCA categories which were finally used as an input data for the AHP analysis. As a result, one obtains a clear and simultaneously detailed evaluation of the compared waste disposal systems. This is a quality very much sought by the decision makers.

In the second case study, Eco-indicator 99 H/A points were used to assess among others the environmental impact of water drinking pattern. The conducted AHP analysis shows measurably the environmental superiority of tap water drinking. It also shows how much progress can be achieved in the city if tap water drinking becomes more common. Such information can be an important guideline for a city management. Using AHP integrated with other environmental engineering tools allows comparison and evaluation of very different city policies.

The third case study presents the methodology of heat pump selection using the AHP method in connection with the ecolabeling program criteria. Through this combination, the selection can be carried out by non-professionals, and the selection is adjusted to the individual needs of the final consumer.

All three case studies show the flexibility and versatility of the AHP method which can be used and serve different customers: professionals, non-professionals and managers.

Acronyms.

AHP	Analytic Hierarchy Process
CBA	Cost-Benefit Analysis
COP	Coefficient of performance
DEA	Data envelopment analysis
GHG	Greenhouse gas
EER	Energy efficiency ratio
GWP	Global warming potential
IWM-1	Integrated Waste Management model
LCA	Life cycle analysis
MSWM	Municipal Solid Waste Management
ORWARE	ORganic WAste REsearch
PBB	Polybrominated biphenyl
PBDE	Polybrominated diphenyl ether
PER	Primary energy ratio
PET	Polyethylene terephthalate
QFD	Quality function development
SQL	Structured query language
SWOT	Strengths, weaknesses, opportunities and threats analysis
US-EPA	Environmental Protection Agency
Web-HIPRE	HIerarchical PREference analysis in the World Wide Web

Author details

Tomasz Stypka[*], Agnieszka Flaga-Maryańczyk and Jacek Schnotale

*Address all correspondence to: agnieszkaflaga@poczta.onet.pl

Cracow University of Technology, Cracow, Poland

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