SELECTING OPTIMAL REGIONAL MSW SYSTEM FOR KRAKOW AREA – PART 1: DEVELOPING PERFORMANCE INDICATORS

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Abstract The article presents the methodology which can help the decision makers in evaluation of different municipal solid waste disposal systems. The results of the well known computer Integrated Waste Management model (IWM-1) are usually too fragmented to allow the final decision. The authors present the scientific background of the IWM-1 results integration. The first article presents the theoretical basics of the IWM-1 model results integration into LCA impact categories. The authors present possible to calculate categories and next calculate them for the two MSWM scenarios for the Krakow area. The presented categories describe the environmental impact of the analyzed system, and are far more easer to identify and understand by the public and by the decision makers. The second paper presents the application of the AHP - multicriteria method in choosing the Krakow MSWM system. Authors use the HIPRE software to make the analysis for the Krakow case study. The used criteria ratios are assumed arbitrarily based on the best knowledge of the authors. The presented sensitivity analysis indicate which assumptions have an important impact on the whole analysis.

Key words Regional municipal solid waste management modeling, LCA, Krakow, AHP – multicriteria analysis.

INTRODUCTION

The decisions in the area of municipal solid waste management are not only very capital intensive, but also difficult from both environmental and social points of view. There is a need to develop, master and implement a simple, but reliable tool that would help the decision makers in the analytical process. There are several mathematical models that can help the decision makers in their tasks though the main decision variable in such models remains cost. The environmental elements (the recycling schemes) have appeared in the models beginning in the 1980s (Jenkins, 1982; Clapham, 1986). Another group of models include the environmental factors in the form of constrains of the economic models (Chang at al, 1996). Some of the models conduct the Life Cycle Analysis (LCA) of the waste disposal system while other only focus on different environmental elements such as noise or traffic (Chang at al, 1996) or CO_2 emissions from vehicles (Wang at all, 1988).

The uncertainty of the parameters is also an important criteria while dividing models into different categories. Deterministic models such as linear programming (LP), mixed-integer programming (MIP), dynamic programming (DP) and multi-objective programming are used to analyze the problems where there is an assumption of the parameters' certainty. To account for uncertainty, the models use the probability theory as well as the fuzzy and grey system theory.

The models can estimate waste generation predictions as well as facility sites selection and facility capacity expansion or operation. Similarly, other models can determine vehicle routing, manpower assignment, over-all system operation, system scheduling, waste flow, environmental performance or technology selection (Bjorklund, 1998).

A separate group of computer models apply the concept of Life Cycle Analysis (LCA). The examples of such models are: the US-EPA (Barlaz at al, 1995), Integrated Waste Model IWM

(White at al, 1997), MIMES/Waste (Sundberg, 1995), ORWARE (Eriksson at al, 2002), ISWM tool Canada, and WISARD (McDougall at al, 2001). These models are readily available applications but in practice most models are still in the development or upgrading stages, with the exception of the IWM model. The ORWARE and MIMES/Waste models are very difficult to use because of their platform and complexity. Therefore, the potential user is left with the IWM models. At present there are two versions of the IWM model: IWM-1 and IWM-2 (McDougall at al, 2001). The two versions differ not only with the applied platform (IWM-1 is an Excel spreadsheet while the IWM-2 is a stand-alone program), but also the IWM-2 produces more accurate data and has a more elaborate thermal treatment section. The choice of the platform results in the level of transparency of the two IWM models. IWM-1 is a transparent model and the experienced user can temper it with the coefficients, adjusting them to the local conditions, while the IWM-2 works in a closed environment. The lack of transparency inherent in the IWM-2 was the reason for using an IWM-1 in the presented project. The results of the IWM models are very fragmented hence not useful for the decision makers. The results of IWM model were integrated for further analysis by the method based on LCA concept. This methodology was applied to compare the MSWM systems in Krakow. Krakow develops its new system expanding the traditional one, based on landfilling and limited sorting and composting facilities. After expansion, waste will undergo the intensive sorting at the source, then extensive composting and finally the restwaste would be incinerated. The landfill is to be used only for disposing the ash from the incinerator.

There is a permanent conflict between the expectations of the decision makers and the experts who help the decision makers in the decision making process. The decision makers are interested in the simple answers which system is the best. This leads to the one criteria analysis. On the other hand, the experts understand that giving such a simple answer is difficult, not to say impossible, because the reality of the analyzed systems is far more complicated. Applying the one criteria approach leads to too big simplifications which often should be avoided. The method which allows the rational answer which system is the best, and in the same time, take into account the variety of the potential analysis criteria is the method called the multicriteria analysis.

Generally, the multicriteria methods, can be divided into two categories based on the amount of the analyzed solutions. In the first category are those methods which analyze limited number of potential solutions and select the best, but not the optimal one. In the second category are the methods which select the best solution from the unlimited number of solutions. SMART or AHP, and the whole family of ELECTRE methods belong to the first category, while, for example goal programming, belongs to the second category.

The second important criteria which allows division of all methods of multicriteria analysis is the stage at which the weighing ratios among the different criteria are taken into account. In the methods such as ELECTRE, SMART or AHP the ratios of all criteria are clearly defined and used in the decision process, while in the DEA method uses the ratios at the very end of the decision making process. The DEA method is able to make same ratings of the solutions even not knowing the scale of preferences.

Taking into account the simplicity of the method, its scientific background of the method which gives sound results of the analysis, method's transparency, and available software, the authors decided to use the method called Analytic Hierarchy Process (AHP) for the decision making.

COMPARISON OF TWO KRAKOW WASTE DISPOSAL SYSTEMS

Description of the systems

The analysis compares the Krakow waste disposal system, operated by the city in year 2001, with the new prospective system employing waste incineration. The detailed description of both systems can be found in the dissertation written by Kopacz (Kopacz, 2003).

In year 2001 the city had 150 recycling material banks. The banks were design for collection of metal, paper, PET bottles, and glass. Additionally, the city had the system of „bring and earn" collection points, where both city dwellers and small business ventures could dispose their waste, suitable for recycling. At that time, the city had the composting facility with the throughput of 6000 tons per year. The facility treated the waste from the city green areas, farmers' markets and the food processing and tobacco industry. The green waste coming from the industry was excluded from the analysis. The charity organizations run the system of collection points for the textile waste.

The new system assumes commissioning the incinerator with annual capacity of 200 000 tons of waste. Additionally, the number of collection banks will be increased up to 450, and a new Material Recovery Facility ready to handle 20 000 tons of recyclables plus two composting facilities for 6 000 and 9 000 tons of green waste will be constructed. In some parts of the town the implementation of the „wet" and „dry" waste collection systems is planned.

Integration method of the IWM-1 results

Generally, the method of the IWM integration is based on application of the one or even two stages of Life Cycle Analysis: Impact Assessment and Interpretation. To calculate these indicators the authors used the methodology which was described in detail in other articles (Stypka, 2005, 2007). The assumption was to use the maximum possible number of categories, which could be calculated based on the IWM-1 results. The list of the selected categories is presented in Table 1.

Table 1. Selected categories of the Life Cycle Impact Assessment

Impact categories	Characterisation 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		
Odour malodorous air	Reciprocal of odour threshold value (1/OTV)	m^3 (air)

Indicators for the different impact categories were selected based on the literature (Guinée, 2002). Unfortunately, not all recommended impact categories can be directly calculated from the IWM-1 result table. For example, the software gives no information about new land designated annually for waste disposal, extracted raw materials or energy sources.

Results of the analysis

The IWM-1 model offers the energy balance for two analyzed scenarios (Fig. 1). The graph shows that in both scenarios the collection stage is the most energy consuming stage of waste disposal. Once the incinerator has been build, it becomes the significant source of energy. On the other hand, at present the landfill is also the significant source of energy due to landfill gas (LFG) combustion. The waste incineration generates about four times more energy than landfill gas combustion. If the waste heat, from the LFG powered co-generation units was also utilized, the energy balance would not be so favorable for the incineration. The total energy balance is negative for the present system because the energy generated and utilized at the landfill covers only half of the energy needed at the collection stage. The future system becomes the net energy producer since the incinerator generates far more energy than is needed at the collection stage and at the sorting and composting facilities.

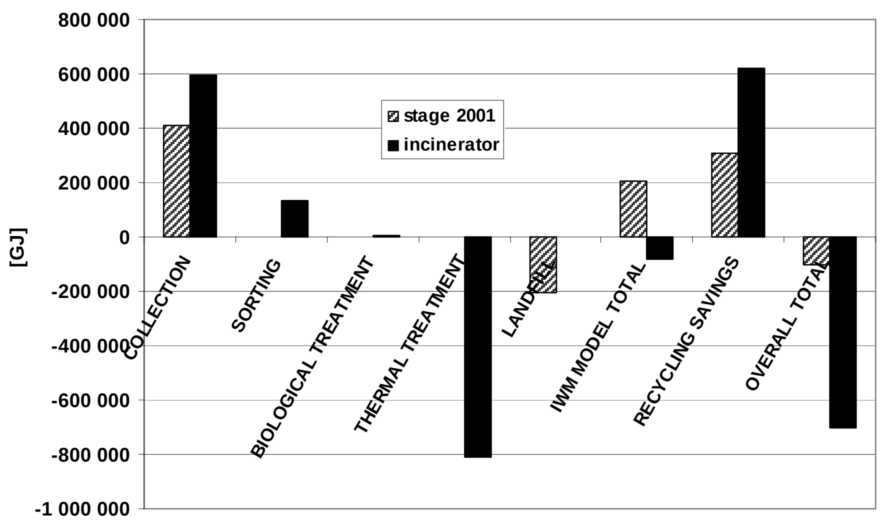

Fig.1. Energy balance for two Krakow MSWSs: present stage vs. incinerator

Both scenarios provide significant energy savings thanks to the recycling programs that can cut down on energy consumption at the paper, plastic and glass producing facilities. Because the future system is much bigger it consumes more energy on the collection stage, however it also saves more energy at the paper plastic and glass producing facilities. Looking from the LCA perspective that takes into consideration the savings of the energy at the raw material production stage, both systems are net energy producers, but the total balance in the future system is seven times bigger.

The main reason for introducing the waste incineration is to reduce waste volume and furthermore to prolong the landfill's lifespan. The IWM-1 model can estimate the efficiency of this process, showing the total amount of waste deposited at the landfill, for two scenarios. For the scenario with the incinerator and a developed recycling program the IWM-1 estimates that the amount of waste will drop four times in terms of both volume and mass load, in comparison with the present model.

Unfortunately, information about the specific emissions into water and air is not customized for the direct application at the stage of the decision making. It has to be further integrated and processed to become useful for the decision makers. The results of such integration and processing are presented in the following part of the article.

Abiotic depletion. This category describes the depletion rate of the natural Earth resources' (including the energy resources) such as oil, metal ores and wind potential. The depletion rate is measured in comparison with the remaining resources. The results of the Krakow analysis are presented in Fig. 2.
The analysis shows that, from the abiotic depletion point of view, the second scenario is far worse that the present solution. During the thermal treatment different elements and compounds are released into the environment in small portions. Those emissions are not necessarily dangerous to the environment, but the elements and compounds are inevitably lost. Mercury emission has the biggest impact on abiotic depletion index. It makes 41% of the index at the combustion stage and 35% of the index calculated for the entire IWM model. When the waste is stored in the landfill, mercury is not transformed into the LFG, hence it is not released into the environment. Additionally, burning of LFG reduces the demand for conventional production of energy and this way gives „small savings" in sulfur oxides, which would be released from the conventional power plants, if this energy had to be produced there.
Resource savings obtained thanks to the extensive recycling planned in the incineration scenario do not change the overall perspective: the present scenario remains superior to the incineration scenario from the abiotic depletion point of view. A significant improvement of this index can be obtained by introduction of intensive collection of source separated, household hazardous waste (HHW). This is particularly important now, when an intensive promotion of energy efficient but mercury containing fluorescent lamps takes place. Such lamps have to be collected separately, and transported to the manufactures for mercury recovery.

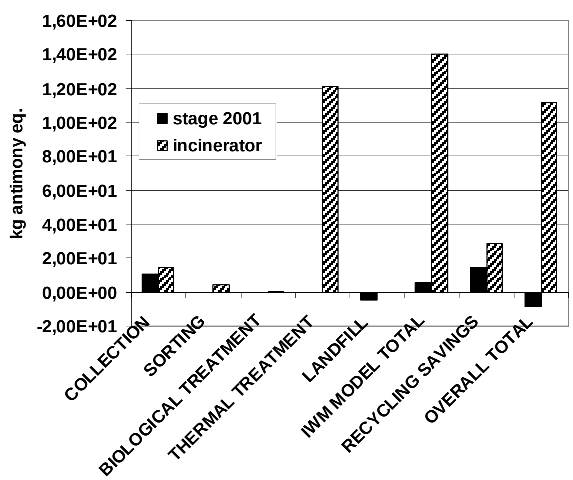

Fig.2. Abiotic depletion for two Krakow MSW systems

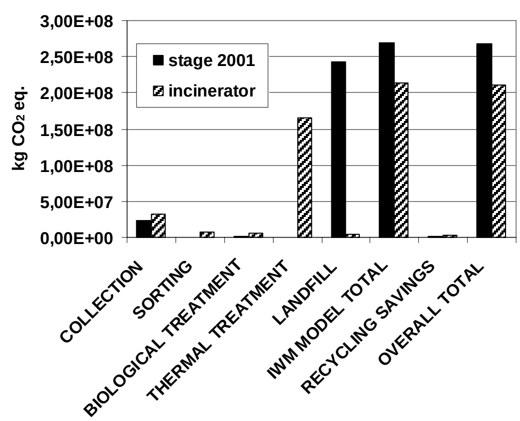

Fig.3. Climate change for two Krakow MSW systems

Global warming – climate change. The comprehensive presentation of the obtained results of the analysis is shown in Fig. 3. Incineration and landfilling are two stages of waste disposal with the strongest impact on the climate change. Collection makes up only 10% of the entire index. Incineration and landfilling are associated with methane and carbon dioxide

generation. Specially methane (generated only in the landfill) is 21 more powerful than carbon dioxide and needs special attention. Part of the methane is captured and utilized in the CHP units. The product of LFG utilization is carbon dioxide and that makes landfills with LFG utilization equally damaging for the climate change as incineration. Unfortunately part of the LFG is released directly into atmosphere increasing the relative global warming impact of the landfill. The total impact of the landfill on the climate change is 50% higher than incinerator's. Recycling, in both scenarios generates the minimal profits for the global environment and therefore the present waste disposal scenario has more deteriorating impact on the global climate than the new proposal.
Recycling has rather a small impact on the global warming index because the boarders of the analyzed system are drawn in such a way that although the energy savings are calculated by the model (Fig 1), the emissions associated with these savings are already beyond the scope of the analysis. As a result, the total impact of the two analyzed scenarios on the climate change, conducted from the local and LCA perspective are the same. The present system of waste disposal discharges annually to the global environment 57 000 Mg of carbon dioxide more then the new scenario.

Human toxicity. This index covers the impact of the toxic substances present in the natural environment on the human health. However, it does not estimate the impact of these substances at the work place. The toxicity of each compound is measured by the coefficient called - Human Toxicity Potential HTP_i. The HTP_i value describes the type of environment into which a compound is emitted, its pathway before reaching the human being, and then inside the human body, as well as its toxicity depending on the pathway it followed within the human body. The HTP_i index measures the toxic impact of the analyzed substance on a human being in comparison with the 1,4 dichlorobenzen. The basic 100 year long perspective of influence was assumed in the analysis.

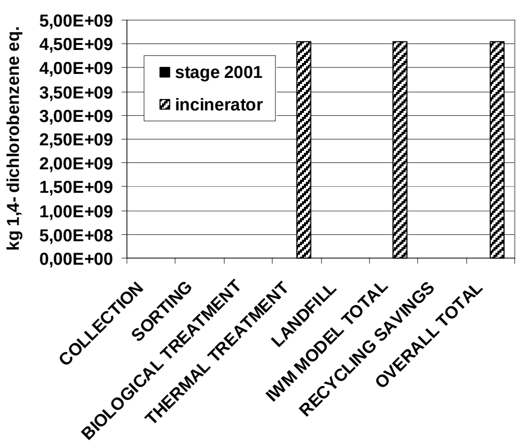

Fig.4. Human Toxicity Impact of two Krakow MSWM systems

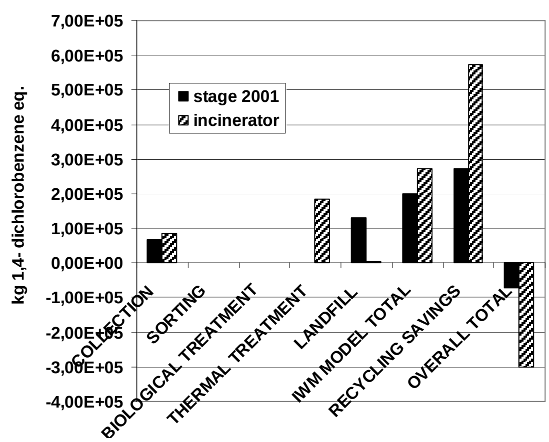

Fig.5. Freshwater Aquatic Ecotoxicity of two Krakow MSWM systems

Figure 4 clearly indicates that the scenario with incineration has a negative impact on the human health. The detailed analysis of the result confirms that although all stages of the waste disposal system have a negative impact on human body, incineration is 10 000 times more powerful than the other ones. The impact of the landfilling is comparable with the collection stage. The main reason for such negative impact of the incineration is not the emissions of commonly feared dioxins and furans, but rather emission of chromium compounds.

The authors assumed that emission of chromium calculated by the IWM-1 model takes place in form of chromium VI, which is the most toxic form of chromium for humans. Dioxins are five hundred times more toxic then chromium, but their emission is only 0,1 gram/year while the emission of chromium is estimated at the level of 1 277 kg/ year. This emission, in terms of human toxicity, is equal to the emission of $4{,}3*10^9$ kg of 1,4 dichlorobenzene eq. Similar to the mercury emission from incineration, which increases the abiotic depletion index, the source separation and reduction of chromium containing products seems the best option to address the issue of toxicity hazard from the incinerator.
Recycling reduces the toxicity of waste disposal to the humans. In the scenario 2001, recycling reduces the toxicity by 1/3, while in the second scenario the development of the more advanced recycling program generates twice as much toxic reduction. Unfortunately, the negative impact of incineration is 10 000 more significant and can not be neutralized by the progress in recycling.
The authors assumed that the chromium was emitted in its the most toxic form, chromium VI. However, even if it is assumed that less dangerous chromium III is emitted and the absolute values of the calculated HTP is lower, but the character of the graphs will not changed. No matter which form of chromium is taken into the analysis the scenario with the waste incineration turns out to be more dangerous for the human beings. If it is assumed that chromium is emitted as chromium III the emissions of nickel and arsenic become more important in the HTP index. The emissions of dioxins still do not have significant impact on the HTP index value.

Freshwater aquatic ecotoxicity. It is one of the many categories describing the impact on the natural environment (ecotoxicity). The category covers the impact on the fresh water only, but not on the sediment. The impact is measured by 1,4-dichlorobenzene eq. in 100 years perspective. The FAETP index measures the toxicity of the given emission (in reference to dichlorobenzene) in the fresh water environment (medium into which the emission took place) and efficiency of substance’s migration from the medium into it was emitted into the water environment. The category calculates the harmful impact on the water environment only, even if the emission took place into air or soil.
Figure 5 presents the impact of the solid waste disposal systems on the fresh water environment. Both scenarios show the negative effect, but the incinerator’s impact is the strongest, stronger even then the landfilling. The more thorough analysis shows that air emissions plays here more important role then into water: the former one makes 99,9% of the total FAET value while the latter one only 0,1% of the FAET. Hydrogen fluoride (HF) is the biggest contributor to the FAET and not because of its high toxicity, but because of the emission volume; half of water environment toxicity is attributed to its presence in water. Copper emissions also significantly contributes to the FAET making 21% of the whole index; emission of nickel contributes to FAET in 19%.
Phenol emissions observed in the collection stage has a negative impact as well. Phenol is emitted into atmosphere during the production of the diesel oil needed for the waste transporting trucks. According to the IWM-1 data, the production of 1000 liters of diesel oil is accompanied with emission of 36 grams of phenol.
Landfills affect the aquatic environment because of the leachate production. Leachate makes 99% of the FAET while the air emissions of the landfill gas make only 1% of the FEAT total value. The most toxic compound in leachete are AOX (AOX –absorbable chlorinated organics; the equivalent amount of chlorine, bromine and iodine contained in organic compounds in water or wastewater, expressed as chloride).
Theoretically the leachate is collected and treated, but in real life part of the leachate is released directly into ground and surface waters. IWM-1 model assumes that 70% of the

leachate is collected, and the rest is released directly into the water environment. It is estimated that the directly released leachate contaminates water environment with 22 kg of AOX per year. AOX makes 89% of FEAT even the FEATP for AOX is very much comparable with mercury, cadmium, nickel, and copper. The final disposal of the ashes from the waste incineration does not have any significant impact on the water environment.

Recycling and its development, has a significant impact on the value of the FEAT. The direct emissions into the water makes 99,8% of the total value of the indicator, with AOX playing the main role. The source of these savings is lower emission of AOX obtained thanks to the reduction of paper production from the virgin material. It is estimated that thanks to recycling programs the production of paper from the virgin material would drop by 44 090 Mg and reduction of AOX emission from the paper mills by 110 kg. Because the value of $FAETP_{AOX}$ is high ($5,2*10^3$ kg 1,4 dichlorobenzene eq.) such drop in paper production equals the reduction of $5,73*10^5$ kg 1,4 dichlorobenzene eq. emission into the aquatic environment. This makes almost 100% of the index value. Phenol is the second important pollutant responsible for the aquatic toxicity. The recycling reduces the phenol emission by $1,17*10^2$ kg 1,4 dichlorobenzene eq., and that makes only 0,02% of the whole index.

Generally, a well organized system of waste management has a significant impact on the water system quality. The analyzed new scenario of the waste management has less damaging impact on the aquatic systems thanks to the more advanced recycling programs, because the incinerator itself affects the aquatic system more badly than the present landfill. Increasing the efficiency of the leachate recovery has also a positive effect on the aquatic environment, if measured by the FAET index.

Terrestrial ecotoxicity. The next index is the terrestrial ecotoxicity. It is measured similarly to aquatic ecotoxicity and expressed with the same units. Even though two indexes are measured in the similar way and have the same units they can not be directly compared or added. All these indexes are the subject of the "unofficial critique" from the LCA community. The extra precaution in the index's interpretation is recommended particularly when the main contributions to the index are chromium (Cr) and beryllium (Be). (Guinée, 2002).

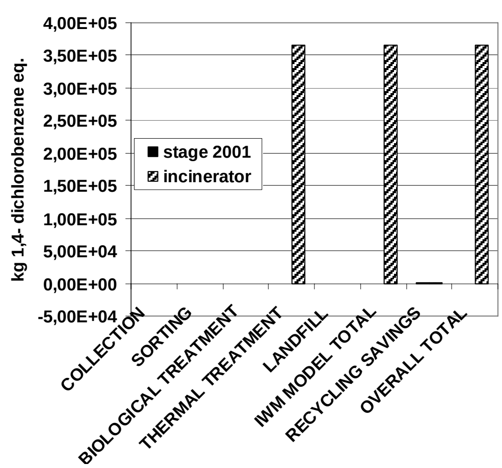

Fig.6. Terrestrial ecotoxicity of the two Krakow MSWM systems

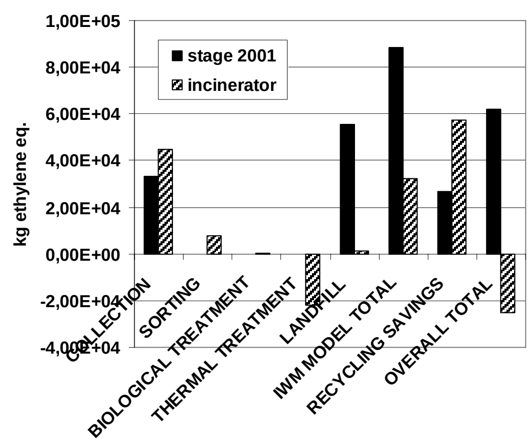

Fig.7. Smog creation by two Krakow MSWM systems

Figure 6 presents the terrestrial ecotoxicity of the two solid waste disposal scenarios. Their impact on soil at different stages of a waste disposal system is very similar to the one observed for the Human Toxicity Impact Index (Figure 4). The waste incineration scenario causes 10 000 times bigger damage to the soil than the present system. In practical terms it means that the present system has an insignificantly small impact on land, if compared with the incineration.

The incinerator affects the soil by flue gases and by emission of heavy metals, in particular. The IWM-1 model estimates that every year the incinerator emits 101 kg of mercury (Hg), 1280 kg of chromium (Cr), 507 kg of arsenic (As) and 507 kg of nickel (Ni) to the air. All these emissions have the negative impact on the soil, but mercury contributes 89% into the Terrestial Ecotoxicity index (TET). Chromium contributes to this index only 7% while arsenic 2% and nickel only 1%.

Analysis of the Terrestrial Ecotoxicity impact of the present scenario of waste disposal produces some interesting conclusions. The existing system has a negative impact on soil and the total value of TET equals 8,56 kg 1,4 dichlorobenzene eq. Recycling has a very positive impact, if measured by TET. Thanks to paper recycling the mercury emission is reduced by 0,0623 kg of mercury/year (equivalent to 197 kg of 1,4 dichlorobenzene), which is twenty times higher than the emission from the present system.

If the recycling systems are more efficient the avoided emissions are proportionally larger.

Photochemical smog. Photochemical smog is a product of chemical reaction of some air pollutants under solar radiation. One of the reaction products is ozone. Ozone is harmful not only for humans, but also for the ecosystem. Human health, manmade environment, natural environment, and natural resources require protection against ozone. Smog is created in the troposphere as a product of photo-oxidation of volatile organic compounds (VOC) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x). Ozone (O_3) and PAN (penoxyacetylnitrate) are ones of many end products of these reactions

A photochemical smog index is measured in the same way as the other indexes, by multiplying the Photochemical Ozone Creation Potentials (POCP) of different complexes by the mass of this complex emission. The total value of the index is the sum of photochemical smog indexes of different emissions. The unit of this category is kg of ethylene eq. (Fig. 7).

The present waste disposal system has a far more negative impact on environment, if measured by Photochemical Ozone Creation, than the incineration system. The smog creating compounds are created both at the level of waste collection and landfilling. The value of the POC at the collection stage is 67% higher than at the landfill. Smog at the collection stage is created by such emissions like hydrocarbons, nitrogen oxides, sulfur oxides, and carbon monoxide. These compounds are by-products of diesel oil combustion and plastic waste containers production. At the landfill site smog is generated as a result of emission of the landfill gas, methane in particular. On the other hand, electricity generated in the LFG replaces the one generated in conventional power plants, which results in reduction of sulfur oxides, nitrogen oxides and reduction of the POC index of the landfilling stage. In the final balance of these two processes, the landfill generates 55 300 kg of ethylene eq. The energy generation from the incinerator is much higher, resulting in larger avoided emission, which makes the POC at the incineration stage even negative.

Development of the recycling stage also reduces the emission of the smog creating compounds. In the second analyzed scenario, with a far more advanced recycling system, the emission of the smog creating substances is reduced almost by half. Concluding, from the LCA point of view, the new scenario of waste management reduces the total smog creation while the present scenario has a negative impact on air quality. On the other hand, from the local perspective, both systems enhance smog creation, though the incinerator scenario does it significantly less.

Acidification. Acidifying pollutants emitted into the environment, have an impacts on soil, groundwater, surface waters, biological organisms, ecosystems, and materials. The major acidifying pollutants are SO_2, NO_x and NH_x. Areas of protection are the natural environment, the man-made environment, human heath and natural resources.

The acidification is measured, as in all the other categories, by multiplying the emissions by their Acidificiation Potential AP_i of each pollutant, and then by adding the products. The Acidification Potential of each pollutant compares the impact of emission of 1 kg of this substance to the emission of 1 kg of sulfur dioxide (SO_2). The value of AP_i represents the maximal potential of each substance to cause the acidic deposits, but its real value can be smaller and depends heavily on the local conditions. In the analyzed case, it was assumed that the acid deposits will affect the City of Krakow, which is sensitive to such impacts as a place of a very high material and cultural value (lime stone historic buildings, steel constructions). That is why the value of the AP was not reduced by any reduction coefficients. The obtained results are presented in Fig. 8.

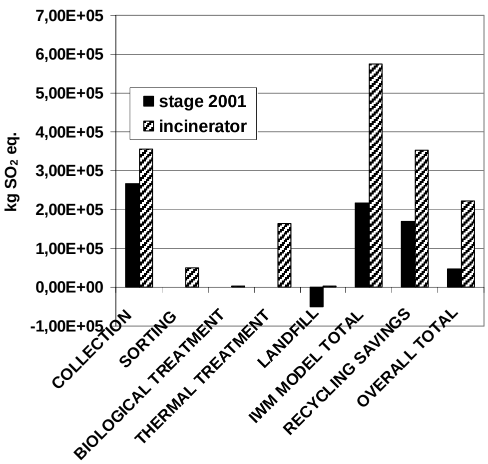

Fig.8. Acid rain creation by two Krakow MSWM systems

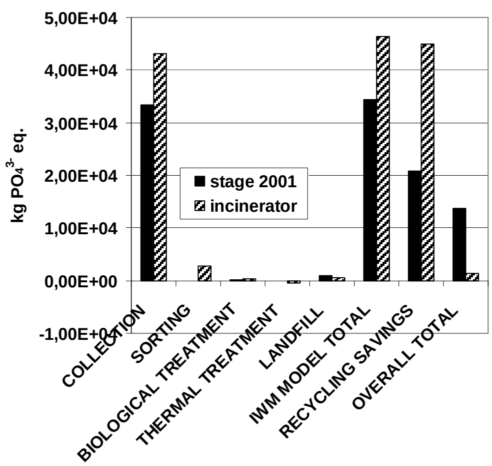

Fig.9. Eutrophication caused by two Krakow MSWM systems

The acidification problem appears at all stages of waste disposal system. It is caused by diesel oil burning during the waste collection, as well as the emissions during the waste incineration. The landfill equipped with the LFG extraction system used to produce electricity is a sink for the acidic emissions, because it generates far less acidic emissions than are generated in the conventional power plants.

The acidic emission during the waste incineration is already reduced by the amount of avoided emission of the electricity generated at the conventional power plants. 54% of the acidification index at the combustion stage is caused by the emissions of sulfur dioxide. The observed "savings" at the recycling stage are mainly caused by the reduction of the energy demand in the production of plastic, paper, and metal from the recycling materials. This reduction includes the energy consumption needed for the transportation of the recycling material to the processing facilities. The development of the recycling program (the second scenario) results in bigger savings during the recycling stage, but this does not change the total picture. The present system of waste disposal causes less damage attributed to the acidification than the planned system based on the waste incineration.

Eutrophication. This category covers all potential effects of excessively high levels of macronutrients in the environment; the most important ones include nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and excessive biomass production in both aquatic and terrestrial ecosystems. In addition, high nutrient concentrations can also make surface water unacceptable for drinking. In aquatic ecosystems a high level of biomass production may result in oxygen depletion (measured as BOD). As emissions of degradable organics have a similar impact, such emissions are also treated under the impact category "eutrophication". The value of this category is measured in comparison with the eutrophication potential of 1 kg of PO_4^{3-} (EP_i). The results for the Krakow case are presented in Fig. 9.

Waste collection is the main stage where euthorpication stimulating compounds are generated. Eutrophication is caused by the emission of nitrogen oxides generated during the diesel oil combustion in trucks, collecting both recyclables and mixed waste. The IWM-1 model estimates that at the present waste disposal scenario a collection stage generates $2{,}57*10^5$ kg of nitrogen oxides/year; it is 97% of the total value of the eutrophication index.

Recycling reduces the total value of eutrophication both into the air and water. In the air emissions the positive effects are obtained thanks to the reduction of nitrogen oxides emissions, while reduction of BOD and TOD are responsible for the effects in water emissions. The positive effects come from different emissions, which take place at the production phase where either virgin or recyclable materials may be used. The emissions from the transportation of the recyclables into processing plant are also included in the calculations. The expected savings are significant. In the incinerator scenario, the advanced recycling program offsets all the negative impacts of the collection. From the eutrophication point of view, the incinerator scenario turns out to be more friendly toward the environment, because the incinerator does not show a harmful impact on the environment and the advanced recycling system fully offsets the negative impact of the collection. In the present system the less efficient recycling does not totally offsets the collection, and the total impact of the system is slightly negative.

Odour – other impact category. Odour becomes a problem when a given concentration of odorous substances is experienced as unpleasant. Whether an odour is experienced as stench will depend on the sensitivity of the particular individual exposed to it. Though, above a certain emission level every individual will experienced it as such. In this case the area of protection is human health.

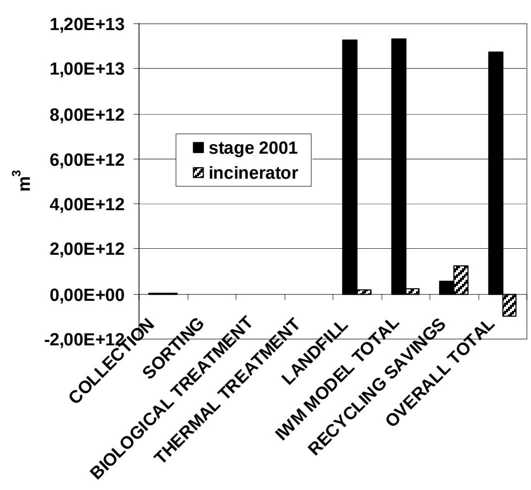

Fig.10. Odour emissions from the two Krakow MSWM systems

Odour may be defined as the observed difference between a sample of clean air and a sample of contaminated air. The concentration at which such a difference cannot quite be observed varies from substance to substance, and depends on the physical and chemical properties of the substance. The odour threshold value of a substance is defined as the concentration under defined standard conditions, when 50% of a representative population sample can just detect the difference between a sample of an air/substance mixture and a clean air sample. Odour can be measured fairly objectively while odour nuisance is more a matter of individual sensitivity. The nuisance associated with odour from each substance is measured by dividing the emissions of potentially malodorous substances by the odour threshold value. The total value of odour nuisance is the sum of all malodorous substances and it indicates how much air has to be added to reach the threshold value. The obtained results for the Krakow analysis are presented in Fig. 10.

The IWM-1 estimates only three emissions of maladorous substances. Never-the-less the obtained results are interesting and confirm the widespread expectations that the scenario with the waste incineration reduces the odour problem. The landfill is the main source of odour. If the model calculated all the aromatic substances emitted to the air with the LFG the description of two scenarios would be even gloomier. Waste incineration reduces approximately 100 times the odour nuisance. This is mainly caused by the reduced emission of hydrogen sulfide (H_2S).

Recycling generates some avoided odour emissions mainly by the reduction of hydrogen sulfide during the paper production. The IWM-1 assumes that reduction of paper production from the virgin material results in the reduction of 12 grams of hydrogen sulfide. In the incinerator scenario the avoided emissions are bigger than the emissions from all stages of waste disposal. From the LCA point of view, the scenario with the incinerator reduces the total level of odours. The problem with such approach is that odour is a local problem and for the people living near one facility the potential reduction of odour at the other location is no an argument. Generally, the waste incineration, in comparison with the present system, reduces the odour problems 45 times.

Brief summary of the obtained partial results of the Krakow MSW regional system analysis.

The presented method of aggregating the results of the IWM-1 model allows the comparison of different municipal solid waste disposal scenarios. However, the obtained results are not obvious in the presented Krakow case study. The present Krakow system, based on landfilling, turned out to be superior when the following criteria were analysed: abiotic depletion, human toxicity, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, acidification, and eutrophication. The second scenario, with advanced waste sorting and incineration, turned out to be better in categories of energy consumption, climate change, photochemical smog creation and odour creation. More detailed analysis of different stages of waste disposal for the two compared waste disposal systems is recommended and possible.

The obtained results still do not give a straight answer about the superiority of one specific scenario. Some of the categories are measured using the same units, but even in this case the comparison between the different categories is impossible. 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. In the analyzed case, the common feature of all categories is that the lower value of the indicator is better then the higher value. The final evaluation of the analyzed scenarios was made using the AHP method.

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SELECTING OPTIMAL REGIONAL MSW SYSTEM FOR KRAKOW AREA – PART 2: USE OF AHP MULTICRITERIA METHOD FOR THE FINAL DECISION MAKING

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Abstract The article presents the methodology which can help the decision makers in evaluation of different municipal solid waste disposal systems. The results of the well known computer Integrated Waste Management model (IWM-1) are usually too fragmented to allow the final decision. The authors present the scientific background of the IWM-1 results integration. The first article presents the theoretical basics of the IWM-1 model results integration into LCA impact categories. The authors present possible to calculate categories and next calculate them for the two MSWM scenarios for the Krakow area. The presented categories describe the environmental impact of the analyzed system and are far more easer to identify and understand by the public and by the decision makers. The second paper presents the application of the AHP - multicriteria method in choosing the Krakow MSWM system. Authors use the HIPRE software to make the analysis for the Krakow case study. The used criteria ratios are assumed arbitrarily based on the best knowledge of the authors. The presented sensitivity analysis indicate which assumptions have an important impact on the whole analysis.
Key words Regional municipal solid waste management modeling, LCA, Krakow, AHP –multicriteria analysis.

BRIEF DESCRIPTION OF THE AHP METHOD

The Analytic Hierarchy Process (AHP) is a structured technique for dealing with complex decisions. The method is based on mathematics and psychology. It was developed by Thomas L. Saaty, from the Pittsburg University, in the 1970s and has been extensively studied and refined since then. The AHP provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions.

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem—tangible or intangible, carefully measured or roughly estimated, well- or poorly-understood—anything at all that applies to the decision at hand.

Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them one to another two at a time. In making the comparisons, the decision makers can use concrete data about the elements (carbon dioxide emissions) or they can use their judgments about the elements' relative meaning and importance (social acceptance). It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations.

The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be

compared to one another in a rational and consistent way. This capability distinguishes the AHP from other decision making techniques.
In the final step of the process, numerical priorities are calculated for each of the decision alternatives. These numbers represent the alternatives' relative ability to achieve the decision goal, so they allow a straightforward consideration of the various courses of action.

The procedure for using the AHP can be summarized as:

1. Model the problem as a hierarchy containing the decision goal, the alternatives for reaching it, and the criteria for evaluating the alternatives.
2. Establish priorities among the elements of the hierarchy by making a series of judgments based on pairwise comparisons of the elements.
3. Synthesize these judgments to yield a set of overall priorities for the hierarchy.
4. Check the consistency of the judgments.
5. Come to a final decision based on the results of this process.

In the analyzed case the problem is to select the best municipal solid waste system for the Krakow area. The evaluating criteria are described in the previous article and include both measurable (noise emission) and immeasurable ones (social acceptance). Some of the criteria are expected to reach high values (social acceptance) for the selected solution, while other should have minimal value (noise, chemical compounds emissions).

In the next step of the analysis the criteria are prioritized in form of the hierarchy structure. Next, all criteria are pairwise compared. The comparison is conducted only within each subcategory. The comparison method is flexible, but it is commonly accepted to use the scale from 1 to 9, where 1 represents equal importance of the elements and 9 is for extreme importance of one element over another. Some software use linear scale to help the scaling process.

The important problem of this stage of analysis is the consistency of the assumed weights of the elements hierarchy. The consistency is measured by the Consistency Index (CI). Theoretically, CI can have the value between 0 and 1. CI equals 0 for absolutely consistent set of priority ratios, but for the acceptable solutions the CI should have the value below 0,2.

The final stage of the analysis is to combine the assumed set of priorities with the performance of the analyzed solutions. As a result, one obtains the score indicating alternatives' relative ability to achieve the decision goal. The solution which scored the extreme number of points is selected the best one.

AHP method can be used without any computer assistance, but there are several software programs which help in this process (Hipre, export choice, ahpproject.com). This article was prepared using the Hipre 3+ available thanks to Helsinki University of Technology (http://www.hipre.hut.fi/).

MULTICRITERIA ANALYSIS OF THE KRAKOW REGIONAL MSW SYSTEM

Using the HIPRE software the authors prepared the hierarchy of goals. This hierarchy stems from the concept of sustainable development and reflexes the ability of IWM-1 model to estimate environmental criteria. Fig. 1.

At the first level, the main goal was divided into three goals: impact on natural environment, economic performance, and social impact of the system. At the next step the impact on the natural environment was divided on the impact on water, air and soil. The last level of goals are the goals calculated earlier as impact categories.

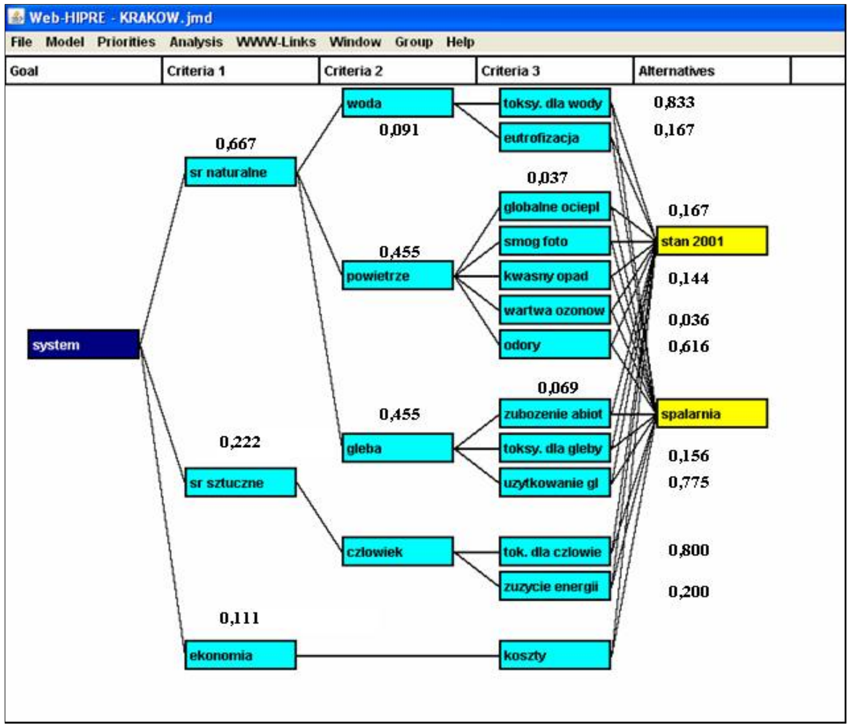

Fig.1. Objective hierarchy and ratings for the Krakow analysis

The next step of the analysis was to conduct a pairwise comparisons of different objectives to determine the their relative weights. At the end of the comparison process the consistence index was calculated. (HIPRE+ calls the index Consistance Measure (CM)) the accepted value is below 0.2.

The authors made arbitrary decisions concerning the assigned weights. The assumption was that the most important goal of the MSW system is its impact on the natural environment. The economical performance was assumed to be the least important, because the decision makers always delegate the cost on the city dwellers and external funds. In practice, the significant external (European) funding makes the economic performance of the system even less important, particularly at this stage of the project.

Within the category „natural environment" the authors assumed that the impact on the soil and air are the most important. These two media are the most politically sensitive ones. The odours are easily detected by the voters on day to day bases, and low burden on land, means in practice, longer running time of the existing landfill, and this problem is at the root of all decisions concerning the municipal solid waste management.

Comparing the goals which lead to low environmental impact on soil, authors assumed that the main goal of the system is to protect the soil surface which will extend the exploitation time of the existing landfill. The global goal, such as abiotic depletion, is significantly far less important particularly at the local level.

Analyzing the different goals leading to the air protection authors assumed that the most important are the local goals (odour), regional goals (photochemical smog, acid rain) are less important, and the global goals (global warming, ozone depletion) are of the least importance to the decision makers.

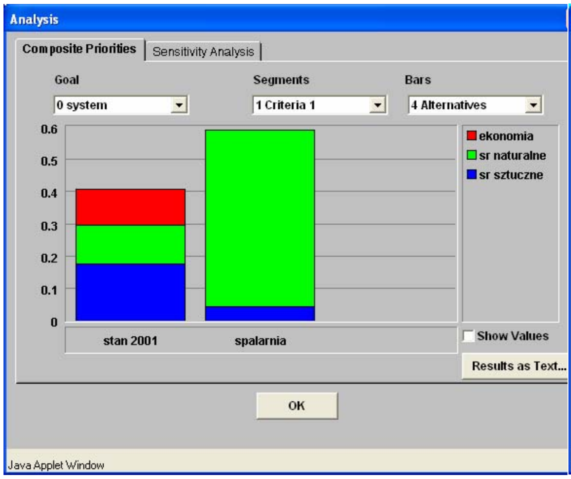

Fig.2. Results of the Krakow AHP analysis

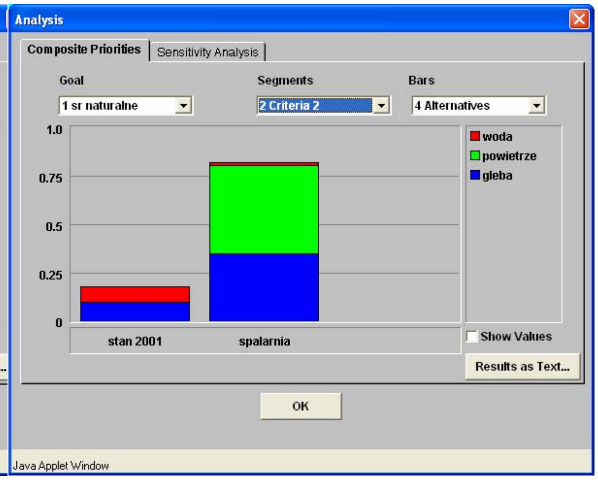

Fig.3. Comparison of the impact of the two Krakow MSWSs on the natural environment

Figure 2 presents the final results of the analysis. The graph shows that for the calculated in the previous part of the paper emissions and assumed relative weights building the incinerator and expanding the recycling system is a better solution than continuation of the present system. The new system "scores" 0,592 while the existing system scores only 0,408. This means that the new system is better by 20% than the existing one.

The new system is superior to the existing one mainly thanks to the better environmental performance. The detailed comparison of the environmental performance of the two solid waste management systems presents Fig. 3. Building the incinerator better protects soil and air while the existing system is superior to the new one in water protection. The superiority of the new system in soil protection is very significant, because of the lower land use, and in all subgoals of the air protection.

SENSITIVITY ANALYSIS

The final outcome of the analysis depends on the assumed hierarchy of goals and on the assigned relative weights of the goals. The performance of the analyzed system has far more limited impact on the final result of the analysis than one may think. Because there were analyzed only two options of the solid waste systems, for the final score it is important if the performance in certain category is superior to the performance of the other system or not. The exact performance, and scale of superiority does not have any impact on the final result. One of the ways to change this situation is to assume acceptable limits for different goals (different than the real emissions), but in reality such values are unknown (for example maximum acceptable carbon dioxide emission from the entire msw system) The only exception is the economic criteria, where it is possible to assume the maximum acceptable cost of the system. The hierarchy of goals is not a subject of the sensitivity analysis, but the assumed relative weights of the goals can be analyzed that way.

The reason why the solution with the incinerator scores better than the present system is its better performance in the category „impact on the natural environment”. The authors assumed the relative weight of this category 0,67, but the sensitivity analysis indicate that if this weight is 0,54 both analyzed scenarios have equal value. (Fig.4) If the weight for the natural environment equals 0,54 and CM is in the proper range, (below 0,1) the other two weights should have the values 0,297 for the impact on the manmade environment and 0,163 for the economic performance. It is up to the decision makers to decide if such distribution of weights is possible.

The new solution with the waste incineration performs better in the category „natural environment” thanks to its good performance in the subcategories “impact on air” and “soil”. Fig. 2. Both weights of these categories are 0,45 while the weight of the category „impact on water” is only 0,1. In this case, to alter the final score, it is necessary to reduce the weight of the “impact on air” to 0,06 which is highly unlikely (Fig. 4).

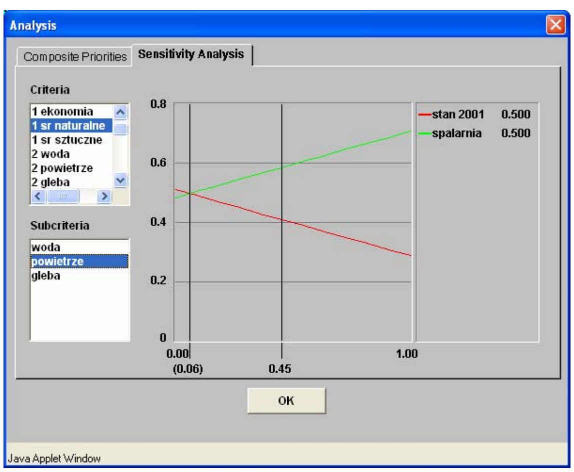

Fig. 4. Impact of the „air” rating on the final result

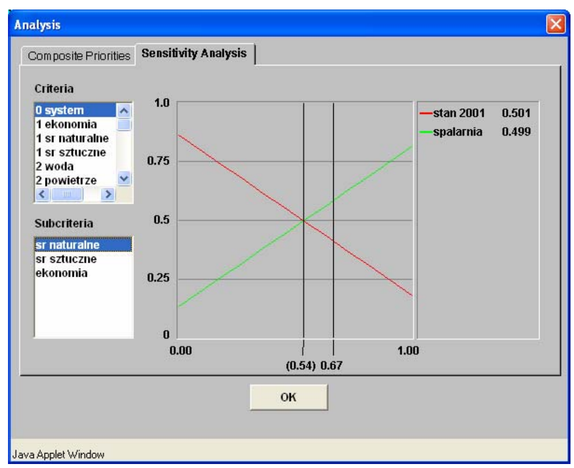

Fig.5. Impact of the „natural environment” rating on the final result

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 categories “impact on air” and on “impact on soil”. If the relative weight of the category „impact on soil” is increased to 0,661 and the weight of the category „impact on water” takes the value 0,272 while the weight of „impact on air” is reduced to level 0,067, the present model of waste disposal turns out to be superior (Fig. 5). Such distribution of weights is possible, because the problem of soil protection (reduction of the waste deposited on the ground) is the driving force behind the changes in the waste disposal system. The problems of surface and ground water contaminations are also very important. Such new set of relative weights yields also a correct value of CM index (0,096).

CONCLUSIONS

The presented analysis shows that the new, proposed system of waste disposal in Krakow is a better solution than the present one. The system with the incinerator and extensive recycling performs significantly better taking into account its impact on the natural environment, while the present system is cheaper and puts less stress on the manmade environment. The new system performs well on the natural environment thanks to a good performance in the categories “impact on air” and on “impact on soil”. The conduced sensitivity analysis shows the critical elements of the whole analytical process. Such elements are the relative weights assigned at the top level of goals hierarchy, and weights assigned within subcategory „impact on the natural environment”. The decision makers should make an extra effort to increase the certainty in assigning these values, because different values can easily change final outcome of the analysis. There is no objective criteria which can help in the process of weights assignment, but the presented AHP method can make to whole process more objective, and gives opportunity to present the points of view of different social groups.

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