MUNICIPAL SOLID WASTE MANAGEMENT MODELS: PRESENT SITUATION AND FUTURE TRENDS

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Abstract:
The article reviews the existing models of municipal solid waste management. Three, the most well known models' classifications are presented. The author discusses the categories developed by MacDonald, Björklund and Morrisey and presents his own classification. The author divides the models into three groups: "white models", "grey models" and "green models". The "white models" category contains all the models which try to describe the solid waste management assuming the full accuracy of the data. This group of models use techniques of linear programming, mixed integer programming and dynamic programming as tools of finding optimal solutions.
The group of "grey models" comprises models, which address the fact that made assumptions do not have to be fully accurate. To solve the problem of uncertainty the models implement the theory of fuzzy sets, grey numbers, and probability.
The last category of models, "green models", includes all the models, which try to solve the problem of solid waste management implementing the concept of sustainable development as the main objective of analysis. This category contains the models based on Life Cycle Analysis, Decision Support System models and models using a multicriteria analysis.
The author presents different models representing each category, focusing specially on the "green models". The critical analysis of all models shows the potential direction of further models' development.

KEYWORDS: municipal solid waste models sustainable development, multi-criteria analysis

INTRODUCTION

The solid wastes are with the human beings from the very beginning of civilization, but only in the last decades we have started seeking the solutions to this problem using scientific methods. Development of technical methods, and the increase of economic burden on the society made the problem of reducing the environmental and social impact of waste more and more important. One of the ways to obtain this goal is to build a waste disposal model, which would measure and evaluate the important impact factors of the selected systems of waste treatment. The article reviews the most well known models and the models' categories and tries to predict the most promising direction of furthers models development.

SOLID WASTE MODELS' CLASIFICATIONS

The first attempt to classify all the solid waste models was made by MacDonald. (MacDonald 1996). In her "state of the art review" the author did not exactly classified the models, but rather selected the main categories of the models and characterizes 15 models using these characteristics. The fist category was model's type. According to MacDonald there were nine types of models:

- Waste generation prediction, WG
- Facility site selection, FS
- Facility capacity expansion, FC
- Facility operation, FO
- Vehicle routing, VR
- Manpower assignment, MA
- Over-all system operation, OS
- System scheduling, Sch
- Waste flow, Flow

Additionally, the models were characterized by: their approach to the time variable (static/dynamic), weather or not they minimize the cost of waste treatment, simulation characteristics, applied solving method (linear programming, mixed integer programming, heurisitic technique, network problem). Finally, the fact whether the models try to measure the environmental impact of the system was found as one of the characterisitic features. The last feature was whether the models try to perform any economic analysis. The author analyzed the known models using presented criteria, but was not able to divide them into categories.

The second attempt to systematize the MSW models was undertaken by Böjrklund (Böjrklund, 1998). Böjrklund developed MacDonald's methodology, introducing new types of models (environmental performance, EP; and technology selection, TS) and different characterisitics: static, dynamic, simulation, optimization, multi criteria optimization (MCO), scenario comparison, input-output analysis (IO), multiple criteria analysis (MCA), geographic information system (GIS). This classification is not disjoint and many models belong simultaneously to many categories, unfortunately. Other introduced categories were: "Objective" (goal of the model), "Environmental Aspects", "Waste types" and "Functions" (types of covered processes)

Both classifications show how difficult it is to clearly classified the models into the disjont sets; the used methodology was applied only to describe the models, but not to assign them into categories. The next attempt to fulfill this task was made by Morrisey and Browne (Morrisey, 2003). They introduced three models' categories: Cost-Benefit Analysis models (CBA), Life Cycle Analysis models (LCA), and multi criteria analysis models (MCA). Unfortunately, this methodology does not give separate sets of solutions either. For example, many multi criteria models use Cost-Benefit Analysis or LCA.

The author proposes to divide the models into three categories called: *white models*, *grey models* and *green models*. Using colors to illustrate certain phenomena is a common technique. It is used in mathematics as well as in environmental engineering. The "white number" is a mathematical term and means the number which value is fully known, while the "grey number" is a number whose exact value is unknown, but what is known is the range. In environmental engineering the terms "white-", "grey-", "black-" water are well established. "Green" generally means "ecological" (green revolution, green party), but also "green water" means, in environmental engineering, the water that has been treated to a quality suitable for provision as a non-potable supply. In the Navy it refers to coastal waters.

One of the distinctive feature of each model is its approach to the problem of data reliability. There are models which assume that all input data are absolutely correct, and based on this assumption seek the best solution using different optimization procedures, such as linear programming. This group of models can be called "*white models*.". Some researchers realize that the reliability of the input data is a problem and try to apply different mathematical tools to address it. These "*grey models*" are based on probability or grey numbers or fuzzy sets theories. Finally, there are models, which seek the solution to the waste management problems using the LCA or work as a Decision Support Systems (DSS) using GIS and professional databases. Also the models, which utilize the multicriteria analysis techniques are in this category of sustainable development models called by the author "*green models*".

WHITE MODELS

This group of models started its development in the 70's, and at the beginning it concentrated on the problem of improved waste collection, only. Cost was the main goal of the models which tried to design the trucks' routes to minimize the total cost of waste collection. Some of those models tried to include into the calculation the fact that different roads have different level of difficulty, and that the left turn is more difficult that the right one, and that not all road crossings are equally challenging for the driver. The first model was developed by Clark in 1970, who tried to find out the location for the trucks bases, which would guarantee the minimal total cost of waste transportation including the route from the base to the served region and finally from the landfill to the base.(Gottinger, 1988). In a simple waste disposal system the collection costs can make up to 80% of the total cost of disposal. That explains why researches focused at the beginning on this element of waste treatment. The problem was defined as a linear programming problem (LP), modified next to integer programming. (Kirby, 1971)

Proper sizing of the collection fleet gives potential for money savings. The linear programming model, which minimized the collection cost with number and size of the collection fleet as the decision variables, was defined by Clark in 1972. (Clark, 1972)

The next development in this category of models focused on waste transportation cost, including transshipment stations with waste mass reduction. This model tried to minimize the cost of transportation taking advantage of the regional cooperation. (Anderson, 1967)

The next stage of models' development was the introduction of time factor. (Esmaili, 1972). Introduction of time required the change of the objective function. The objective function in the Esmaili's model was the cost of transportation and processing, measured as the discounted sum of costs occurring in different periods of time. The processing cost was presented as the sum of fixed and variable costs.

A very advanced mathematical model was presented by Gottinger (Gottiner, 1988). This model seeks the minimal cost of waste disposal, which includes the cost of collection, treatment and landfilling. Processing cost is treated as a sum of fixed and variable costs, while the linear variable cost depends on the size of the facility. The model does not include the time factor and the revenues from selling the recyclables and energy from incinerator.

The same approach, but in more advanced form, was presented by Chang (Chang, 1998). This model included not only the income generated from the produced by the incinerator electricity, but also the revenues from the sold recyclables. The model tried to minimize the total cost of waste disposal, taking into account also the limit of electricity production. This constrain is in contradiction with the demand for a high level of recycling, which reduces the heating value of the restwaste, hence making the electricity production more difficult. The Chang model was formulated as a non-linear problem, because the functions describing the conversion of waste into energy are not linear.

Environmental constrains became introduced into the models in the 80s. (Jenkins, 1982; Clapham, 1986). Environmental elements were introduced into the linear programming models in form of additional constrains or incorporating Life Cycle Analysis (LCA) into the models. The Chang's model is the example of the first approach. (Chang, 1996). The model helps to locate new waste treatment facilities in the region and selects the moment of the investment in the way, which minimizes the total treatment costs. Additionally to the traditional constrains of the mass balance for each node, the model ensures that new facilities meet the legal requirement concerning air protection and leachete generation.

The environmental problems of additional noise and traffic caused by the waste collecting trucks and treatment facilities were addressed by the Chang and others (Chang, 1996). As a result they generated a mixed integer linear programming model (MIP), in which the objective function was the total cost of treatment and the constrains included the noise level and a traffic increase, measured at the most sensitive locations. The authors concentrated on the noise problem, as the biggest environmental nuisance, forgetting about the odor which seems to be more important.

GREY MODELS

This category of waste management models includes all the models, which address the issue of data certainty. This problem is addressed by fuzzy set theory or by grey numbers theory. (Chang, Ni-Bin & Wang S.F., 1997), (Chang, Ni Bin, Chen Y.L & Wang S.F., 1997), (Chen H.W. & Chang Ni-Bin., 2000), Chang Ni-Bin & Wei Y.L., 2000), (Huang G.H., Baetz B.W. & Patry G.G.,1993), (Chang Ni-Bin, & Wang S.F.,1996). The basic assumption behind the fuzzy set theory is that it is not correct to set up a sharp limit to certain quality values. In reality, the solutions change the value in more a continues form, described in the fuzzy set theory by a membership function. For certain range of parameter values the membership function is 0 (that is totally unacceptable) while for other parameter values, which are fully acceptable, it is 1. In the remaining range the membership function takes the continues values from 0 to 1. The waste management models try to define the objective function as a sum of products of membership function and each parameter. The set of constrains are build the same way as they are in the regular linear programming models.

Chang, Ni-Bin i Wang (Chang, Ni-Bin, Wang, 1997) applied this methodology to build a model, which helps to locate and size the waste treatment facilities the way, which meets four independent goals: economical, noise level, traffic intensity and air pollution. The economical goal was defined as a sum of discounted investments and running costs of all facilities, including revenues from recycled material received both by companies and individuals. The goal concerning the noise level was defined to minimize the traffic increase in front of all facilities. The same way the noise level goal was defined; its increase was measured at certain, socially sensitive locations. The last goal was defined as the sum of certain pollutants emitted from the waste incinerator located at selected locations. The model was defined as the Fuzzy Goal Programming (FGP) problem, where the objective function was defined as the sum of products of membership functions of each parameters and the assigned parameters' weight. The constrains described the mass balances at each facility, technical limitations of the processes, and legal limitations concerning the environmental impacts.

The developed model is very complex and requires high mathematical skills. At the same time, the pollution and noise propagation models are not very precise, hence the final results of modeling can be of low accuracy. Additionally, the two environmental goals (noise and traffic) are significantly correlated. Also the model assumes that the incinerator is the only source of air pollution, neglecting the pollution coming from the composting facility.

The authors improved the model trying to solve the problem of data uncertainty using grey numbers. (Chang, Ni Bin, Chen Y.L.& Wand S.F., 1997). The idea behind grey numbers is that certain parameters take values from the certain range, but the probability of the distribution is not known. All what is known is the range. Using this concept the authors build the model called:

fuzzy, interval, multiobjective mixed integer programming (FIMOMIP). The result of the analysis is in form of values, which also can take a form of grey numbers. That includes binary decision variables to build or not to build the facility and the parameters of the solution, such as total cost, which is presented as a grey number that is a number which takes a value from the certain range. The same research team was developing the same concept, making different models by modifying the objective function and constrains. Mathematically it is called a Grey Integer Programming, GIP. (Chen H.W. & Chang Ni-Bin., 2000), (Huang G.H., Baetz B.W., Patry G.G., 1993) (Huang G.H., Baetz B.W., Patry G.G., 1995). Generally, this approach leads to development of the models than are not general tools of solving the problems and can not be generalized and used in other cases. Such models are more the set of equations that solve very unique problems, defined for this specific case. By no means the models can be called “user friendly”.

GREEN MODELS

The introduction of the concept of sustainable development made it clear that the mature models of waste management have to take into account other than economical goals of analysis. In mathematical models even introduction of one or two environmental goals, as is done in goal programming, is not enough. Implementation of Life Cycle Analysis (LCA) as a tool of models' development and evaluation seemed to be the proper answer to this challenge.

The main advantage of implementing LCA into waste management is that LCA gives a lot of information concerning environmental impacts. This offsets the drawback of mathematical models which focus on economical analysis. At present there are approximately 50 different software programs to carry out inventory analysis of different processes or products. (http://lca.jrc.ec.europa.eu/lcainfohub/toolList.vm). The waste management process is a special one, because it includes many products, but covers only the last stage of their lives. The software for such a process should have the following abilities:

- Should respond to a change in fractional waste composition, such as varying content of e.g. paper or plastic.
- Should respond to elemental waste specific emissions, such as for example mercury content in newspaper.
- Should respond to waste management processes' operating specific emissions, such as the amount of dioxin emitted.
- Should include substitution with energy systems and manufacturing of primary resources, eg. such as aluminium.
- Should be able to include country –specific energy mix in the calculation.
- Should include the assessment of an integrated and interconnected system composed of number of transportation and waste management processes, from collection to landfilling. (Gentil, 2010).

Only the following eight programs meet those requirements:

- EASEWASTE: (Kirkeby et al., 2006) (http://www.easewaste.dk)
- ISWM Canada: (EPIC, 2000) (Environment Canada, 1998)
- IWM-1, IWM-2: (White et al., 1997) (McDougall et al., 2001)
- LCA-IWM (Boer, 2005)
- MSW-DST (Barlaz et al., 1995),
- ORWARE (Eriksson et al., 2002),
- MIMES/Waste (Sundberg, 1995),
- WISARD (McDougall et al., 2001).

According to literature review there are other waste management models such as ARES, HOLIWAST, LCA-LAND, WAMPS, MSWI but they focus on one technology of disposal only, or they are not the LCA tools.(Gentil, 2010).

The main problem of the models is that all the LCA models use the same methodology and similar data bases, but come up with very different results. Winkler (Winkler, 2007) conducted a comparative calculations for the city of Dresden comparing the three potential waste treatment systems. He made simplifying assumptions concerning the systems to allow all the models correct reflection of the reality. The obtained results presents Figure 1

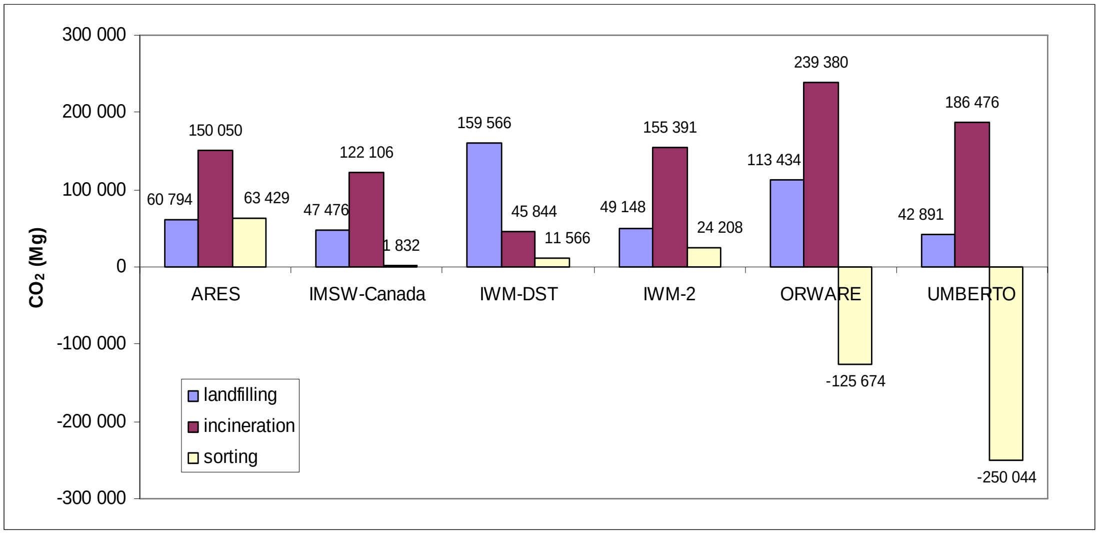

Figure 1. Comparison of the results of carbon dioxide emissions for the landfill, incineration and MRF scenarios

Different models come up with very different results, and what is more important in many models the hierarchy of solutions is also different. For example, UMBERTO indicates that "sorting" is the best solution giving significant negative/evoided emission of carbon dioxide, and the incineration seems to be the worst scenario. In the same time, if one uses IWM-DST model one will not have the negative emissions, and the worst solution, giving the highest emission is "landfilling". Also the range of obtained by different models results for different scenarios overlap making the decision process unclear. Gentil (Gentil et al., 2010) tried to find out the reason of such big discrepancy. They evaluated:

- Functional units,
- System boundaries
- Waste composition and properties,
- Energy aspects
- Waste management processes.

The authors concluded that only the functional units in all models are similar. All other elements differ significantly. System boundaries have to be seen as the boundaries between technical system and the environment, but also as the time boundaries, boundaries between the technical system and other technical systems (upstream or downstream), and boundaries between significant and insignificant contributions.

The technical boundaries are important for the final results. Different models describe the waste composition differently which can cause the discrepancies. Additionally the models use country specific data which can be a source of additional errors. Time horizon is important particularly when comparing landfilling. The emission of heavy metals from the leachate can last up to 10 000 years. Some models take 20 year perspective while the other even 500 year. Different models estimate the landfill gas production based on different assumptions. Even the models which assume the amount of produced gas as a function of deposited waste assume different unit gas production and that leads to different results.

Generally, the boundaries between the technical system and other systems are the same but some models include the transportation of recyclables and pretreatment for final processing into analysis. This makes a significant difference in the results. There is also a difference among the models which contributions they assume to be important and which they neglect. For example emissions generated during the construction of the facilities and during the transportation of landfill covering materials are in some models included into the calculation.

Another source of error is that different models assume different waste morphology. Models divide waste into different fractions, assume different chemical composition, and find different components important (For example some models neglect water in the waste stream while other neglect cellulose). The models also differ in their approach to the source of carbon. Some models do not differentiate between bio and non bio source of carbon while one model differentiate whether carbon comes from starch, fat, cellulose, protein or sugar assuming that the source of carbon effects the decomposition process hence carbon dioxide emission. Elementary composition of waste is different in different models and that is particularly important for heavy metals emissions.

Assumed energy mix has a significant impact on the results of the LCA analysis. Some of the models give the possibility to adjust the parameters to national or local conditions while the other use pre selected values.

The options of waste treatment and the assumed parameters of unit process are different in different models which leads to further differences in the obtained results.

The result of the models comparison leads to the conclusion that they differ in all element, but the functional unit. That does not mean that one model is better than the other, but the researcher has to be very aware about the assumptions which were made by the model’s developers. It looks that the only way to minimize this problem is to make the model as transparent as possible to allow the user tuning and corrections to the local conditions.

The LCA models can be described as:

- Models do not seek the optimal solution, but only estimate the emissions to the environment not even measuring their impact.
- LCA is not the only tool of environmental management, and other multi criteria solutions should be used to help in the final decision process.
- LCA models have a problem with defining different boundaries between the system and the environment. The theoretically simple problem is difficult in practical implementation.
- LCA models are region sensitive. They produce the results based on their own data bases which can be very inaccurate in local conditions (energy mix).
- LCA models focus on environmental impact neglecting social and economical consequences of the analyzed solutions.
- Very limited social impact analysis makes the models invalid from the sustainable development’s point of view.

The Multicriteria Decision Analysis models (MCDA) constitute the separated category of the models. Such models allow:

- Thorough analysis and understanding of the problem,
- Inclusion of quantitative and qualitive parameters into the decision process,
- Inclusion of different group interests into the analysis process,

- Elasticity of the decision process, which is missing in the economic models,
- Finding the preferable group of the models, living the final decision to the decision makes,
- Changing the results of the modeling by changing the values of subjective parameters,
- Application only by experienced users due to difficult vocabulary and procedures,
- Analysis of waste disposal, but without the stage of waste avoidance. (Morrissey, 2004)

To implement the MCDA researches use several techniques treating each problem as an individual case.

There is no user friendly software for solving the municipal solid waste problems using the MCDA techniques.

The Decision Support Systems (DSS) models form separate category in the category of sustainable development models. Generally, DDS is an intelligent computer software which helps the decision maker in the decision process. Such programs are used in the medicine and economics, but also in the field of the environmental engineering. Some experts define environmental engineering DSS as an expert system which uses Geographical Information Systems (GIS). There is difficult to find such a model in the filed of solid waste management. The example of this approach is a Bhargava model (Bhargava, 1997) which, based on GIS information and current prices of recyclables, helps the user to find route to deposit banks which maximizes the profit taking into account cost of traveling and expected revenues. The Bhargava model is a development of former WRAP model (Waste Resource Allocation Program) prepared by the US EPA in the 80s.

Very advanced is a Spatial Decision Support System (SDSS) prepared for the California region. The program helps in all seven steps of the decision process. The program uses not only GIS, but the expert databases and the AHP multicriteria method for making the final choice. The criteria include not only the economic information, but also the amount of consumed water (a factor important in the California region) and required number and qualification of the personnel. The environmental impact of the proposed system is also estimated. (MacDonald, 1996).

CONCLUSIONS

Based on the presented review one can say that there in no dominant municipal solid waste management model. The research goes in many directions using of many tools. One of the research areas is finding the optimal regional system using the linear programming software. The optimization models sought, at the beginning the cheapest solutions, including later other goals into the analysis. The simple linear programming transportation and transshipment models has became more and more complicated. The problem of variables certainty was addressed by introducing fuzzy sets and grey numbers theories. This made the solved problems mathematically complicated and did not result in any models which could be used "from the shelf". This group of models give specific answers for individual problems only. For each case the problem has to be individually defined and solved and the obtained results can not be applied in other regions.

The LCA models, from the *green* group models, seem to be the best choice when seeking the best sustainable development solutions. There is no dominant LCA model. There is a need to develop the LCA model which will have the following features:

- Should be based on the proven LCA model.
- Should be flexible to be able to model complex real systems. So far IWM-2, MSW-DST and UMBERTO were find to be the most flexible ones.
- Should be able to handle time varying variables.
- Should try to seek the optimal solutions using the sustainable development criteria, that is including economic, environmental and social impacts of the analyzed system.

- Should model the recyclables' transportation for processing. This part of the waste process has a significant impact on the whole analysis.
- Should be transparent. This increases the reliability of model and allows it development and tuning to the local conditions. It also helps solving the problems of the selection of the system's boundaries.
- Should present the results of the analysis in the form which is understood by the decision makers. That means integrating the results using the multicriteria decision analysis methods.

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