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“Optimization model for the planning of a regional waste management system”

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ABSTRACT (GERMAN)

Die vorliegende Arbeit entwickelt ein Model zur ganzheitlichen Planung von regionalen Abfall-Management-Systemen. Das vorliegende Model erstellt dabei einen Bezugsrahmen für die simultane Analyse von theoretisch uneingeschränkt vielen technischen Lösungen, beachtet Bezugsgrößeneffekte und entwickelt eine Methode, bei der Umweltverschmutzungsbedingungen in die Kostenfunktion einbezogen werden können. Des Weiteren verschafft die Arbeit einen Überblick über Festmüll-Behandlungstechnologien und nutzt eine Lebenszyklus Methode (life cycle assessment - LCA) für die Einschätzung der Umweltverschmutzung. Die entwickelte Methode zielt darauf ab sowohl die Probleme von momentan generiertem Abfall, sowie bereits existierenden, unbearbeiteten Deponien mit zu behandeln, was die Notwendigkeit für einen optimalen Planungshorizont verdeutlicht. Im vorliegenden Beispiel zeigt die entwickelte Methode dabei einen Profitzuwachs von 2 Prozent auf.

ABSTRACT

This thesis develops a model for the holistic planning of a regional waste management system. The model creates a framework for simultaneous analysis of a theoretically unrestricted number of technological solutions, accounting for possible scale effects, and proposes a methodology for the incorporation of environmental damage terms into the cost function. The paper also includes an overview of solid waste treatment technologies, and employs life cycle assessment (LCA) methodology for environmental damage valuation. The goal of this proposed method is designed to solve the problems of managing currently generated waste and the problem of treating the already existing unmanaged landfills, which in turn reveals a need for determining an optimal planning horizon. In the calculated example the method has yielded a 2% NPV increase in comparison with the approach of solving the two aforementioned problems separately.

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ABBREVIATIONS

AP	Acidification Potential
EOQ	Economic Order Quantity
EP	Eutrophication Potential
ESIs	Environmental Sustainability Indicators
FGP	Fuzzy Grey Programming
GWP	Global Warming Potential
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LP	Linear Programming
MRF	Materials Recycling Facility
MSW	Municipal Solid Waste
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
RDF	Refuse Derived Fuel
SWM	Solid Waste Management
WDF	Waste Derived Fuel
WTE	Waste-to-Energy

1 TOPICALITY AND NOVELTY OF THE APPROACH

The aim of this paper is to build a universal optimization model for planning regional waste management systems based on thorough system analysis and simple mathematical tools. This work can be attributed to holistic waste management, because it is designed to solve the task of long-term planning and takes into account both economic and environmental aspects.

The existing waste management problems are topical due to scarcity of natural resources, land, world population growth trends, a positive correlation between financial prosperity and per-capita waste generation rates, and the limitation of environmental goods, such as clean air and fresh water.

The major novelty[1] of this developed model is that it solves both problems of treating continuously generated municipal solid waste and existing unmanaged landfills. This approach allows for full capacity utilization through the whole equipment life-span, which implies an increase in efficiency and a reduction in total costs of the regional waste treatment system. To corroborate this improvement, the city of Beijing is analyzed and yielded a 2% project NPV increase in comparison with the approach of solving the two problems separately. This effect is reached due to long-term fluctuations in the quantity of waste generated by cities.

For example, when considering projected population growth, a factory should be able to process the quantity of waste that will be produced in the next couple of decades, which leads to an excess capacity at the beginning of the operation period that can be used for processing waste from landfills.

The second unique idea arises from the appropriation of environmental damage into the problem of existing landfills. Due to the fact that landfills cause environmental damage, it seems to be logical to calculate an optimal value of money to be allocated to solving this problem, which is equivalent to choosing an

[1] According to the author's knowledge

optimal capacity or time during which the landfill waste should be processed. Taking into account that the solution of the developed inter-temporal optimization model depends on the number of considered periods, it becomes obvious that the planning horizon should also be optimized. Aside from proposing a rule for determining the minimal number of periods that should be considered in the main optimization model, the paper offers a method for the calculation of an optimal time of processing waste from unattended landfills based on total cost minimization approach.

Apart from the aforementioned ideas, this paper proposes a few novel “technical” solutions, which include the adaptation of EcoIndicators’99 for the monetary valuation of environmental damage and the incorporation of non-linear effects to a linear model by substituting non-linear functions with pairs of corresponding vectors. The last idea is very similar to the idea of analog data sampling (Zeijl, 1998), which is rather old; however its application in describing a relationship between the facility size and the dependent parameters seems to be rarely used.

The paper proposes some values as estimates of environmental damage caused by the landfills during their different life phases. These predictions are based on recent research on emissions to air and leachate, as well as the EPS2000 indicators.

Among other things, the combination of certain technical properties in one model, such as possible delays of building treatment capacities, module structure of factories, equipment lifetime limitation, accounting for scale effects, consideration of theoretically unrestricted number of treatment technologies, make the model unique.

The paper should be regarded as a proposal for a further research, because a large number of values need to be determined in order to calculate the model. The data on waste composition, technologies, and costs that are brought in the first sections of this paper are rather specific for the cases considered in each of the cited papers, and should be regarded as a qualitative overview of the topic rather than robust data that can be used for the practical calculations.

2 INTRODUCTION

The aim of this work is to build an optimization model that allows for the planning of waste management systems for any geographic region that includes waste producers, existing unmanaged landfills, and potential locations for waste treatment facilities.

In general, the model can be applied to the problem of treating any kind of waste, though it does not offer a solution for different types of waste simultaneously. In order to synchronize this paper with real-life problems, we will consider municipal solid waste (MSW) and define waste producers as cities.

Waste management is a socially important topic, as it deals with the unavoidable day-to-day needs of citizens. It possesses a special importance in urbanized areas (Xu, et al., 2010) due to population densities and growing rates of waste generation. For instance, according to OECD Environmental Data, Compendium 2006–2008, the per-capita waste production has increased by 8% in the North America and by 14% in the EU during the 11 year period between 1995 and 2006 (Ghiani, et al., 2012).

Waste management systems can be divided into several processes, such as waste generation, transportation, treatment, and disposal (Xu, et al., 2010; Wilson, 1985), each of which is associated with both socio-economic and environmental considerations (Chang & Wang, 1997).

Waste can be classified by its source, which includes municipal solid waste (MSW), waste waters, specific industrial waste, and medical waste. In addition, it can also be distinguished by the degree of its hazardousness, ranging from organic residues of agricultural industry to highly dangerous nuclear waste. In general, a plethora of waste classifications exist; for example, one can look at (NSW government, 2012) or (Department of Environment and Climate Change NSW , 2008).

It has been ascertained that waste generation can be correlated with GDP per capita, infant mortality rates, household size, life expectancy at birth, labor force in agriculture, and populations aged 15-59. As a template, one can postulate that waste generation pattern is closely related to a level of economic development of a country. (Kollikkathara, et al., 2010; Beigl, et al., 2003)

Although the solid waste generation rate is fuzzy, its uncertainty can be limited by proper application of the conventional prediction technique, such as through regression analysis. (Chang & Wang, 1997)

One can track changes in motivation for waste management through the history, starting from basic hygiene to today's necessity of environmental protection. History goes back to the year 1839, when the Sanitation Commission in London established a direct connection between the poor sanitation conditions and the high number of disease cases. It was believed that infectious diseases, such as cholera, were caused by the decaying processes in organic matter. The findings resulted in the Public Health Act in 1848 and the 1875 Public Health Act, which forced households to collect their waste in movable containers and regulated the authorities to empty these containers on a weekly basis, thus creating an institutional driver for waste management. During the late 1960s and 1970s, the topic of waste disposal gained traction on political level, due to the increased attention and questions relating to environmental protection. Climate change issues have therefore played a crucial role in the development of an environmental driver. Usage of landfills for storage of biodegradable wastes has been reduced after landfills were discovered to be one of the largest contributors of GHG emissions. (Wilson, 2007)

For instance, it has been established that emissions from the landfills were the third largest anthropogenic source of methane emissions in the US in 2011 (USEPA, 2013).

There are multiple governmental and international regulations regarding waste management. The notion of "waste hierarchy" has been introduced for the first time in the EU's Second Environment Action Programme (1977) which called to abandon the disposal of waste and to move towards waste reduction policies, recycling of materials, and recovery of energy. (Wilson, 2007)

The aforementioned hierarchy, as it has been specified by the European Commission in 2001, means that the first priority should be given to waste prevention, whereas the recovery of materials and energy from inevitably produced waste are set as a secondary priority. (Mitropoulos, et al., 2009; Holmgren & Henning, 2004)

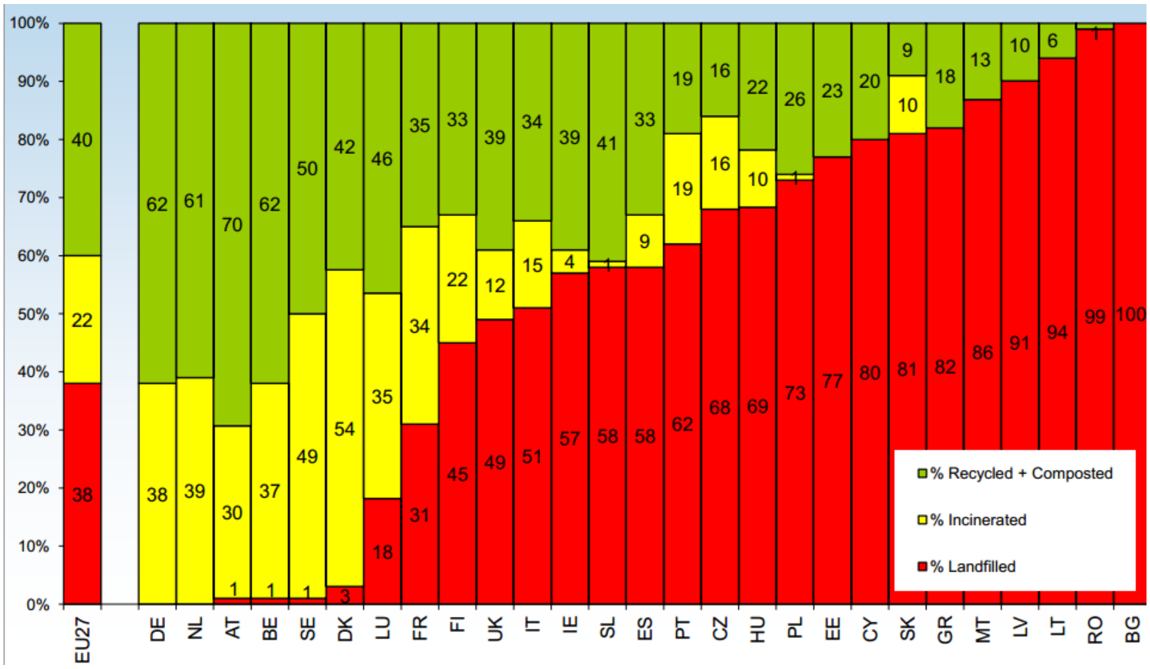
The EU policy concerning waste management encourages any method of waste treatment, which includes production of secondary raw materials or generation of energy, as a result of waste processing. On the other hand, there are alternative policies which stipulate the reduction of harmful emissions, which result in a conflict between the policies. For instance, waste incineration plants in Finland have encountered problems due to high rates of emissions. Apart from that, the Finnish Association for Nature Conservation claims that energy recovery plants do not support the target of waste prevention, therefore creating an obstacle for the installation of new plants. (Luoranen & Horttanainen, 2007)

The EU Landfill Directive (1999) was triggered by the waste hierarchy approach and the danger of climate change. The directive directs countries to decrease the percentage of the landfilled biodegradable waste to 35% until 2020. Certain countries have even banned landfilling non-stabilized waste. (Wilson, 2007)

Waste management practices can differ from country to country, due to some specific circumstances and local requirements. For example, landfills were never popular in Japan due to the scarcity of space; therefore, incineration technologies have historically played there a major role. (Gohlke & Martin, 2007)

Figure 1 exposes the current mix of practices used in waste treatment industry in the EU countries.

Figure 1: Municipal waste treatment in 2010 in EU27



(CEWEP, 2012) Based on Eurostat data

Ghiani et al. (2012) pointed out that efficient waste management requires taking strategic, tactical, and operational decisions, which include the selection of waste treatment technologies, locating waste treatment sites and landfills, calculation of future capacity expansion requirements, waste flow allocation, service territory zoning, collection scheduling, root optimization, and the composition of collection truck fleets. This paper contributes to the topic of improving efficiency on a strategic level by proposing an optimization model for adopting technology-related choices, capacity planning, and waste flow allocation. The smallest considered time unit is one year; whereas, determination of a minimal optimal planning horizon is based on a total cost minimization approach or application of the Value of Statistical Life (VSL) concept, which will be explained in a chapter devoted to planning horizon.

Municipal solid waste (MSW) and industrial waste management is limited in many countries to residue collection and the disposal at uncontrolled dump sites. This practice leads to local and global air, water, and soil contamination, as well as the disuse of economic benefits of energy and materials recovery. Whilst local pollution affects population’s health, flora, and fauna in a limited geographical area, the transboundary pollution created by countries with less stringent environmental regulation diminishes any pollution reduction effort of more environmentally-concerned countries. Despite the obvious fact that pollution problems cannot be solely attributed to mismanagement of waste, waste management problems noticeably contribute to it. As a result, the dissemination of the effective waste management practices is expected to have a positive long-term effect both on population health and the sustainability of economic development on a global scale.

The inherent property relating to strategic waste management problems is the long-term planning horizon. A modest estimation of the lower bound time period, during which landfills cause major environmental damage, is roughly one century. By contrast, the total period of pollutants emission is estimated to be up to 100,000 years (Sundqvist, et al., 2002). Consequently, it is sensible to consider treatment of both already existing unmanaged landfills and of the waste which is steadily produced by the cities and industry.

There exist several waste treatment technologies, which broadly include landfilling, recycling, and incineration. More thorough review will indicate many technical solutions for each of the options, and a number of alternative solutions at different stages of development. It is expected that each technology has its advantages and disadvantages and can be more or less beneficial depending on local conditions. Moreover, it is reasonable to consider scale effects for each of the technologies available.

Developing countries are expected to have a distinct advantage in planning and implementation of a holistic, state-of-the-art, sustainable waste management solutions. This is due to the possibility of building the system from scratch in the most efficient manner by using costly practical experience, which was originally ascertained in leading countries via a trial-and-error method.

3 LITERATURE REVIEW

A reasonably large number of linear, dynamic, integer and multi-objective models have been developed for supporting decisions in MSW management since the 1960s (Li, et al., 2008). The early works concerning this topic have emphasized the cost-effectiveness principle by designing linear programming (LP) models with a single-objective optimization (Chang, et al., 2012). Mitropoulos et al. (2009) note that “most of the location models for planning a regional SWM system are based on the considerations of Marks & Liebman (1971), who first introduced a capacitated trans-shipment facility location problem for refuse collection”. The paper also mentions Karagiannidis & Moussiopoulos (1998), the authors who designed a model which takes into account multiple treatment technologies.

Some models, for instance the one designed by Costi et al. (2004), take into account both economic and environmental issues. However, they keep the objective function purely economic, whereas putting environmental considerations into constraints (Minciardi, et al., 2008). Lu et al. (2009) have established an inexact dynamic optimization model that incorporated GHG components into the system objective.

Some other studies concentrate on improving the current situation in certain cities by optimizing the existing system, such as Xi et al. (2010) who developed a strategy for prolonging the lifespan of landfills with minimum system cost and maximum treatment efficiency in Beijing. In addition, Cheng et al. (2003) have designed an optimization model for determining a site for a new landfill in the city of Regina, such that it causes the least negative economic and environmental consequences. Nie et al. (2009) have considered a solid waste management system with several cities, a landfill, and a waste-to-energy (WTE) facility; for which they have designed capacity expansion schemes, and optimal waste flow allocations throughout N periods.

Galante et al. (2010) write that Zimmermann (1978) has indicated two main methodologies employed in waste management models in his works; firstly a multi-attribute decision making process which is applied to discrete decision making variables, and a multi-objective decision making model applied to continuous decision making variables. One type of multi-objective programming is goal programming, which in turn can be separated into programs with non-preemptive (or weighted) goals and preemptive (or lexicographic) goals. In the first case, the goals are considered to be of an equal importance, whereas in the second one the goals are ranked according to the decision maker's preferences (Chang & Wang, 1997). Furthermore, Galante et al. (2010) have reported the three most significant approaches to multi-objective optimization, which include "utility function (Keeney & Raiffa, 1976), goal programming (Ignizio, 1976) and compromise programming (Zeleny, 1982)".

Several studies use a deterministic planning horizon; for example, Xu et al. (2010) have conducted the calculations for a fifteen years period divided into three five-year stages.

Alternative studies have concentrated on modeling micro parameters of MSW management systems. For instance, Ghiani et al. (2012) have developed an integer programming model for choosing the sites and capacities for waste collection bins in a city.

Minciardi et al. (2008) have developed an approach to sustainable municipal solid waste (MSW) management, based on non-linear multi-objective optimization, which supports decisions regarding the optimal flows of waste sent to different types of treatment plants.

Alternate models concentrate on the issue of uncertainty by applying stochastic optimization techniques. For example, Chang & Wang (1997) have applied the Fuzzy[2] Grey Programming (FGP) method in order to determining the optimal parameters of the SWM system in the city of Kaohsiung in Taiwan. Xi et al. (2010)

[2] According to Zadeh (1965) a fuzzy set is characterized by a membership function, which assigns a value between zero and one to each object of a domain, which shows to which degree an object belongs to the set. (Chang & Wang, 1997)

have created an inexact chance-constrained mixed-integer linear programming model, which was capable of dealing with multiple uncertainties for the purpose of supporting the long-term planning of MSW management in Beijing. Li et al. (2008) have used interval programming in their model, in addition to stochastic and integer programming.

Chang & Wang (1997) have used the FGP method to include the objectives that were non-statistical in nature and which couldn't generally be described by traditional probability distribution, due to the absence of sharp boundaries in information. Their model takes into account both economic objectives and environment-related factors such as the impacts of noise, traffic congestion, air pollution, and material recycling within the long term planning horizon. The introduced analytical framework ties together the interactions among the effects of waste generation, source reduction, recycling, collection, transfer, processing and disposal.

Cheng et al. (2003) have adopted the fuzzy set theory for incorporating linguistic terms into their model. Under the term "linguistic", one should understand the degree of imprecise assessments that can be described by terms such as ''high'', ''low'', and ''medium'' for example in regards to the severity of ground water contamination risk from different locations that can be used for landfills. Cheng et al. (2003) have also considered in their analysis factors such as land value drop, agricultural sustainability, wildlife habitation, hydrogeology, reliability, public acceptance, political concern, historical heritage, and potential for traffic accidents.

Galante et al. (2010) have employed goal programming, weighted sum and fuzzy multi-objective techniques in order to determine the best means of compromise between the economic and the environmental objectives in the task of localization and capacity of waste transfer stations. These particular techniques are used at an intermediate level in the logistic chain between municipalities and the incinerating plant. They have also determined the number and type of trucks involved in the transportation problem.

The model developed by Galante et al. (2010) was used for “selection of the most adequate technologies (landfill, incineration, composting, RDF production) and corresponding centralized/decentralized management model”. Nevertheless, the set of options was limited to some predefined solutions: for example a single incineration plant located in a fixed, predetermined position was used. The authors evaluated the obtained results according to “eight different criteria, including economic parameters, technical considerations, environmental and social issues, such as initial investment and operating cost, reliability, greenhouse effect, manpower increase and air pollution”. It has been deduced that setting cost optimization as a main goal leads to a centralized system design, consisting of two large plants, whereas giving the first priority to environmental objectives leads to a decentralized solution consisting of seven smaller plants. The centralized solution allows for economies of scale, whereas the decentralized solution minimizes fuel consumption. (Galante, et al., 2010)

4 OVERVIEW OF TECHNOLOGIES

4.1 General review

As mentioned earlier in this paper, there are (roughly speaking) three categories of MSW treatment solutions: dumping at a landfill site, incineration without pre-separation, and recycling presuming the prior separation of materials.

Landfills, in turn, can be divided into unmanaged (or even spontaneous) (Mitropoulos, et al., 2009), and modern landfills, where waste is separated from the ground by isolation materials and covered from above in order to avoid water contamination and the accumulation of gases (Chang, et al., 2012; Gajski, et al., 2012). For example, Mitropoulos et al. (2009) mentioned that more than 2200 non-monitored and non-stuffed open air dump sites existed in 2005 in Greece. They also indicated that such dumps imply extreme risks of fires and pollution.

Methane and carbon dioxide are the major pollutants responsible for high global warming potential (GWP) in solid waste management systems (Chang, et al., 2012). Landfilling practice is the cheapest option in the short run (Gohlke & Martin, 2007), but is not desirable in terms of energy efficiency and environmental protection (Ragoßnig, et al., 2008). Despite this, there are different studies that arrive at controversial results regarding the overall performance of modern landfills, such as in comparison to incineration (Dijkgraaf & Vollebergh, 2004; Marchettini, et al., 2007; Cherubini, et al., 2009).

Chang & Wang (1997) have found in their analysis that prioritizing environmental quality objectives leads to a decrease in capacity of waste incinerating plants and an increase in capacity of landfills. Chang et al. (2012) have concluded that recycling has a higher priority than landfill disposal under the sustainable waste management framework. Although methane can be efficiently recovered from landfill sites for the purpose of reducing GWP and creating carbon credits, methane generation rates are uncertain and the recovery is capital intensive. They also argued that this finding is consistent with most of the literature.

Nonetheless, the general conclusions on this topic are not particularly robust, due to the differences in methodology and the presence of conditions that are specific for a studied location and implemented technical solution (Björklund & Finnveden, 2005).

Combustion of unsorted MSW leads to the creation of various hazardous compounds which have to be filtered by employment of pollution control technologies. Naturally, this increases costs and generates a low volume of highly hazardous residues, which either have to be disposed at specialized storage locations or recycled (Quina, et al., 2008).

Whilst incineration implies substantial emissions of carbon dioxide, landfills have a high environmental impact, due to emissions of methane which has a GWP many times higher than carbon dioxide (Chang, et al., 2012). The combustion process can be used either for heat generation, power generation, or cogeneration (Reimann, 2005). Cogeneration is found to be the most efficient from the above-mentioned technologies (Reimann, 2005), but its “real” efficiency is dependent on the demand for heating: as a result, industrial consumers which provide a constant demand are preferred (Ragoßnig, et al., 2008). Cogeneration plants are often serving district heating systems, however demand for heat varies considerably through the year in most countries. One technological solution for useful heat utilization in hot months, which has already been practiced in the US and in Scandinavia, is district cooling (Ragoßnig, et al., 2008; Cook, 1998). This scheme reduces the demand for electricity by minimizing the usage of conventional air conditioning systems and allows utilization of heat in a sorption-based cooling process (Ragoßnig, et al., 2008).

Typically, materials recycling facility (MRF) combines manual and mechanical sorting (Emery, et al., 2007). The materials separation approach allows for a large variety of further treatment options. Firstly, nonorganic materials such as metals and glass can be recycled. Secondly, manual screening of non-hazardous waste allows for the filtration of valuable objects, for example batteries from cell-phones, which can be sold to the specialized companies. The organic (in this case means the carbon-containing matter) fraction can be further separated into different materials or used for production of refuse derived fuel (RDW), also known as waste derived fuel (WDF). WDF production contradicts the recycling objective; therefore one should analyze costs, energy consumption, and environmental effects of both options.

When waste is used as a fuel, the consumption of other fuels is diminished. On the other hand, when waste is transformed into materials, the virgin materials are saved, as well as the energy that would have had to be used for the production of these materials. Usually, energy requirements for materials recovery are lower than for production of virgin materials. (Holmgren & Henning, 2004)

Recycling of metals saves more energy than recycling of glass; however, both should be recycled, because incineration of those fractions does not generate heat (Holmgren & Henning, 2004). The research conducted by Morris has shown that if recycling and electricity generation from waste are compared on a energy basis, recycling saves more energy than can be generated by combustion of heterogeneous waste for twenty four out of twenty five materials (Morris, 1996). However, if the cogeneration process is used for energy generation, it has been found that paper and HDPE plastics should be recovered from waste, whereas carton and biodegradable waste generate more energy when combusted (Holmgren & Henning, 2004).

The proportion of WDF produced from municipal solid waste (MSW) depends on garbage composition and technological process. The survey conducted by the European Commission indicates that MSW to WDF transformation rate varies from 23% to 50% by weight of treated waste, depending on the country and employed technology. (European Commission , 2003)

Other options of an organic fraction processing apart from production of WDF are biological treatment (Fricke, et al., 2005), which can be also conducted prior to MSW separation (Rada, et al., 2007); and treatment by high temperature processes. Biological treatment includes composting, anaerobic digestion (Mata-Alvarez, et al., 2000; Walker, et al., 2009), and bio drying (Ragazzi, et al., 2011;

He, et al., 2010). The typical end products of MSW anaerobic decomposition are CH_4, CO_2, and NH_3. This process is used for the production of biogas and compost. (Chang, et al., 2012)

High temperature processes can be applied to WDF or in fact to any carbon-containing matter generally. They include simple incineration, pyrolysis (Baggio, et al., 2008), gasification (Belgiorno, et al., 2003), and plasma gasification (Zhang, et al., 2012). Plasma gasification can be used for MSW treatment, but the major advantage of this technology is that it can be used to destroy medical and other hazardous waste (Moustakas, et al., 2005). By contrast, pyrolysis is a thermal process which flows in oxygen-deficient conditions. Gasification is a modified pyrolysis process which is achieved at a relatively higher temperature than pyrolysis with the insertion of a controlled amount of oxygen. (Chang, et al., 2012) The majority of products of gasification and pyrolysis can be used as a feedstock in chemical industry or as a fuel.

In general, mechanical or mechanical-biological treatment requires less complicated equipment than any high temperature processing. It results in lower maintenance costs and, more importantly, it demands a less skilled workforce to undertake maintenance procedures. Although this argument may seem trivial in comparison to other considerations, the availability of qualified local workers poses a hard constraint for the project viability in some cases.

The life cycle assessment (LCA), conducted by Emery et al. (2007) showed that the incineration option is more favorable than both landfill disposal and recycling combined with composting. However, the costs of incineration were found to be higher than of the other two options.

An article written by Morrissey & Browne (2004) states that by the time it has been written there was no waste management software that could determine a correct mix of waste treatment options.

4.2 Quantitative indicators for selected options

This chapter presents more precise but yet incomplete information on several waste treatment technologies. Prices, costs, and environmental performance indicators should be regarded as very rough estimates, as these parameters depend on local economic and geographic conditions, equipment configuration, waste composition, and, as assumed in the model developed in the following chapters of this paper, on the size of a plant. Following the approach adopted by the authors cited below, the developed model uses Life Cycle Assessment (LCA) methodology for the quantification of environmental impact.

Table 1 shows six technological alternatives which were considered in the study conducted for the Achaia region in Greece by Mitropoulos et al. (2009). The indicators were calculated for a system of plants processing 150,000 tons of waste a year. The article mentions that each of the discussed options does not require any pretreatment, which means that the option of anaerobic digestion, aerobic digestion, and biological drying includes waste separation as a part of a process.

Table 1: Technological alternatives of the SWM system in Achaia

Technological alternative	Waste reduction by weight	Energy production KW/ton	Material production	Processing cost (EUR/ton)
Landfilling	-	-	-	35
Anaerobic Digestion	60%	73.3	Compost	53
Aerobic Digestion	68.3%	246.7	Material recovery	120
Biological Drying	39.4%	-	Material recovery	64
Biological Drying with Energy Utilization	75%	293.3	Material recovery	73
Mass-Burn	84%	420	-	88

(Mitropoulos, et al., 2009)

The figures for the six alternative solutions mentioned in table 1 are presented here for the purpose of giving the reader some understanding of relation between the discussed alternatives. The numbers are subject to change when considering any particular project, due to changes in labor costs, fuel prices, local heat and energy demand, local weather conditions, garbage composition, and particular equipment used in each type of plant.

Emery et al. (2007), citing Materials Recycling Week magazine (2003), have used the following prices for the recovered recyclable materials delivered to a local re-processor: see Table 2.

Table 2: Prices for recovered materials

Material	Price (EUR/ton)
Ferrous metals	24
Glass	26
Non-ferrous metals	794
Paper-recyclable elements	12
Plastic dense	71
Green waste	n/a

(Emery, et al., 2007)

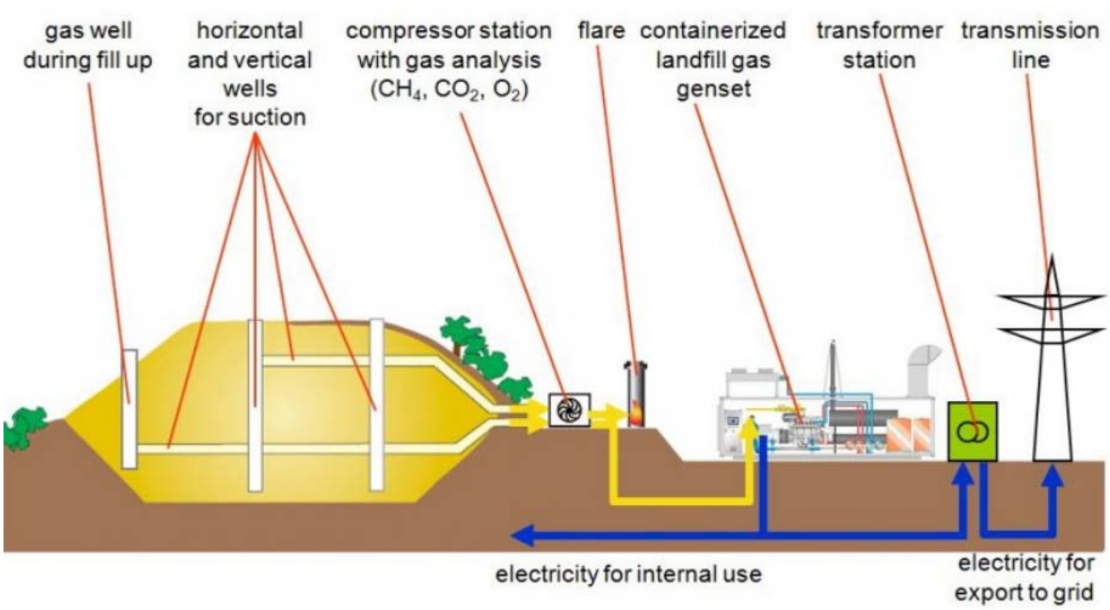
The paper written by Cherubini et al. (2009) considers four waste treatment scenarios for the city of Rome, analyzing it in a LCA framework. The scenarios include landfill, landfill with energy recovery, recycling, and mass incineration.

In scenario zero, waste is delivered to a monitored landfill without any further treatment. During the course of anaerobic decomposition, landfill biogas, which consists of CH_4 (58%), CO_2 (41%), traces of H_2S, HCl, HF and other chemical compounds, is released. The annual methane production rate is estimated to be

140 Nm^3 (normal cubic meter) per ton of waste, 50% of which is assumed to be captured and burned and 50% directly emitted to the atmosphere.

It is also assumed in the first scenario that 50% of the biogas naturally released by the landfill is collected, treated and burned to produce electricity; whereas, 25% is just burned, and 25% is directly released to the atmosphere. The assumed biogas minimal heating value is 17.73 MJ/m^3. In turn, the electricity generation efficiency is assumed to be 28%. Figure 2 shows a possible scheme of a sanitary landfill with energy recovery.

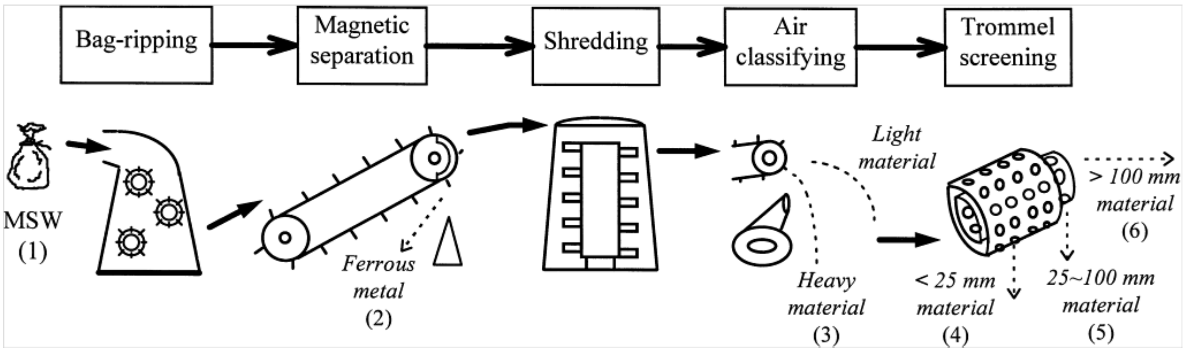
Figure 2: A sample scheme of sanitary landfill with energy recovery (scenario 1)



(Western Branch Diesel , 2013)

In scenario two, a sorting plant is available at the landfill site for the separation of the organic fraction, which is essentially made of kitchen garbage, ferrous metals, lighter materials such as paper and the heavy fraction (e.g. glass) of the waste. The organic portion undergoes anaerobic digestion, which results in production of biogas at a rate of 3740 MJ/ton of waste, containing 70% of methane and 30% of carbon dioxide (the mentioned calorific value is contained in methane). In addition, compost which can be used as a fertilizer is created. Afterwards, the biogas is upgraded through a dry sorption process, which has an energy demand of 11% of the energy content of the biogas. This increases the methane content to 97% and cleans the gas from hydrogen sulfide and other impurities. The upgrading process obviously has its cost, but it is necessary in order to achieve output gas specifications that are acceptable for further usage, for instance as a fuel for generators.

Figure 3: A sample scheme of a waste separation facility (scenario 2)



(Chang, et al., 1998)

The inorganic (in a sense of not being directly related to living matter, but organic in a chemical sense) fraction, which mainly consists of plastics, paper and cardboard, wood, textiles and rubber, is delivered to a Refuse Derived Fuel (RDF) production plant. RDF has a higher heating value (a minimal heating value of 17 MJ/kg) and a more homogeneous chemical composition. It creates less emissions when burnt and is easier to be stored than the untreated waste. The RDF bricks are used for the generation of electricity through combustion with process efficiency of 30%, while the process residues are transported to a landfill. This treatment option is associated with 85% waste mass reduction.

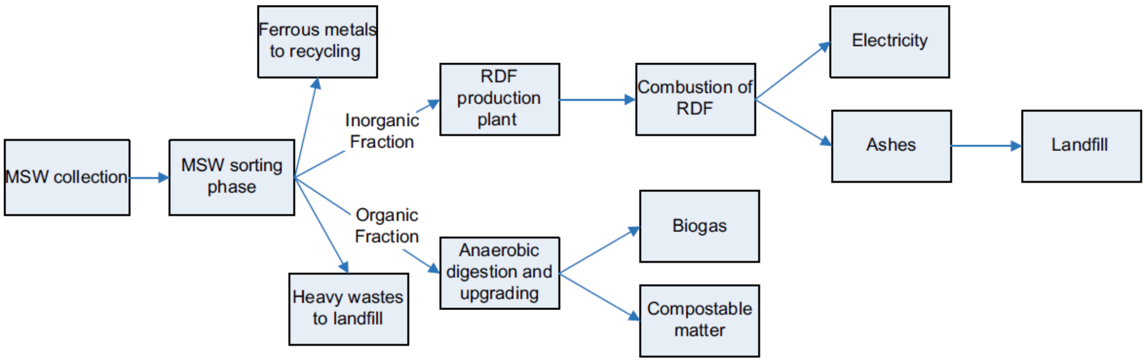
Table 3: Comparison of emissions for incineration of peat and RDF

Component	Emission factor			
	Peal	Variation range	RDF	Variation range
NO_x	235 mg/MJ	200–245	150 mg/Mj	90–160
CO_2	110 g/MJ	100–120	100 g/MJ	80–110
N_2O	30 mg/MJ		–	–
SO_2	120 mg/MJ	102–157	180 mg/MJ	120–400
dust	16.5 mg/MJ		20 mg/MJ	10–60
As	10 μg/MJ	2–24	–	–
Cd	0.5 μg/MJ	0.07–1.5	0.02 mg/MJ	0.02–0.06
Hg	0.01 μg/MJ	0.001–0.03	0.1 mg/MJ	0.06–0.3
Pb	15 μg/MJ	2–51	0.1 mg/MJ	0.1–0.2

(Hokkanen & Salminen, 1997)

Table 3 shows the emission factors for RDF incineration. The values are compared with the incineration of peat.

Figure 4: Scheme of the scenario mechanical-biological treatment & RDF production



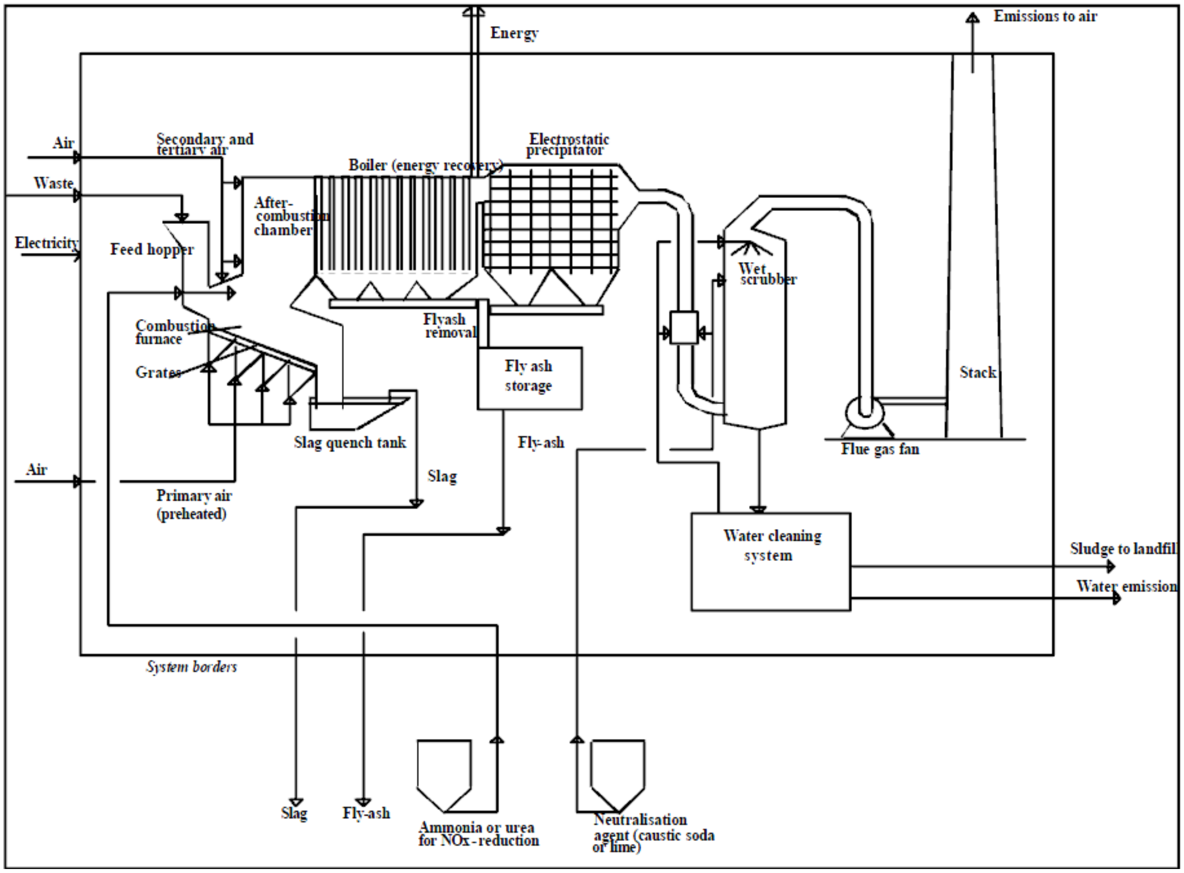
(Cherubini, et al., 2009)

Figure 5 schematically illustrates the design of a waste incineration plant. The considered technical solution assumes electricity as the only useful output of RDF incineration; however, in cases where a local demand is present, it is possible to produce either heat or a simultaneous mix of both heat and electricity.

In general, an incineration plant creates ash from a burning process and hazardous products of the flue gas filtering process which need to be transported to a landfill. These residues are considered to be stabilized wastes, in the sense that they cannot produce methane or carbon dioxide emissions. Nonetheless, these products are toxic and cause a high concentration of heavy metals in leachate.

In scenario three, electricity is produced by direct incineration of waste with 27% efficiency. The lower heating value of non-differentiated waste is estimated to be 8.85 MJ/kg. This option is associated with 80% waste mass reduction.

Figure 5: A sample scheme of a waste incineration plant (scenario 3)



(Sunqvist, 1999)

Cherubini et al. (2009) have concluded that there is a conflict between local and global environmental objectives. The landfill option leads to lower quantities of local emissions and higher quantities of CH_4 and H_2S, whereas scenarios two and three (waste separation and direct incineration) cause more local emissions due to the combustion steps.

Tables 4 and 5 show the quantitative results for local and global pollution impact in the case of each of the four waste treatment options. The authors have also generalized the results by stating that the landfill options (scenarios zero and one) cause higher environmental impacts, whereas "a sorting plant coupled with electricity and biogas production (scenario two) is very likely to be the best option for waste management, despite the non-negligible problem of local emissions (NO_x, PM10, heavy metals, Polyciclic Aromatic Hydrocarbons (PAH), among others)". The authors have also indicated that significant environmental benefits are achieved through higher energy recovery measures. (Cherubini, et al., 2009)

The gross values in table 5 refer to effective emissions released in each of the scenarios; by comparison, the net values show the total environmental impact, which is determined as a difference between the effective emissions and the emissions avoided through energy production. The calculation of the avoided emissions heavily depends on the degree of the success of the energy generation options. For instance, if electricity is produced by nuclear or hydro-electric power plants, the calculated avoided emissions would be close to zero. Alternatively, if one considers energy production from coal, the calculated environmental benefits of energy generation from waste would be very large. The authors of the discussed study have used the values for avoided emissions which were based on the analysis of Italian power grid.

Apart from this, one can also calculate avoided energy and resource consumption for the recycled materials that substitute virgin materials.

Table 4: Impact categories of the considered scenarios (global scale)

Scenario	GWP, kt CO_2	AP, t SO_2	EP, t NO_3	Dioxins, g TCDD
Scenario 0				
Gross	1914	546	126	0.24
Net				
Scenario 1				
Gross	966	338	126	0.35
Net	868	186	126	0.29
Scenario 2				
Gross	704	852	n.a.[a]	0.25
Net	−340	−441	n.a.[a]	−0.28
Scenario 3				
Gross	948	1902	n.a.[a]	1.38
Net	224	780	n.a.[a]	0.92

[a] For these scenarios landfilled wastes are without a significant organic content.

(Cherubini, et al., 2009)

The functional unit in this research was defined as the 1460 Kton of waste produced in Rome in 2003 (Cherubini, et al., 2009); therefore, one should divide the values from the tables 4 and 5 by 1.46E+06 in order to obtain the average per ton estimates.

As a critical remark to this approach, it should be mentioned that even though the environmental impact can be assessed for different scenarios by using one functional unit, the general economic evaluation should take into account the lifetime of equipment and the associated costs in each of the scenarios.

Table 5: Comparison of airborne emissions in g (local scale)

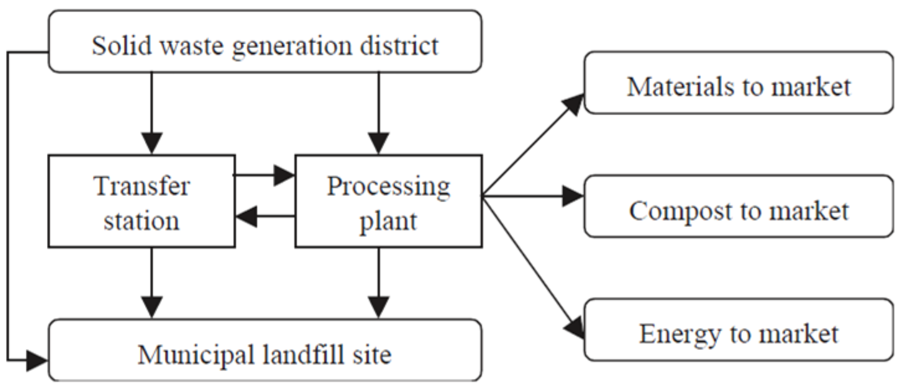
Species (g)	Scenario 0	Scenario 1	Scenario 2	Scenario 3
CO_2	3.15E+11	3.95E+11	6.51E+11	1.44E+12
CO	1.60E+08	7.38E+07	3.92E+07	2.11E+09
NO_x	2.45E+07	6.27E+07	5.43E+08	1.09E+09
PM10	1.13E+05	5.02E+05	7.83E+06	2.60E+07
SO_2	1.13E+08	1.14E+08	3.13E+07	8.10E+08
CH_4	7.55E+10	3.78E+10	1.30E+05	2.01E+04
N_2O	n.a.	5.27E+03	2.35E+07	1.17E+08
HCl	4.80E+07	2.75E+07	2.74E+07	1.61E+08
HF	4.58E+06	8.10E+05	2.74E+06	n.a.
H_2S	1.60E+08	8.02E+07	n.a.	n.a.
Hg	2.81E+01	2.81E+01	3.92E+04	1.46E+06
Pb	5.54E+02	5.54E+02	3.88E+05	7.81E+04
Cd	3.51E+00	3.51E+00	3.92E+04	4.81E+05
Cu	3.53E+02	3.53E+02	n.a.	4.81E+04
Zn	9.07E+02	9.07E+02	n.a.	1.24E+05
Ni	3.87E+01	3.87E+01	n.a.	4.90E+03
Cr	1.00E+02	1.00E+02	n.a.	1.31E+04
TCDDeq	0.24	0.35	0.19	1.38
PAH	1.01E+02	1.01E+02	n.a.	1.38E+04

(Cherubini, et al., 2009)

5 BASIC SETUP

Figure 6 shows a general structure of a SWM problem. In contrast to Cheng et al. (2003) the present model does not explicitly allow for multi-step processing, which means that the transfer stations are not modeled.

Figure 6: General structure of a waste management system



(Cheng, et al., 2003)

The model is supposed to answer the following questions:

- In which of the potential locations should the waste treatment facilities be built?
- Which technological solution should be chosen for each location?
- When should the waste treatment facilities be built?
- What capacity should be installed in each case?
- What quantity of waste should be treated in each period in the locations, and from where does it have to be delivered?

Obviously, each of the above-stated questions is not new and has been elaborated in classical literature; whereas, the developed model is novel due to its capability of answering all these interconnected questions in relation to the specific waste management problem. For example, the ware-house location problem has been considered by Baumol & Wolfe (1958), the capacitated plant-location problem by Sa (1969); whereas Sridharan (1995) has reviewed various methods for solving the capacitated plant location problem. The problem of the optimal technology choice has been considered, among others, by Cohen & Halperin (1986); whereas the paper by Wickart & Madlener (2007) can be mentioned as an example of a model dealing with the optimal technology and investment timing choices in energy sector.

The downside of the model proposed in this thesis is that it doesn’t take into account any existing waste treatment facilities - ideally, it should be applied to a region where modern waste management technologies have not been implemented yet. The model does not explicitly allow for optimizing multi-step technological processes, which means that if there are two treatment steps with two technological options per step, there can be four different combinations, each of which has to be considered as an independent technological solution. Aside from that, the model does not allow for the execution of sequential treatment steps in different locations. All the above-described limitations can be considered as possible topics for further research.

The major computational complexity can be avoided by comparing technologies before inserting their quantitative values into the model, which means excluding the options which result in higher cost and higher environmental damage under any conditions.

Following the idea mentioned by Chapman & Yakowitz (1984) and subsequently cited by Chang et al. (2012), and Emery et al. (2007) the present paper proposes a model which allows for economies of scale. The model develops a framework for incorporating economies of scale factor into decision-making process, but does not provide any specific functional forms or coefficients for different technologies, as this information has not been detected despite extensive research conducted by the author.

Aside from the above-mentioned technological choice, the model has to take into account module structure of the waste treatment facilities. The fact that the range of technically feasible module capacities varies for different technologies also has to be modeled. Moreover, the costs associated with each module can have a non-linear relation to the module size.

The restriction that heat can only be consumed locally makes it necessary to take local demand into account.

Different waste treatment processes yield different outputs, including the proportions of various hazards that have to be stored at landfills. As a result, a requirement for storage of waste produced by treatment processes should be reflected in the model.

When considering a waste management optimization problem, the question of methodology is essential. One possible approach is to maximize the NPV. The second possibility is to minimize environmental damage, which yields a third option of finding a compromise between the two criteria. Although this choice is an arbitrary decision which should reflect planner's priorities, there are few simple arguments that can apply.

First of all, the cost minimization approach (in its strict understanding) implies doing nothing in the case where revenues do not cover costs. Second of all, the whole topic of environmental management is based on the idea that we should take the impact of human activities on nature into account. However, the economic feasibility (or expediency) can act as a hard constraint for the implementation concerning even socially-significant projects; it therefore seems reasonable to assume that the most realistic approach should take into account both costs and environmental damage. In general, it is quite common to consider different scenarios which emphasize different objectives. In fact, Xi et al. (2010) have discussed three scenarios, one of which was based on a current situation, the second one on a mix of the current practices with the long-term objectives, and the third one exclusively on long-term objectives.

The next question which arises relates to finding a correct method for minimizing costs and damage together. The choice should be made between incorporating both terms in one objective function, which requires expressing damage in monetary terms, and multi-objective optimization, which, as it has been mentioned in the literature review part, allows for goal prioritization. The first option is preferable due to reduced mathematical complexity comparing to multi-objective optimization, but it opens up the question of quantifying environmental damage in monetary terms. Unfortunately, this cannot be answered unambiguously, since there exist multiple valuation methods, none of which stands out as superior. This thesis does not have an aim of finding the one and the only correct valuation method, but includes a short review of available options and proposes using certain environmental indicators mostly on the grounds of computational convenience.

Following Chang & Wang (1997) and several other authors, the “objective function for cost minimization is formulated for calculating the discounted cash flow of all quantifiable system benefits and costs over time”. The factors of noise and traffic congestion mentioned by Chang & Wang (1997) were not considered in the present paper.

The model does not handle any uncertainties. Nevertheless this disadvantage can be fixed by using a proper waste generation forecast and choosing potential locations for the treatment plants that are associated with acceptable levels of risks.

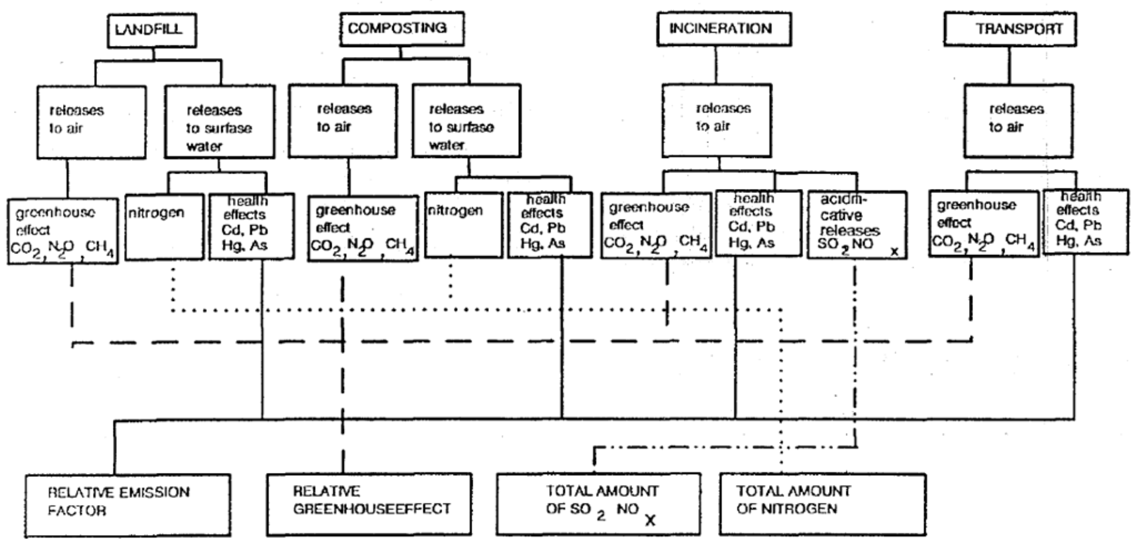
On the other hand, the developed model can be easily converted into an interval mathematical programming model (IMP) or interval linear programming (ILP), following the examples presented by Xi et al. (2010), Cheng et al. (2003), and Xu et al. (2010), by substituting some parameters with intervals. As it has been mentioned by Xu et al. (2010) “the ILP can be transformed into two deterministic sub-models, which correspond to upper and lower bounds of the desired objective-function value”. “Then these two sub-models can be solved as simple linear programming functions and the result can be combined together” (Cheng, et al., 2003). Among other benefits, the ILP method notably does not lead to complicated intermediate models and does not require distributional information, which makes it very attractive for practical applications (Xu, et al., 2010).

In contrast to the claim by Chang & Wang (1997) that “due to the impreciseness of the decision maker's preferences associated with each goal, a conventional deterministic goal programming model cannot fully reflect such complexity”, the present paper develops a model in which the decision maker’s preferences do not have to be explicitly taken into account, because all the objectives are expressed in monetary terms and combined into one objective function. In order to be more precise, it should be mentioned that the decision maker’s preferences are in fact used at the weighting step of the damage coefficients calculation, conducted under such LCA methods as EPS2000 or Eco-Indicators’99 (will be discussed in the following chapters). Although it cannot be argued that the proposed approach reflects all the complexities, it considerably simplifies the model without losing the essence of the problem.

6 ENVIRONMENTAL DAMAGE ASSESSMENT

Figure 7 depicts the major pollutants released by the waste management activities. It also gives a brief overview of the affected compartments (where the emission occurs) and impacted categories for each pollutant.

Figure 7: Environmental effects of waste management activities



(Hokkanen & Salminen, 1997)

For the purpose of planning an optimal waste management system, one should be able to quantify the environmental damage created by unmanaged landfills, modern landfills, transportation, and any considered waste treatment processes. In general, one should distinguish between local and global pollution and study their effects on people and nature. Some of the effects can be immediate, whereas others might be observed after a certain delay. Given the inherent complexity of the problem (Chang, et al., 2012) it is quite clear that finding some unified measures for all above-mentioned effects would greatly simplify the analysis. This task has been accomplished by deriving environmental sustainability indicators (ESIs) (Harger & Meyer, 1996). The examples of ESIs used are the Global Warming Potential (GWP), stratospheric Ozone Depletion Potential and other indicators discussed in the next subchapter.

6.1 Damage coefficients

The Life Cycle Assessment (LCA) methodology recommended by ISO considers several impact categories, the classification of which varies in specific calculations. Nevertheless, a general definition of the following categories can be proposed:

- abiotic resources
- biotic resources
- land use
- global warming
- stratospheric ozone depletion
- ecotoxicological impacts
- human toxicological impacts
- photochemical oxidant formation
- acidification
- eutrophication
- work environment

(European Environmental Agency, 1997)

Global warming, also known as greenhouse effect, is the effect of an increase in the temperature of the lower atmosphere to above-normal levels, due to reflection of the solar radiation reflected by the soil back to the earth by “greenhouse” gasses (carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (NO_2), chlorofluorocarbons etc.) (European Environmental Agency, 1997) The table with global warming potentials (GWP) can be found from the research of the European Environmental Agency (1997).

A depletion of the stratospheric ozone layer increases the amount of incoming solar radiation, which in turn can cause skin cancer, cataracts, a decrease in the immune defense of people and noticeable negative externalities on natural organisms and ecosystems (European Environmental Agency, 1997). The table with ozone depletion potentials (ODP) can be found through the European Environmental Agency (1997).

Ecotoxicological impacts and human toxicological impacts depend on exposures to chemical and biological substances. The potential effect on ecosystems and humans depends on the actual emission and fate of the specific substances emitted to the environment. Consequently, it is rather difficult to make a quantitative assessment of this impact category. (European Environmental Agency, 1997)

The photochemical ozone formation can be quantified by using photochemical ozone creation potentials (POCP) for the organic compounds which again can be found through the European Environmental Agency. In essence, the effect can be described as the degradation of organic compounds in the presence of light and nitrogen oxide, which cause the formation of smog and tropospheric ozone. These are harmful to the health of both humans and plants. (European Environmental Agency, 1997)

Acidification is caused by release of protons and causes damage to forests and the wildlife which inhabit them. Additionally, any organisms living in aquatic ecosystems can be adversely affected. Buildings, constructions, sculptures, and other objects can be also damaged by the acid rain. (European Environmental Agency, 1997, pp. 87,90)

“Eutrophication can be defined as the enrichment of aquatic ecosystems with nutrients, leading to increased production of plankton algae and higher aquatic plants. These in turn lead to deterioration in water quality and a reduction in the value of the utilization of the aquatic ecosystem.” The consequent effect of dead organic materials decomposition can be described as decreasing oxygen saturation and the creation of anaerobic conditions which may subsequently lead to a number of other unfavorable consequences. (European Environmental Agency, 1997)

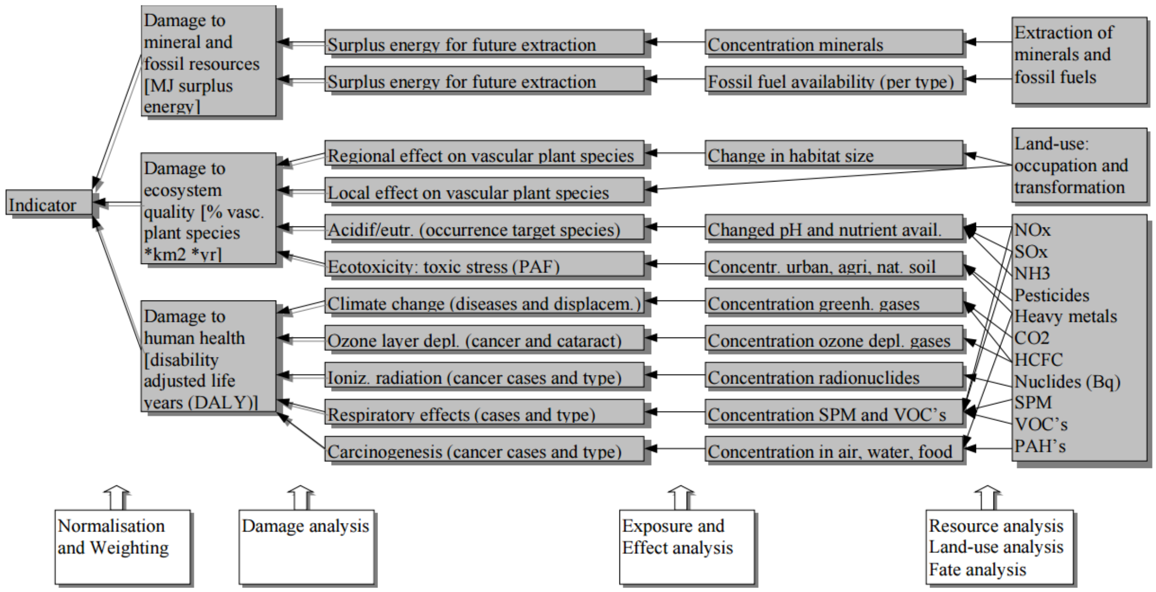
The work environment category describes the impacts on humans on a scale limited to walls of a factory. Besides the toxicological effects it includes impacts of heat, noise, and monotonous working conditions. (European Environmental Agency, 1997)

An extensive and up-to-date report on existing environmental damage valuation methods, which aggregate the effects on the above-described impact categories according to life cycle assessment (LCA) approach, has been recently purposed by Hischier et al. (2010). The present paper considers two methods - Eco-indicators'99 and EPS2000, which were selected by the author due to computational convenience.

Eco-indicators'99 offers a list of damage indicators for a diverse list of substances expressed in unified units (points). A factor for conversion into monetary terms is calculated further in the paper, which differs from EPS indicators as they are already calculated in Euros. This added convenience means that, by expressing damage coefficients for substances with different effects on various categories of objects in common units, one damage function can be written instead of many. The benefit of this is that these units can now be expressed in monetary terms and allow for the incorporation of environmental damage into one objective function, together with costs and revenues.

The values for the EPS2000 indicators can be found in Chalmers (n.d.). Eco-indicators'99 for production processes can be found in the addendum of the Manual for Designers (PRé, 2000). A list of Eco-indicators'99 can also be found on the above-mentioned Chalmers website. The full and up-to-date list of indicators, including the indicators for emissions to different compartments, for both methods can be found in “SimaPro”, a software package used for LCA.

Figure 8: Eco-Indicators'99 methodology



(Goedkoop & Spriensma, 2001)

Eco-indicators'99 calculate environmental damage on a European scale for most cases, whereas damage from substances such as GHGs, ozone-depleting gases, and radioactive elements is estimated on a world-wide basis (PRé, 2000). The absence of damage factors for emissions of nutrients and acids into water and soil constitutes as the major disadvantage of the Eco-indicators 99 report. The report states that damage factors for air can be used as a temporary substitution. (Hischier, et al., 2010)

Table 6: Normalization and weighting factors for the three perspectives and three impact categories

	Hierachist (EI'99 H/A)		Egalitarian (EI'99 E/E)		Individualist (EI'99 I/I)	
	Normalisation	Weights	Normalisation	Weights	Normalisation	Weights
Human Health	0.0154 DALYs(0,0)	40%	0.0155 DALYs(0,0)	30%	0.00825 DALYs(0,1)	55%
Ecosystem Quality	5130 PDF*m2*a	40%	5130 PDF*m2*a	50%	4510 PDF*m2*a	25%
Resources	8410 MJ	20%	5940 MJ	20%	150 MJ	20%

(Hischier, et al., 2010)

Eco-indicators'99 are expressed in "points", which are calculated as a weighted sum of normalized scores for three categories: Human Health, Ecosystem Quality, and Resources (Hischier, et al., 2010). According to the Eco-indicators'99 methodology, the initial "points" are multiplied by 1000; therefore, the notation mPt (millipoints) would be mathematically correct (Hischier, et al., 2010). One can recalculate the indicators in terms of DALYs, by dividing points by the normalization factor for Human Health category (0.0154 for the Hierarchist perspective – see table 6). Due to the fact that one DALY represents a loss of one year of healthy life (Goedkoop & Spriensma, 2001) one can express the indicators in monetary terms by using the concept of "Value of Statistical Life" (VSL).

A detailed description of the VSL concept can be found in many sources, for example in (Viscusi, 1998). Viscusi & Aldy (2002) published a review of more than 60 VSL studies and Miller (2000) has calculated the VSL for a large list of countries (in which VSL studies were not conducted) by using the regression analysis. For instance, Miller (2000) has found that the best estimate for the average value of statistical life in EU was 2730 thousands of 1995 US dollars. The recent publication by Lindhjem et al. (2012) proposes that the average VSL for OECD countries lies in a range between $1.5 million and $4.5 million, with a base value of $3 million, whereas for EU-27, the corresponding range is between $1.8 million and $5.4 million, with a base value of $3.6 million (in 2005 US dollars). According to the Bureau of Labor Statistics (2013) $3.6 million in 2005 USD is equivalent to $4.3 million in 2013, which is approximately 3.3 million EUR (Google, 2013).

Taken all the above mentioned considerations, we can calculate the conversion factor for Eco-Indicators'99 as $VSL/(1000 \times DALY\_normalization\_factor \times life\_expectancy)$, which is equal to $3{,}300{,}000/(1000 * 0.0154 * 79.7) = 2689$ EUR/mPt In case we take an average life expectancy at birth in the EU-27 which equaled to 79.7 years in 2009 (Eurostat, 2013).

The EPS default method considers the average impact of emissions on a global scale. It is sensible to recalculate the indicators for every considered location, which allow for an increase in the precession to a more significant degree. (Steen, 2000)

According to the EPS methodology, the categories are weighted with the willingness to pay "to restore impacts on the safeguard subjects, as measured amongst today's OECD inhabitants." (Steen, 2000)

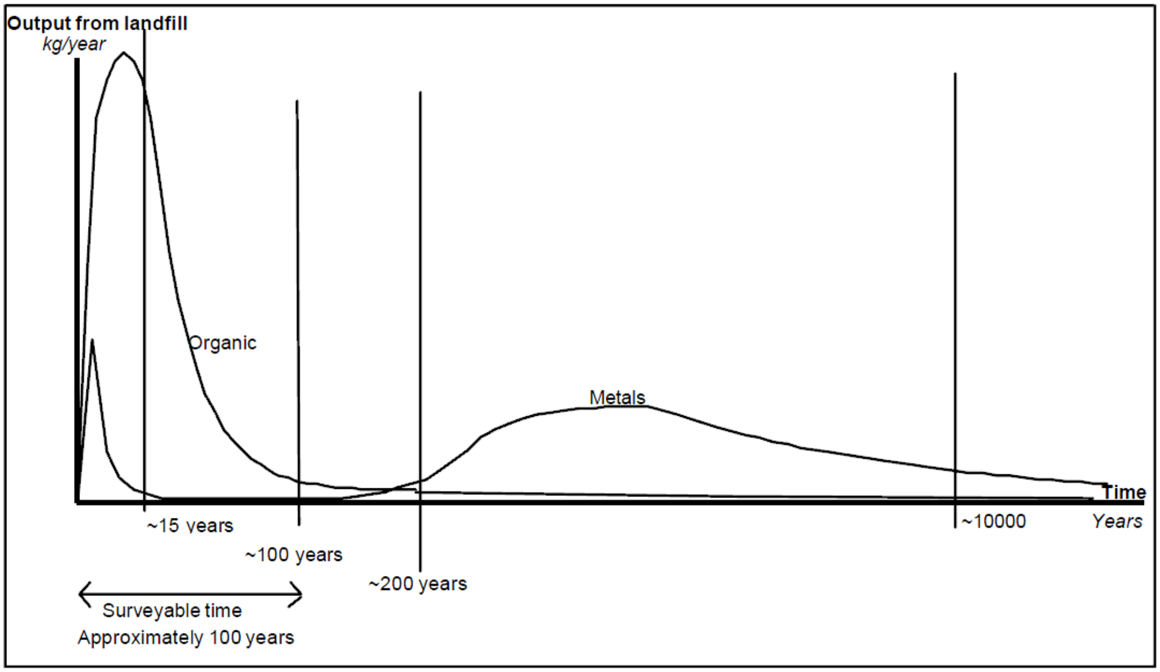
EPS employs a Contingent Valuation Method (CVM), which is based on interviews and follows a special procedure for the estimation of non-market environmental values. “In the EPS-system the CVM technique is used for category indicators of morbidity and nuisance and for recreation values.” It has been found that neither the market nor individuals were able to reflect the willingness to pay (WTP) for the preservation of the category “abiotic stock resources”, because it is mostly a concern of the future generations. As a result, the authors of the method have created a market scenario in which production costs of substances similar to the abiotic natural resources are used instead of WTP. (Steen, 2000)

The results of the EPS indicators calculations are expressed in ELU (Environmental Load Unit), where 1 ELU=1 EUR (Steen, n.d.), making the indicators especially convenient for the practical application. The main problem of the EPS indicators is that it has been calculated for an extremely incomplete list of substances.

6.2 Damage from Landfills

A landfill cannot be considered an isolated system; instead, it should be viewed as a chemical reactor which stays active for thousands of years, the outbound products of which are inevitably being transferred to the environment. (Cherubini, et al., 2009)

Figure 9: Emissions from landfills in a long-term perspective



(Sunqvist, 1999)

Sunqvist (1999) has reported that emissions from ash landfills, metal hydroxide sludge landfills and mine tailings, were particularly small during the surveyable period of about 100 years, in comparison with the hypothetical infinite period. It was therefore proposed to introduce a critical time period, which should be the period during which the major emissions occur, to solve this inherent problem.

Moreover, Obersteiner et al. (2007) argues that the installed barriers such as sealing sheets deteriorate in time, which leads to the release of the remaining pollutants but at a later point in time. This consideration leads to an idea that the landfills should be monitored for a longer period and that not only unmanaged landfills, but even modern sanitary landfills, do not constitute a sustainable solution.

Although the emissions during the surveyable period obviously underestimate total emissions, they still can be used as a good approximation for practical applications until the more precise information for a longer period is available. The Society of Environmental Toxicology and Chemistry (SETAC) recommends, as it has been cited by Obersteiner et al. (2007), that the emissions from landfills should be integrated over an infinite period or over a period of 100 years if the first option is not implementable.

Table 7: Waste composition, according to Pennsylvania's Department of Environmental Protection in 2004

Generated Items	Category		Composition, mass fraction (%)
Paper	Corrugated	(13%)	
	Newsprint	(75%)	35
	Mixed	(12%)	
Yard Trimmings			10
Food Scraps			15
Plastics			12
Metals	Aluminum	(60%)	
			5
	Steel Cans	(40%)	
Rubber, Leather, Textiles			7
Glass	Clear	(30%)	
			5
	Mixed	(70%)	
Wood			7
Other			4
Total			100

(Chang, et al., 2012)

The landfills composition varies between regions and even between the landfills in one region, not to mention the variations in time. For instance, Xi et al. (2010) have reported that the averaged composition of the landfills in Beijing in 2010 included 59.25% of organic materials, 9.44% of paper, 9.74% of plastic, 3.81% of glass, 1.10% of metal, 0.83% of tile, 2.45% of textile, 6.58% of wood, and 6.8% of ash.

Lave et al. (1999), citing the book "'Rubbish! The archeology of garbage" published in 1992, have stated that the averaged composition of landfill mass deposited in the 1980s in the US "was roughly 40% paper, 8% organics, 8% plastic, 11% metal, 6% glass, 12% construction/demolition waste, and 15% additional, unclassified waste". Tables 7 and 8 show the composition of waste according to Pennsylvania's Department of Environmental Protection and the composition of waste in Wales in 2000 respectively. In each case, not only did the composition vary, but also the applied classification, therefore it is essential to have a reliable analysis of the waste composition when solving practical problems.

Table 8: Composition of waste in 2000 in Wales

Material	Percentage
Ferrous metals	4
Fines	6
Glass	7
Miscellaneous combustibles	5
Miscellaneous non-combustibles	6
Non-ferrous metals	1
Paper (total)/recyclable element	25
Plastic dense	6
Plastic film	4
Putrescibles (green waste)	32
Textiles	4
Total	100

(Emery, et al., 2007)

The emissions from landfills can be classified by two types: leachate, which contains heavy metals, toxins, and organic compounds; and gaseous emissions, which contain CH_4, hydrocarbons, halogenated hydrocarbons, SO_2 and NO_x. The exact composition, intensity, and duration of these emissions depend on the landfill design, waste composition, and location of the landfill. (Obersteiner, et al., 2007)

Table 9 lists the landfill types which are currently used or were formerly used in Europe, Austria, Germany, and Switzerland. Open dump is a type of landfill which is addressed in the present paper and is considered to be the single landfill type in many countries currently available. Therefore, if other is not specified, the notion of “damage from landfills” further mentioned later in the paper should be understood as the damage created by waste disposed at open dumps.

Table 9: Former and actual landfill types in EU, Austria, Germany, and Switzerland

EU	Austria	Germany	Switzerland	Explanation
Open dumps	Open dumps	Open dumps	Open dumps	Landfills for untreated municipal waste, without specific technical safety measures
Sanitary landfills	Sanitary landfills	Sanitary landfills	Sanitary landfills	Landfills for untreated municipal waste, with physical barriers to protect the public from waste
Landfills for hazardous waste	–	Landfill class III		Landfills for hazardous waste
Landfills for non-hazardous waste	Massenabfall-deponie	Landfill class II	–	Landfills for MBT waste
	Reststoff-deponie	Landfill class I	Residual material landfills	Landfill for MSWI residues
Landfills for inert waste	Bodenaushub-deponie	Landfill class 0	Inert material landfills	Landfill for excavated earth
	Baurestmassen-deponie			Landfill for construction and demolition waste

(Obersteiner, et al., 2007)

Other mentioned landfill types can instead be attributed to the treatment options considered in the model, because only disposal at open dumps constitutes an absence of treatment.

The present research uses the paper by Obersteiner et al. (2007) as the main source of information about the landfills as it has been found to be one of the most recent, comprehensive, and clear reviews on this topic. Therefore, the model assumptions used by the authors are cited in the table 10. An alternative extensive research on leachate composition with a subdivision for young, medium age, and old landfills, can be found in Renou et al. (2008). Unfortunately, the latter does not contain explicit definitions of these terms.

Table 10: Summary of assumptions for the landfills models

	Open dump	Sanitary landfill	MBT-landfill	MSWI-landfill
Annual landfill rate (t)	242,958/104,483[a]	104,483	29,315	26,762
Average landfill height	10 m			
Bulk density	1 ton/m^3	1 ton/m^3	1.4 ton/m^3	1.5 ton/m^3
Bottom layer	No	State of the art	State of the art	State of the art
Cover layer	No	Methane oxidation layer	Methane oxidation layer	Recultivation layer
Operation period (I)	5 years			
Active aftercare period (II)	30 years			
Modelling period (III)	100 years			
Landfill gas potential	120 m^3/ton FM	120 m^3/ton FM	15.6 m^3/ton FM	–
Period I	22%	22%	30%	
Period II	75%	75%	60%	
Period III	3%	3%	10%	
Active landfill gas collection				
Period I	No	No	No	
Period II		45%		
Period III		No		
Methane oxidation rate (Periods II and III)	No	90%	90%	–
Average annual rainfall	1300 mm	1300 mm	1300 mm	1300 mm
Amount of leachate [% of rainfall]				
Period I	50%	50%	50%	65%
Period II	50%	30%	5%/30%[a]	30%
Period III	50%	30%	5%/30%[a]	30%
Leachate treatment				
Period I	No	B-MF-RO	RO	PF-AC-Ox
Period II		B-MF-RO	RO	PF-AC-Ox
Period III		No (impermeability of bottom layer uncertain)		

B-MF-RO: Biological treatment, MicroFiltration, Reverse Osmosis.
PF-AC-Ox: Precipitation/Flocculation, Activated Carbon filter, Oxidation.
[a] Two variations considered.

(Obersteiner, et al., 2007)

Appendix II includes six tables from (Obersteiner, et al., 2007) which provide the data on gaseous and liquid emissions from different types of landfills during the three considered periods, accounting for 100 years in total. Combining this data with the previously discussed damage coefficients, such as Eco-Indicators'99 or EPS2000, allow for the construction of a damage function for the landfills. The necessary approximations and transformations are mentioned in the next paragraphs, whereas the Excel spreadsheet provides the calculations which can be downloaded via this link

https://docs.google.com/file/d/0B0J-JwC4EVi5VWczc3RmSWEtcGc/edit?usp=sharing

Whilst the data for gaseous emissions can be used directly, the concentrations of contaminants in leachate need to be recalculated in terms of emissions per one ton of waste.

As mentioned in table 10, an average annual rainfall is assumed to be 1300 mm, and the amount of leachate is equal to 50% of the rainfall. Taking the assumption of 1 ton/m^3 density of waste and the assumed landfill height of 10m, we can assume that the concentration of the pollutant that can be reached in leachate that permeates one cubic meter (or one ton) of waste is 10 times less than the original value. We can approximate the amount of leachate that goes through one ton of waste with $1.3\, m^3 * 1000\, \frac{liters}{m^3} * (50\%\, of\ rainfall)/(10\, m) = 65\, \frac{liters}{m^3}$. The concentrations of pollutants in leachate are measured in g/l, and following our approximation can be converted to kilograms of pollutant per ton of waste by multiplying the values by a coefficient equal to 0.065.

Therefore, the damage function for MSW can be written as following:

$$D(t) = \begin{bmatrix} \sum_{x=1}^{n} \tau_x^I \cdot d_x \_\_ for \_\_ 1 \le t \le 5 \\ \sum_{x=1}^{n} \tau_x^{II} \cdot d_x \_\_ for \_\_ 6 \le t \le 30 \\ \sum_{x=1}^{n} \tau_x^{III} \cdot d_x \_\_ for \_\_ 31 \le t \le 100 \end{bmatrix}$$

Where τ_x^I is an amount of contaminant x released from one ton of MSW during the first period, and d_x is a damage coefficient for contaminant x.

Hence, the total potential damage from MSW can be calculated as

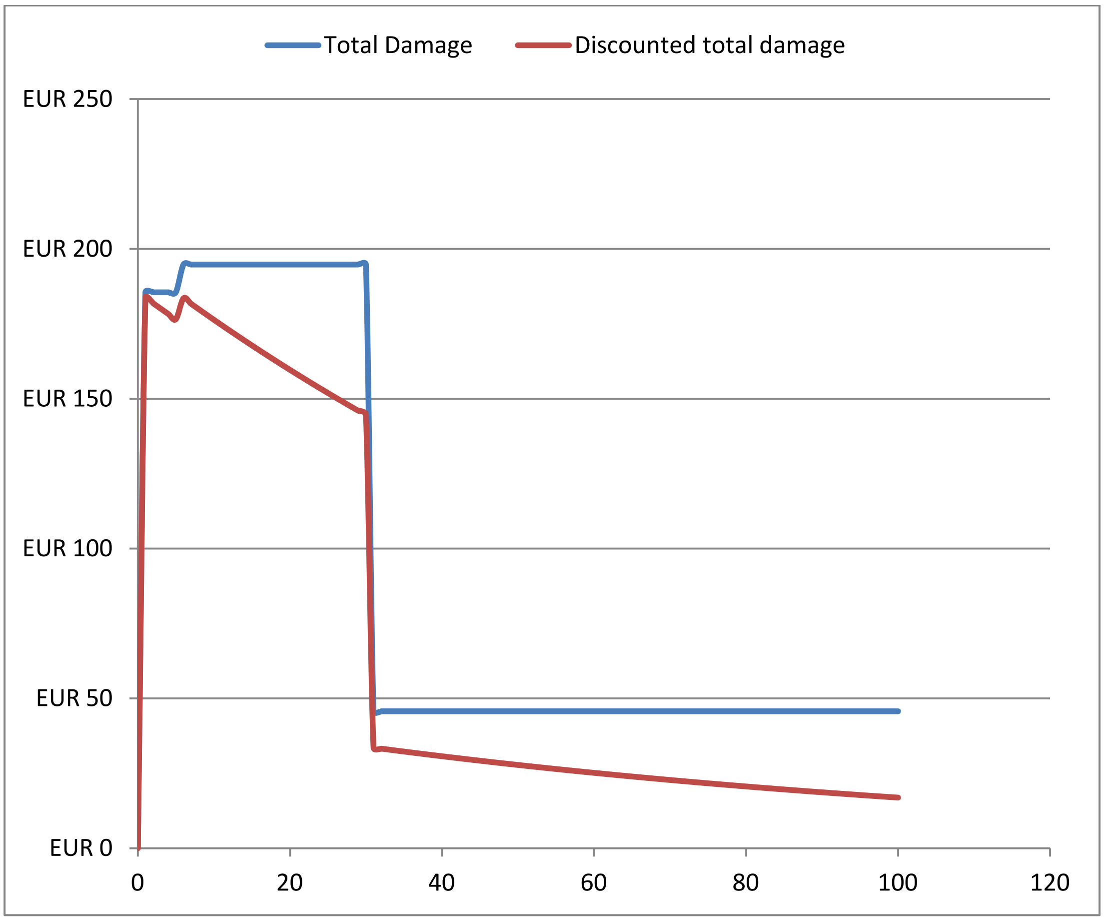
$$\int_0^{100} D(t)dt \approx 5 \cdot \sum_{x=1}^{n} \tau_x^I \cdot d_x + 25 \cdot \sum_{x=1}^{n} \tau_x^{II} \cdot d_x + 70 \cdot \sum_{x=1}^{n} \tau_x^{III} \cdot d_x$$

A rough calculation of the environmental damage caused by the MSW stored in an open dump using the available incomplete list of EPS indicators is shown below. In some cases, these missing indicators were substituted by the indicators for the different compartments, and in some cases omitted. The following function expresses damage in Euros and is normalized for one ton of waste (see appendix III for more details):

$$D(t) = \begin{bmatrix} 186\_\_ \; for \; \_\_ 1 \le t \le 5 \\ 195\_\_ \; for \; \_\_ 6 \le t \le 30 \\ 46\_\_ \; for \; \_\_ 31 \le t \le 100 \end{bmatrix}$$

$\sum_{t=0}^{100} D(t) \cdot (1+r)^{-t} = 6683$ EUR, where $r = 1\%$

Figure 10: Damage function for 1 ton of MSW, EPS2000



(Own figure)

A further question relating to the valuation of environmental damage from landfills is whether only active chemical components create damage, or if such inert materials like glass and plastic, that can stay unchanged for hundreds of years, should be counted. The author's personal point of view is that this factor should be counted at least in a form of foregone profits from renting out or selling the land occupied by landfills.

7 PLANNING HORIZON

7.1 Theoretical considerations

In many studies, as for instance in Xi et al. (2010), the time horizon is either determined arbitrarily or is chosen based on some legal or historical considerations. However in the present study a different approach is developed.

The considered problem can be decomposed into two parts: treatment of a continuously generated flow of waste from the cities and treatment of the already existent unmanaged landfills. Planning of the first part should be based on a forecast of waste generation, which can be calculated by using conventional statistical techniques. Therefore, a time horizon for this problem is constrained only by the forecasting period.

Despite this, if we analyze the second part of the problem, it becomes obvious that the planning horizon depends on a speed with which the landfill waste is treated. In case we agree with the statement that landfills continuously cause environmental damage, we should decide how fast we want to eliminate this damage. In this situation, a tradeoff between speed of damage reduction and investment in treatment facilities is faced: the higher the initial investment, the faster the damage is reduced, and vice versa. Therefore, the planning horizon becomes a subject for optimization.

The model that is developed in the next chapter possesses a property of automatic selection of an optimal time of processing the landfill waste, based on the minimization of monetary and environmental costs. However, this feature only works correctly if the number of considered periods is large enough. Consequently, the optimal time of processing waste from landfills should be regarded as the minimal number of periods that should be considered in the optimization problem.

Taking into account the above discussed considerations, the rule for choosing a planning horizon for the joint problem can be formulated as following: the minimal number of periods for which the model is calculated should be equal to optimal time of landfill waste processing if it is larger than the lifetime of any considered plant types, or to the lifetime of the most long-living plant type otherwise.

The profit-maximizing conditions differ depending on a problem. First, we can consider a case with zero fixed costs, zero initial investment, and convex variable costs. In order to imagine this case, one can think of mercury leakage liquidation: there is a certain cost of gathering the main puddle, it costs more to gather the dispersed drops; whereas, the cost of identifying and capturing the mercury molecules is even higher. At the same time, the benefit of neutralizing each milligram of mercury in terms of avoided environmental and health damage is constant. In this case, the optimum can be found in the point where marginal cost equals marginal benefit.

In the second case we add fixed costs and initial investment, but the operating costs stay convex. Here we should also choose a degree of project realization that corresponds to the point where marginal costs equal to marginal benefit, but only if average total cost in this point is smaller than the marginal benefit. Otherwise, the project should not be implemented at all.

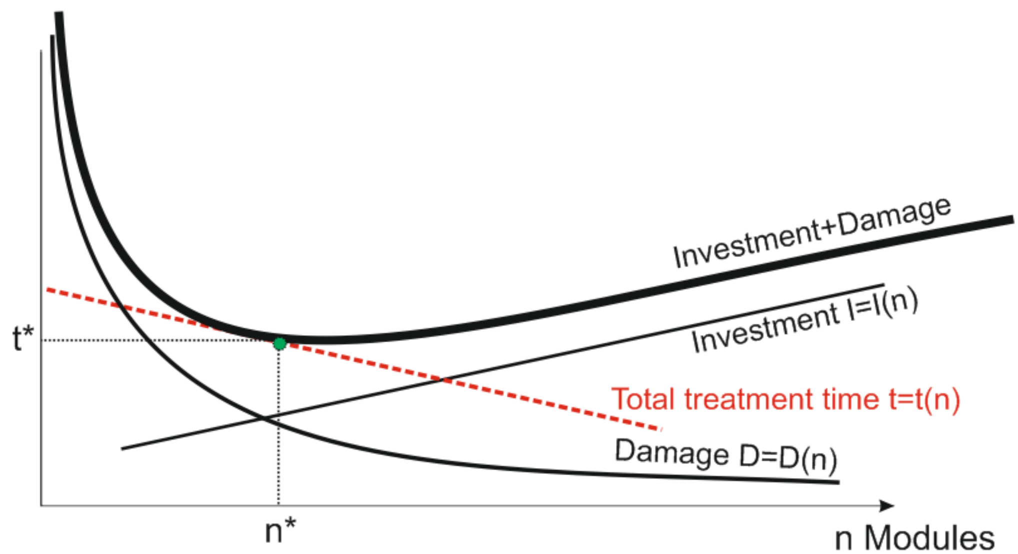
Finally, in the third case, when operating costs are concave or linear, the project should be realized to a maximal possible degree if average total cost in this limit point is smaller than marginal benefit. It is important to mention, that the cost can also be called marginal in a sense that it is the cost of the last produces unit, but the mathematical definition of marginal cost as a derivative with respect to quantity is not applicable here, because it would imply disregarding the fixed terms. An example of this problem would be a plant with high investment cost and linear variable costs. The profitability of the first produced unit is the same as of the last one, but the average total costs are falling down. In this example profit maximization is constrained by the equipment lifetime.

Coming back to our problem, the model that can be used is an adapted EOQ model (Trippi & Lewin, 1974) in which inventory holding costs are replaced with a monetary value of environmental damage. The model is designed for finding a very rough estimate of the optimal time horizon and falls into the second category of cases described above.

In order to solve this problem, it is suggested to use several simplifications, such as one waste treatment technology, unconstrained equipment lifetime, and a linear relation between the development costs and the built capacity.

The equation $\pi = A + U - (I + V + F)$ means that the profit is equal to the sum of an avoided environmental damage and a salable useful output from the treatment process less the sum of an investment, fixed and variable costs.

Figure 11: Optimal time horizon for the landfills treatment problem



(Own figure)

First of all, we define the variables:

- π [Euros] is a total profit over the whole planning horizon;
- W [tons] is a total amount of waste stored at landfills;
- D [Euros] is a total damage created by one ton of waste over infinite time horizon (or over the first 100 years);
- d [Euros] is a damage created by one ton of waste in one year, expressed in monetary terms. In cased d is expressed in some abstract damage units

it has to be converted into monetary terms, for instance by multiplication by a constant VSL/d_l, where VSL stands for value of statistical life (Viscusi, 1998) and d_l is such amount of damage, that has a potential of killing a statistical person. The weakness of this approach is that the local damage caused to nature and global atmospheric effects in this case are recalculated in terms of statistical lives, which is a problematic idea because it implies substitution between people and other objects of nature.

- n is a number of modules;
- l [tons/year] is a capacity of a module;
- $W/(nl)$ is a number of years needed for treating the total quantity of waste W with n modules of capacity l;
- An avoided damage A [Euros] is equal to $W\left(D-d_p-dW/2nl\right)$, where d_p is an environmental damage caused by processing one ton of waste and $W^2d/2nl$ is a damage created by landfills during the period of project implementation[3];
- $U=W(p^Tu)$ [Euros] is a useful output, where u is a vector of transformation coefficients (output vector), p is a price vector, and W is a scalar;
- $I=c\cdot n$ [Euros] is an investment, where c is cost of a module and n is a number of modules
- $V=W\cdot v$ [Euros] stands for variable costs, where v is a variable cost per ton treated;

[3] The factor of 2 in denominator reflects the assumption that the damage decreases linearly and equals to a half of the area of a rectangle, the sides of which are equal to a number of years that processing of the landfills waste will take and the damage that is yearly created by landfills before the project has started.

- $F = s \cdot n(W/nl) = sW/l$ [Euros] stands for fixed costs, where s is a fixed cost per module and per year, l is a capacity of a module, and $W/(nl)$ is again a number of years.

$$\pi = W\left(D - d_p - \frac{Wd}{2nl}\right) \cdot \frac{VSL}{d_l} + Wp^T u - cn - Wv - \frac{sW}{l}$$

Alternatively, one can consider the total cost function, minimization of which yields the same result as the profit maximization:

$TC = \frac{W^2 d}{2nl} \cdot \frac{VSL}{d_l} + cn + Wv + \frac{sW}{l}$, where $\frac{VSL}{d_l}$ is a constant only needed for a case when damage is expressed in some abstract units.

When omitting the optional constant (in case damage is already expressed in monetary terms), the first order condition can be written in the following form:

$$\frac{\partial TC}{\partial n} = -\frac{\partial \pi}{\partial n} = c - \frac{W^2 d}{2n^2 l} = 0$$

Solving the equation of the first order condition yields the number of modules and the corresponding time needed for the treatment of waste.

$$n^* = \sqrt{\frac{W^2 d}{2cl}}\ ;\ t^* = \frac{W}{n^* l} = \sqrt{\frac{2c}{ld}}$$

Following the approach described in the beginning of the chapter the next step that is necessary for determining if such measure should be implemented at all is checking if the profit is positive in the found optimal point:

$$\pi = W\left(D - d_p - \frac{Wd}{2n^* l}\right) \cdot \frac{VSL}{d_l} + Wp^T u - cn^* - Wv - \frac{sW}{l} \geq 0$$

Alternatively, we can check if marginal benefit is larger than average total cost:

$VSL \geq \dfrac{\left(cn^* + Wv + \dfrac{sW}{l} - p^T Wu\right)d_l}{W\left(D - d_p - \dfrac{Wd}{2n^* l}\right)}$, where $W\left(D - d_p - \dfrac{Wd}{2n^* l}\right)\Big/ d_l$ is a number of statistical lives saved[4].

7.2 Example

We now attempt to calculate an optimal landfill waste processing time using the above-developed methodology. Table 11 shows the data assumptions used for the sample calculations; whereas, the calculations can be found online:

https://drive.google.com/file/d/0B0J-JwC4EVi5UlNLYTNOVEwwQjQ/edit?usp=sharing

Table 11: Data for the time horizon calculation example

Parameter	Notation	Value	Value, EUR
Cost of module, USD 1991		110000000	84233000
Cost of module, USD 2012	c	289000000	221085000
Total waste inventory (landfills), tons	W	354000000	
Variable cost per ton (without damage), USD	v	68	52
Damage from one ton of waste per year, USD	d	60	46
Damage from one ton of waste (last 70 years), USD	D	4183	3200
Capacity of a module, tons/year	l	262800	
Revenue per ton treated, USD	$p * u$	0	0
Damage from 1 kg of CO2, ELU (USD)		1.44	1.1
Annual Greenhouse Gas Production, pounds of CO2		600000000	
Annual Greenhouse Gas Production, tons of CO2		272155	
GHG production per ton of waste, tons of CO2		1.04	
Environmental damage per ton treated, ELU (USD)	d_p	1491	1139
Fixed costs (in the present example are already included in variable costs per ton), USD	s	0	0
Damage that can kill one statistical life	d_l		3300000
Value of Statistical Life	VSL		3300000

(Own table, based on the sources mentioned in the next paragraph)

[4] The number of lives saved does not correspond to the number of people that can die from the negative environmental impact caused by landfills, but stands for a sum of smaller health damages which result in reduction of healthy life years by many individuals.

The value for W, 354 million tons of waste has been taken from the report "Landfill inventory for Russia" (The NP Ecological Resource Center, 2009) and corresponds to the amount of accumulated waste dumped at the registered landfills in Russia. According to the report the annual waste generation rate in Russia equals to 24.6 million of tons. In order to satisfy such demand, for example by using the technology described in the table 11, one should construct 94 modules. This number has been calculated for comparing the capacity needed for treating the currently generated waste with the capacity needed for processing the landfill waste.

In this example it is assumed that an average age of the landfills is equal to 30 years; therefore, the total avoided damage has been calculated as a sum of damages from year 31 to year 100, resulting in €3200 and an average yearly damage of €46.

The rest of the data from table 11 has been taken for the WtE facility, constructed in the city of Spokane in 1991 (Spokane Waste to Energy, 2010?). The sum invested in the plant in 1991 has been recalculated into current prices, yielding $289 million (MeasuringWorth, 2013). In the considered example the cost of treating one ton of waste includes a portion of fixed costs and also takes into account the value of salable output.

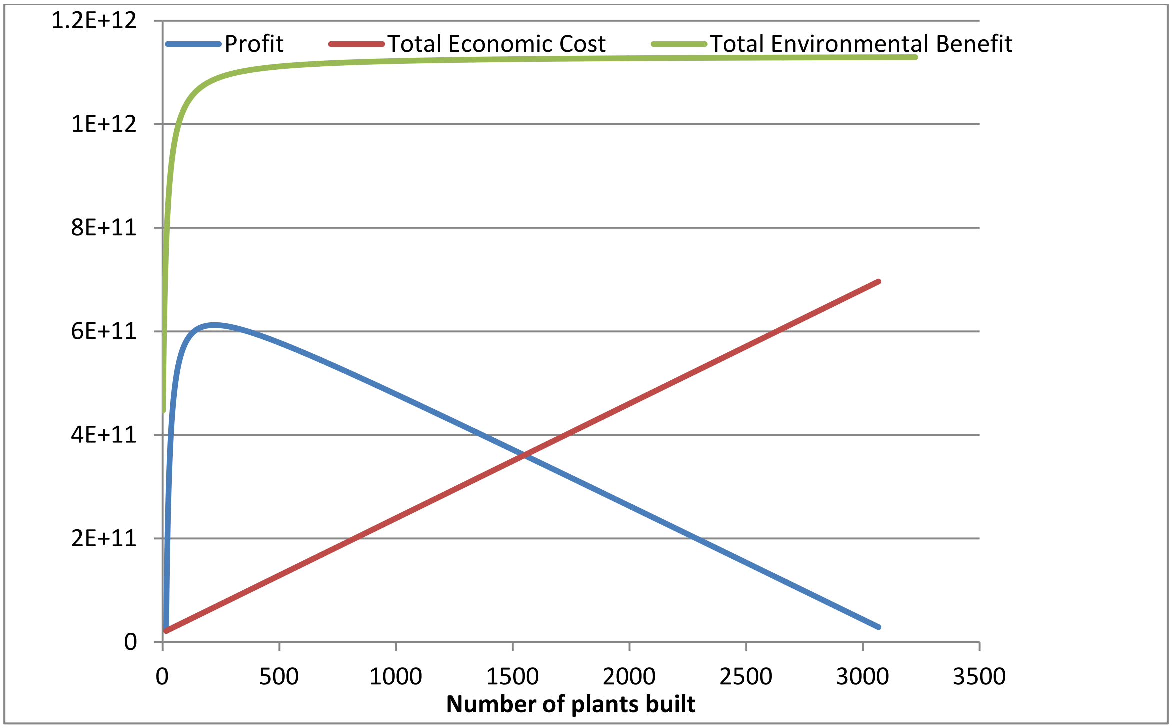
Due to the fact that environmental damage in the current example is already expressed in monetary terms the quantity of damage that kills one statistical person can be taken equal to the value of statistical life.

The calculations have shown that the optimal landfill waste processing period is equal to six years which corresponds to building 223 plants.

The measure passes the cost-benefit analysis by offering a positive profit that is equivalent to €612 billion.

The two graphs below illustrate the example and the found solution.

Figure 12: Costs, benefits and a profit in the considered example



(Own figure)

Figure 13: Benefits and costs in terms of statistical lives

(Own figure)

Figure 12 shows the graph of the total environmental benefit, which is calculated as $W\left(D-d_p-\frac{Wd}{2n^*l}\right)$ and that has a limit of $WD-Wd_p$ when the number of plants tends to infinity or the processing time tends to zero. The total economic cost is equal to $cn+Wv+\frac{sW}{l}-p^TWu$, which is a sum of an investment and operating costs corrected for monetary revenues from selling useful outputs of the treatment process. As it has been previously mentioned the profit equals to $\pi=W\left(D-d_p-\frac{Wd}{2n^*l}\right)\cdot\frac{VSL}{d_l}+Wp^Tu-cn^*-Wv-\frac{sW}{l}$, which is a difference between the environmental benefit and the expenses.

Figure 13 shows the number of lives saved as a function of a number of plants built. The expression $W\left(D-d_p-\frac{Wd}{2nl}\right)\Big/d_l$ tends to its limit when the number of plants tends to infinity. It can be mentioned that the function is concavely growing, which means that the benefit of building an additional plant declines. On the other hand, the function of an average cost of life saved $d_l\left(cn+Wv+\frac{sW}{l}-p^TWu\right)\Big/W\left(D-d_p-\frac{Wd}{2nl}\right)$ has a minimum, which in the considered example corresponded to a lower number of plants than the number that corresponds to the profit maximizing point.

7.3 Conclusions

1) The result of the calculation depends on the assumed average age of landfills. An exclusion of the first 30 years period reduces the environmental damage estimate by 65% from €8997 to €3200 per ton of MSW.

2) The total cost minimization method has yielded a time-period that is shorter than the equipment lifetime; therefore, the lifetime of equipment should be used as a minimal planning horizon in the main optimization model.

3) The optimal landfill waste processing period of six years calculated by the total cost minimization method is suboptimal from the pure economic point of view, because the plants' exploitation period is shorter than the equipment lifetime due to inclusion of environmental damage terms into the analysis.

4) The optimal period of landfill waste processing that is smaller than the equipment lifetime does not necessarily imply economic inefficiency, because afterwards the equipment can be used for processing waste continuously generated by cities. An application of this consideration would imply building such number of plants that is slightly higher than the number of plants needed for processing waste from cities. This idea leads to another approach to the minimal time horizon determination: it should be a period that would be taken for processing waste from landfills by means of such number of plants that is needed for treating waste generated by cities.

5) Therefore, the new rule for determining the minimal planning horizon for the main model can be formulated. One should calculate the model for a number of periods that is larger than each of the following numbers:

   a. the lifetime of the most long-living plant type;

   b. the optimal landfill waste processing time estimated by using the profit maximization model;

   c. the number of years that would be taken for processing landfill waste with such number of plants that is needed for treating waste generated by the cities.

This rule is important due to the fact that the main model (see the next chapter) is designed in such a way that it produces an optimal solution when it is calculated for a large enough number of periods. It means that after a certain number of periods any solution is expected to be optimal. However, considering the model for too little periods would lead to overinvestment. Therefore, the three aforementioned criteria are the three guesses what the shortest optimal time horizon can be.

6) In the considered example the measure of processing landfill waste easily passes the cost-benefit test. The average cost of life saved at the profit-maximizing point is equal to €206222, which is 16 times smaller than the value of statistical life in the EU.

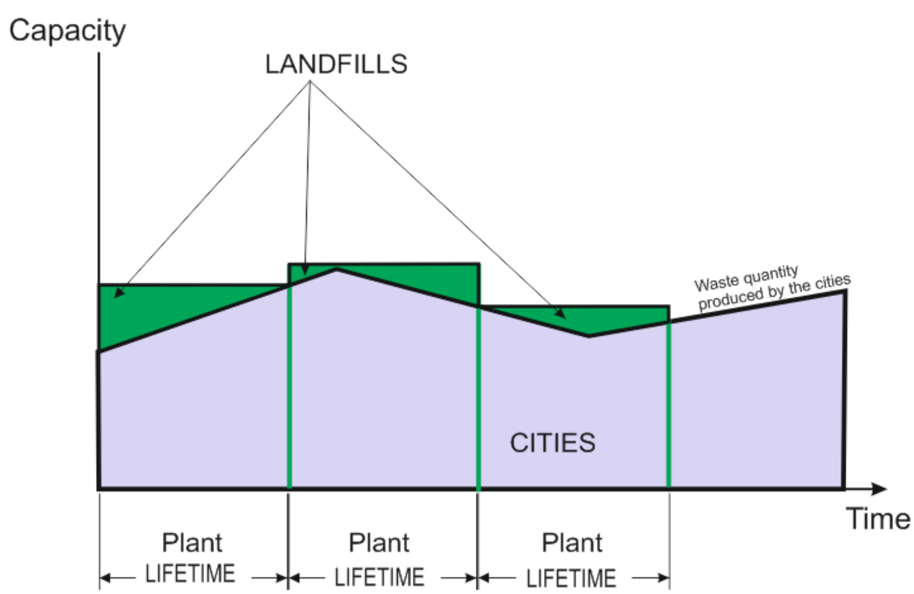
7) In the calculated example the minimum of the average cost of saving a statistical life corresponds to a smaller number of plants than the point of the profit function maximum. Therefore, it can be noted that in case projects aimed at life risk reduction are funded on the cost per life saved basis, regardless the fact that such solution is suboptimal from the economic point of view, it can be reasonable choosing a degree of measure realization (in this case a number of plants) that corresponds to the lowest cost per life saved in order to rise the probability of project being financed.

8 THE MODEL

8.1 Qualitative model description

First of all, the joint treatment of waste currently produced by the cities and the waste stored at the landfill sites can potentially bring efficient gains through full capacity utilization, as it is shown on figure 14. The fluctuations of waste quantities produced by the cities due to population growth or shrinkage, alongside a requirement of covering peak demand, create excess capacity at the off-peak periods which can be used for the treatment of waste from landfills. However, the economical viability of this solution depends on transportation costs and geographical location of factories. The second potential efficiency gain appears to be possible through economies of scale. It is expected that if the factor of economies of scale outweighs the transportation costs, the model will produce a centralized solution. Likewise, if transportation costs appear to be high, the solution will be decentralized.

Figure 14: Joint treatment of waste from cities and landfills



(Own figure)

The following example illustrates the above-stated idea. According to China Daily, Beijing was generating 18000 tons of trash daily in 2009 and this figure was growing by 8% per annum (Qian, 2009), which means that the annual waste generation rate was $6.57 * 10^6$ tons and in 30 years after 2009 it should be equal to $66.1 * 10^6$ tons per year. In the excel spreadsheet, which can be found in the link below, it is shown that under certain assumptions regarding the employed waste treatment technology, interest rate, environmental damage valuation, and age of the existing landfills, the discussed approach yields a 2% profit increase for the Beijing case.

https://docs.google.com/file/d/0B0J-JwC4EVi5N2hscmRRTjZ6YlE/edit?usp=sharing

The full description of the calculated example can be found in appendix IV.

The model allows for the analysis of a theoretically unlimited number of technological possibilities, described by the output vectors, land requirements per module; construction, maintenance, fixed, and variable costs; equipment lifetime; and module terminal value, which can come at a cost if disposal is required.

Due to the fact that some waste treatment technologies allow for heat production, the local demand for heat should be taken into account.

Special attention should be paid towards choosing a discount factor. For instance, Chang & Wang (1997) adjusted the nominal interest rate to inflation, thus obtaining the discount factor. However it is also possible to calculate the model in current prices. The more important question is if one should use the current interest rate as a discount factor or if it should be chosen by applying some other considerations. Due to the fact that the analyzed problem is socially important and the considered time period can be quite long it should be reasonable to use quite a moderate interest rate irrespective to the current interbank rate. For example, Galante et al. (2010) have used a 3% interest rate in their analysis.

In general, the considered cost function is very similar to many other models, for example the one which has been elaborated in (Chang & Wang, 1997) and (Lu, et al., 2009).

In the present paper the objective function that has to be minimized combines economic terms with environment-related terms and is constructed in a following form[5]:

$$\begin{aligned} & Construction\ costs + land\ costs + maintenance\ costs + fixed\ costs \\ & \quad + variable\ costs + transportation\ costs \\ & \quad + cost\ of\ residue\ landfilling\ \pm factory\ terminal\ value \\ & \quad - value\ of\ salable\ output - GHG\ credits \\ & \quad - municipal\ fee\ for\ waste\ treatment + cost\ of\ waste \\ & \quad + damage\ from\ untreated\ waste + damage\ from\ treatment \\ & \quad - damage\ from\ production\ of\ a\ same\ quantity\ of\ useful\ output \\ & \quad + damage\ from\ transportation \\ & \quad + terminal\ damage\ from\ untreated\ waste \\ & \quad + foregone\ profits\ from\ using\ the\ land\ occupied\ by\ the\ landfills \end{aligned}$$

In case it is preferred to avoid monetary valuation of environmental damage one should split the objective function into two, one of which will correspond to profit, whereas the second one will correspond to environmental damage.

The model includes the following constraints:

1. Capacity constraints: the total quantity of waste delivered to any location s at any period y should be smaller or equal to the total capacity installed in location s at a period y.
2. Land constraints: the area occupied by all modules in location s at a period y should be smaller or equal to the total available land area in location s. It is also assumed that if the lifetime of a module has finished, the space that it has occupied can be reused.
3. Residue constraints: the total amount of residues from the waste treatment process should not exceed the norm. It is also possible, and probably even more sensible, to set these constraints for each period. Aside from that we can distinguish between the different types of residues by degree

[5] All notations for the below described model can be found in appendix I.

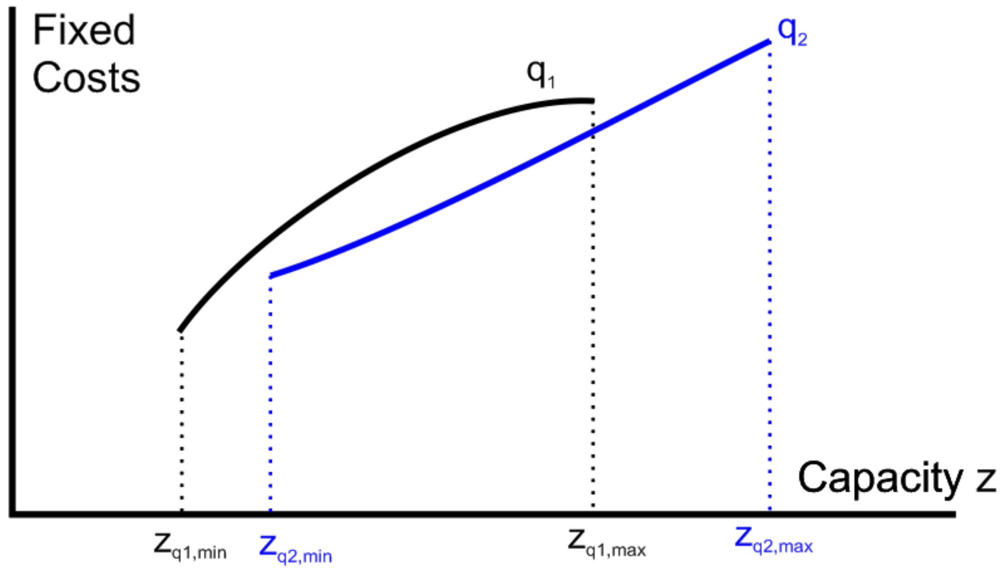
of their hazardousness. For example, we can consider three types of residues: inert, active and hazardous and to set constraints for each type.

4. Landfills waste constraints: the total quantity of waste transported from any landfill l to all locations s in all the periods should be smaller or equal to the initial quantity of waste at landfill l.
5. Cities waste constraints: the quantity of waste transported from any city n to all locations s at any period y should be smaller or equal to quantity of waste produced by city n at period y.
6. Non-negativity constraints: the decision variables, namely quantities of waste delivered from landfills and cities to all locations s, and number of factory modules built in every location in every period y, should be non-negative.
7. Number of modules is an integer variable.

8.2 Decision variables and parameters

It is sensible to model a plant capacity by modules of a standard capacity, because each technology implies some size restrictions. For example, Chang & Wang (1997) have mentioned the need for differentiating the size of incinerators on a planning stage because the planned size might not be consistent with the industrial specification. Therefore, a plant capacity in any location s should be defined as a multiple of a standard module for any given technology q. However, in reality the technology allows for the construction of a module of any capacity which lies between the minimal size z_{min} and the maximal size z_{max}. As a result, we can construct a function for any technology q that will show a relationship between a module size and any related parameter, such as construction cost, maintenance costs, etc. This approach allows for the consideration of a potentially non-linear relation between the module size and costs.

Figure 15: Illustration of potentially non-linear relation between a module size and the associated costs



(Own figure)

Figure 15 shows a hypothetical relationship between the module capacity z and the fixed costs per module for the technologies q_1 and q_2. The similar functions can be built for the investment costs, maintenance costs, space requirements, and etc. In case it is found to be practically useful, one can approximate these functions through analytical expressions by using curve fitting software.

In order to avoid non-linearity in the model whilst keeping its possible effects, it is proposed to discretize the function by constructing vectors of capacities and the corresponding costs for a several points from the graph. An example of such vectors can be found below. Z_q is a vector of capacities for the technology q, and F_q is a vector of NPVs of the corresponding fixed costs.

$$Z_q = \begin{bmatrix} z_{q,\min} \\ z_{q,2} \\ z_{q,3} \\ . \\ z_{q,\max} \end{bmatrix} \qquad F_q = \begin{bmatrix} NPV(f_{q,z_{\min}}) \\ NPV(f_{q,z_2}) \\ NPV(f_{q,z_3}) \\ . \\ NPV(f_{q,z_{\max}}) \end{bmatrix}$$

In order to simplify the objective function we substitute all future payments associated with the factory exploitation with the sum of these payments, discounted to the moment of factory construction.

Table 12: An example of maintenance schedule and associated costs

Technology q_1, capacity z	
Period	Maintenance costs
1	0
2	0
3	$m_3*(1+r)^{-3}$
4	0
5	0
6	0
7	$m_7*(1+r)^{-7}$
…	
T_{q1}	0
NPV	$\sum_{t=0}^{T_{q1}}[m_t(1+r)^{-t}]$

(Own table)

For example, we can consider table 12, which shows the payments schedule for the maintenance costs for a module of capacity z for the technology q_1. The sum is calculated over T_q periods, which is a lifetime of a factory built according to a technology q. For example Galante et al. (2010) have assumed a service life of 30 years for structures of transfer stations and of 10 years for the equipment.

Table 13 shows an example of the construction of the vectors which incorporate output related parameters. The useful (and also potentially revenue-generating) outputs are marked with green, whereas the outputs associated with environmental damage or costs are marked with red. The output vector O_q shows how much salable output, pollutants, and residues of diverse types, that need to be stored at landfills, can be obtained by treating one ton of MSW with technological process q.

It should be noted that the model does not consider a transportation problem for delivering the residues created by treatment process to the landfill sites. However, the price vector includes negative prices for the outputs that have to be landfilled, which turns it into costs. From the author's point of view, it is sensible to include into these numbers the costs of the landfill construction, variable costs, and perhaps some average estimation of transportation costs. One can regard this cost of landfilling as the price paid for a service if it could have been provided by an external company.

The price vector has a zero value for the heat, because revenues from selling heat depend on local demand and therefore need to be modeled separately. The price for heat will appear later in the text as P_h.

The vector of damage coefficients incorporates the coefficients, which show the relative hazardousness of the pollutants, as it has been previously discussed. The monetary value of damage can be obtained by assigning price to the relative damage units.

The vector D_{altern}^{coeff} shows how much damage could have been created by producing the same useful output with conventional methods instead of obtaining it from waste. These values are measured in the same relative damage units, as the damage coefficients, and are calculated by summing up the weighted quantities of pollutants that are normally emitted in a process of production of one unit of the considered good. The avoided damage can be more easily calculated with the help of LCA software, or even simply picked up from a table, because these values have already been calculated for many production processes.

The last column of the table 13 includes products of the uncontrolled waste decomposition process. See appendix II.

Chang & Wang (1997) reported that the possible recoverable resources include paper, glass, metal, plastics, steam, and electricity, but they also assume that a portion of materials can be separated by households and thus can be directly recycled. In the current model, it is assumed that households do not separate any of the recoverable materials, which is true for many countries.

Table 13: Construction of vectors employed in the model

Output	**Output vector O_q for technology q**	**Price vector P**	**Vector of damage coefficients D^{coeff}**	**Damage from conventional production D^{coeff}_{altern}**	**Products of MSW landfill uncontrolled decay**
Heat	O_q^h	0	0	$d_{altern1}$	0
Electricity	O_q^2	p_2	0	$d_{altern2}$	0
Hydrogen	O_q^3	p_3	0	$d_{altern3}$	0
Methane	O_q^4	p_4	0	$d_{altern4}$	x_4
Glass	O_q^5	p_5	0	$d_{altern5}$	0
Aluminium	O_q^6	p_6	0	$d_{altern6}$	0
RDF	O_q^7	p_7	0	$d_{altern7}$	0
…	…	…	…	…	…
CO_2	O_q^{n-5}	0	d_{n-5}	0	x_{n-5}
NOx	O_q^{n-4}	0	d_{n-4}	0	x_{n-4}
Mercury	O_q^{n-3}	0	d_{n-3}	0	x_{n-3}
Output to be landfilled (nontoxic – type A)	$O_q^{res\,A}$	$-p_{n-2}$	0	0	0
Output to be landfilled (toxic - type B)	$O_q^{res\,B}$	$-p_{n-1}$	d_{n-1}	0	0
Output to be landfilled (toxic - type C)	$O_q^{res\,C}$	$-p_n$	d_n	0	0

(Own table)

The decision variables are also grouped in vectors and include:

1. $J_{y,s,q}$, a vector of quantities of modules of each possible capacity constructed in period y at a site s according to a technology q;
2. $W_{l,y}^{s}$, a vector of quantities delivered to location s in period y from all landfills;
3. $W_{n,y}^{s}$, a vector of quantities delivered to location s in period y from all cities.

Therefore, the model has $Q \cdot Y \cdot S \cdot Z + S \cdot Y \cdot L + S \cdot Y \cdot N = SY \cdot (QZ + L + N)$ variables, where Z is a number of discrete values of a module capacity chosen to be considered for each technology. For example, if we consider a problem with 20 potential locations for factories, 100 years, 3 technologies, 5 possible capacities, 10 landfills, and 10 cities we will have 70000 variables, 30000 of which are integers.

8.3 Objective function modeling

The total capacity installed in location s in period y can be written as $\theta_{y,s} = \sum_{q=1}^{Q} \sum_{x=y-T_q}^{y} J_{x,s,q} \cdot Z_q \cdot H(x)$, which is true for $\forall y, \forall s$. This expression takes into account module lifetime, meaning that all capacity that has been installed in a current period and up to T_q periods back should be counted. The sign of the transpose operation is omitted here and later in the formulas in order to avoid visual overload of the formulas, but is obviously implied.

x is an auxiliary variable that is used for counting back, which can become non-positive for $y \leq T_q$. In order to solve this problem one can use Heaviside function $H(x)$ that multiplies the whole expression by zero for all $x < 0$. Other ways of solving this problem is defining $J_{x,s,q} = 0$ for all $x < 0$.

Similarly one can define installed capacity in location s in period y which functions according to technology q: $\theta_{y,s,q} = \sum_{x=y-T_q}^{y} J_{x,s,q} \cdot Z_q \cdot H(x)$.

Using the first and the second expression one can calculate a share of the installed capacity in location s in period y that functions according to technology q: $\Theta_{y,s,q} = \frac{\theta_{y,s,q}}{\theta_{y,s} + \xi}$, where ξ is an arbitrary chosen small number (e.g. 10^{-6}) that allows the avoidance of the problem of $\frac{0}{0}$ uncertainty and hardly changes the solution for the non-zero cases.

The expression $\phi_{y,s,q} = \left[I^T W_{l,y}^s + I^T W_{n,y}^s \right] \Theta_{y,s,q}$ corresponds to an amount of waste treated in location s in period y with technology q. This formula assumes that if several plants that function according to different technologies exist in the same location simultaneously all waste that is delivered to the location s is divided between the plants proportionally to the capacities. This rule does not ensure an optimal solution in case there are two factories which work according to different technologies in one location and when the amount of waste delivered to this location is smaller than the total installed capacity. Therefore, it can be a point for the model improvement. However, it should be noted that firstly, the cases when more than one technology is used in one location are expected to occur rarely. Secondly, the model design assumes running plants at full capacity in most cases which makes the above-mentioned rule only a technical detail that does not influence optimality of the solution.

The costs specific for each technology q can be written down in a following form:

$\sum_{y=0}^{Y}\sum_{s=1}^{S}\sum_{q=1}^{Q}(1+r)^{-y}\cdot J_{y,s,q}\cdot\left(C_q+M_q+\mathrm{P}_q\sigma_s+\mathrm{X}_q\right)$, that can be shortened to $\sum_{y=0}^{Y}\sum_{s=1}^{S}\sum_{q=1}^{Q}(1+r)^{-y}J_{y,s,q}\Psi_q$ if land prices σ_s are the same for all locations.

The expression for the fixed costs $\sum_{y=0}^{Y}\sum_{s=1}^{S}\sum_{q=1}^{Q}(1+r)^{-y}J_{y,s,q}\cdot F_q\cdot E(\theta_{y,s})$ takes into account a possible factor of economies of scale $E(\theta_{y,s})$ for any location s and period y, which depends on total capacity installed in location s. It is assumed that if there are several plants in the same location which even employ different technological solutions there should be cost saving effect, at least for such services like HR or accounting. This topic needs to be further researched, but one can also assume that the factor of economies of scale should apply to all fixed costs including construction, maintenance and other costs, which would allow the incorporation of F_q into Ψ_q. It is also possible to assume that the economies of scale factor should depend on total installed capacity in all locations; however, all these assumptions need to be checked empirically.

The following expression can be used for the variable costs $\sum_{y=0}^{Y}\sum_{s=1}^{S}\sum_{q=1}^{Q}(1+r)^{-y}\phi_{y,s,q}\cdot v_q$ which are assumed to be constant irrespective to the plant capacity; however, a factor of economies of scale can also be added if it is found to be existent.

Modeling of revenues from selling the output products of waste processing is a bit trickier because the heat output should be handled separately from the rest of the products. This is due to the fact that heat can be sold only locally. Therefore, irrespective of the quantity produced the plant can sell only up to a limit of locally demanded quantity. For instance, Hokkanen & Salminen (1997) have also incorporated demand for the products of recycling into their model.

$$\sum_{y=0}^{Y}\sum_{s=1}^{S}\sum_{q=1}^{Q}(1+r)^{-y}\begin{bmatrix}\phi_{y,s,q}\cdot O_q\cdot P \\ +H\left(\phi_{y,s,q}\cdot O_q^h - B_{y,s}\right)\cdot B_{y,s}\cdot P_h \\ +H(B_{y,s}-\phi_{y,s,q}\cdot O_q^h)\cdot\phi_{y,s,q}\cdot O_q^h\cdot P_h\end{bmatrix}$$

The first term of the above-stated expression corresponds to revenue from all output types except heat. The second term corresponds to the revenues earned in case the produced quantity of heat exceeds the demanded quantity. The third term shows the revenues from selling heat in case demand exceeds the production. This particular method of modeling does not take into account seasonal demand fluctuations if the heat is supplied to a district heating system but is perfect if the plant is connected to the industrial heat user with constant demand. This problem can be solved by taking one month as a basic period instead of a year, but it will obviously increase a number of decision variables by a factor of twelve.

The expression for transportation costs includes cost per kilometer and a fixed cost per ton, which can be interpreted as the cost of loading and unloading. According to Galante et al. (2010) it is sensible to multiply the transportation costs by a factor of two in order to take into account the return trip of a truck. Following the above-mentioned approach the first term in the brackets in the expression below is multiplied by two. The downside of this approach is that it does not take into account a difference in fuel consumption by fully loaded and empty trucks.

$$\sum_{y=0}^{Y}\sum_{s=1}^{S}(1+r)^{-y}\left[\left(D_l^s W_{l,y}^s + D_n^s W_{n,y}^s\right)\cdot 2\cdot c_{km} + \left(I^T W_{l,y}^s + I^T W_{n,y}^s\right)\cdot c_{ton}\right]$$

It is assumed that the company which operates the project is able to obtain the GHG credits for reducing pollution (Lu, et al., 2009; Chang, et al., 2012). The vector Δ_q^{GHG} is constructed from the differentials of quantities of GHGs emitted by the unmanaged landfill and a processing with technology q. Therefore, the revenues from selling the obtained credits is equal to $\sum_{y=0}^{Y}\sum_{s=1}^{S}\sum_{q=1}^{Q}(1+r)^{-y}\phi_{y,s,q}\Delta_q^{GHG}P_{GHG}$.

It is assumed that the operating company buys waste from the landfills paying p_w and gets paid p_m by the municipalities for the treatment of the waste produced by the cities. In general, the prices can take the negative values, which leads to an opposite interpretation of the conditions. An analysis of the optimal solution with respect to p_w and p_m should yield the conditions for economic feasibility of the project. However, it should be noted that one should analyze the function which only includes the cash flow-related terms. Finding such values for p_w and p_m that set the profit function to zero have direct policy implications. Obviously these prices can compensate each other creating the subsidization effect between treatment of waste produced by the cities and treatment of waste from the landfills.

$$\sum_{y=0}^{Y}\sum_{s=1}^{S}(1+r)^{-y}\left[I^T W_{l,y}^s \cdot p_w - I^T W_{n,y}^s \cdot p_m\right]$$

The term $\sum_{y=0}^{Y}(1+r)^{-y}kA_l^T \times H\left(W_l - \sum_{x=0}^{y}\sum_{s=1}^{S}W_{l,x}^s\right)$ corresponds to the foregone profits from not renting out the land occupied by the landfills, where H is a vector of binary values. Despite the possibility that the land resources are abundant this term can serve as a measure of environmental damage caused by the inert waste components with very long decay time, such as glass or plastic, which do not result in air or ground waters pollution, but still cannot be regarded as non-existent.

The resulting profit function can be written in the following form:

$$\sum_{y=0}^{Y}(1+r)^{-y}\sum_{s=1}^{S}\left[\begin{array}{l} I^T W_{l,y}^s(p_w+c_{ton})-I^T W_{n,y}^s(p_m-c_{ton})+\left(D_l^s W_{l,y}^s+D_n^s W_{n,y}^s\right)\cdot 2\cdot c_{km} \\ +\sum_{q=1}^{Q}\left[J_{y,s,q}\left(\Psi_q+F_q E(\theta_{y,s})\right)-H\left(\phi_{y,s,q}\cdot O_q^h-B_{y,s}\right)\cdot B_{y,s}P_h\right] \\ +\sum_{q=1}^{Q}\phi_{y,s,q}\left[v_q-O_q P-\Delta_q^{GHG}P_{GHG}-H(B_{y,s}-\phi_{y,s,q}\cdot O_q^h)\cdot O_q^h P_h\right] \end{array}\right]$$
$$+\sum_{y=0}^{Y}(1+r)^{-y}kA_l^T\times H\left(W_l-\sum_{x=0}^{y}\sum_{s=1}^{S}W_{l,x}^s\right)$$

The first term of the environmental damage function, i.e. damage from untreated waste, includes three parts: damage from the untreated landfill waste during the Y periods of the project, damage from the landfill waste that is left after Y periods (terminal damage), and the damage from the untreated waste produced by the cities.

$$\sum_{y=0}^{Y}(1+r)^{-y}\cdot\sum_{l=1}^{L}\left[\left[w_l-\sum_{x=0}^{y}\sum_{s=1}^{S}w_{l,x}^s\right]\cdot D(T_l^0+y)\right]+\sum_{l=1}^{L}\left[\left[w_l-\sum_{y=0}^{Y}\sum_{s=1}^{S}w_{l,y}^s\right]\cdot(1+r)^{-Y}\int_{T_l^0+Y}^{\infty}D(t)e^{-rt}dt\right]$$
$$+\sum_{y=0}^{Y}(1+r)^{-y}\cdot I^T\times\left[W_n^y-\sum_{s=1}^{S}W_{n,y}^s\right]\cdot\int_0^{\infty}D(t)e^{-rt}dt$$

The model does not presume a delay in the treatment of the waste produced by the cities. Moreover, the possibility of damping the waste without processing is not considered. However, it is assumed that adding the damage term results in immediate treatment of waste produced by the cities because the “fresh” waste has a higher damage potential than the waste that has already partially decayed at a landfill.

$D(T_l^0+y)$ is a damage caused by a landfill aged T_l^0+y in a period y

$\int_{0}^{\infty} D(t)e^{-rt}dt$ is an integral of a NPV of damage caused by MSW from the moment of its creation until it naturally becomes inert. Practically, the integral can be replaced with a constant after establishing the damage function and calculating the value. The example which was calculated in the chapter devoted to the damage from landfills yielded a value of 6683 EUR for the damage discounted at 1% per year.

The next term of the damage function is a difference between the environmental damage caused by waste processing and the avoided damage that could have been caused by alternative production of the same quantity of outputs by conventional means. In general, the avoided damage is hard to be exactly defined because, for example, the production of electricity from coal creates a lot of air pollution, whereas nuclear power plants create almost no air pollution. Therefore, one should refer to the locally implemented technologies in order to assess the avoided damage correctly. $\sum_{y=0}^{Y}\sum_{s=1}^{S}\sum_{q=1}^{Q}(1+r)^{-y}\phi_{y,s,q}\cdot O_q\cdot\left(D^{coeff}-D^{coeff}_{altern}\right)$

The last term of the function is the damage from transportation of waste which is based on an average value of damage created by transporting one ton to a distance of one kilometer. This damage is again multiplied by the factor of 2 as it has been done for the transportation costs.

$$\sum_{y=0}^{Y}\sum_{s=1}^{S}(1+r)^{-y}\cdot\left(D_l^s W_{l,y}^s + D_n^s W_{n,y}^s\right)\cdot 2\cdot D_{km}$$

The final expression for the damage function can be written in the following form:

$$\sum_{y=0}^{Y}(1+r)^{-y}\cdot\begin{bmatrix}\sum_{l=1}^{L}\left[w_l-\sum_{x=0}^{y}\sum_{s=1}^{S}w_{l,x}^{s}\right]\cdot D(T_l^0+y)\\ +I^T\left[W_n^y-\sum_{s=1}^{S}W_{n,y}^{s}\right]\cdot\int_0^\infty D(t)e^{-rt}dt\\ +\sum_{s=1}^{S}\sum_{q=1}^{Q}\phi_{y,s,q}O_q(D^{coeff}-D_{altern}^{coeff})\\ +\sum_{s=1}^{S}\left(D_l^sW_{l,y}^{s}+D_n^sW_{n,y}^{s}\right)\cdot 2\cdot D_{km}\end{bmatrix}+(1+r)^{-Y}\sum_{l=1}^{L}\left[\left[w_l-\sum_{y=0}^{Y}\sum_{s=1}^{S}w_{l,y}^{s}\right]\cdot\int_{T_l^0+Y}^{\infty}D(t)e^{-rt}dt\right]$$

Remark: in order to be consistent with the LCA methodology it should be correct to incorporate the terms which reflect environmental damage from building the waste treatment facilities into the objective function. An example of such analysis can be found in Cherubini et al. (2009). In terms of the developed model, the discussed damage values should be calculated for modules of each capacity for each technological alternative.

8.4 Constraints

The verbal description of the constraints can be found in chapter 8.1 “Qualitative model description” on pages 57-58.

1. Capacity constraints

$$\left[I^TW_{l,y}^{s}+I^TW_{n,y}^{s}\right]\le\sum_{q=1}^{Q}\sum_{x=y-T_q}^{y}J_{x,s,q}\cdot Z_q\cdot H(x)=\theta_{y,s};\ \forall y,\forall s$$

2. Land constraints, where Ω_s is area available in location s

$$\sum_{q=1}^{Q}\sum_{x=y-T_q}^{y}J_{x,s,q}\cdot\mathrm{P}_q\cdot H(x)\le\Omega_s;\ \forall y,\forall s$$

3. Optional constraint for volume (weight) of residues from waste treatment process by type of residue $\gamma_{y,i} = \sum_{s=1}^{S}\sum_{q=1}^{Q}\left[I^T W_{l,y}^s + I^T W_{n,y}^s\right]\Theta_{y,s,q} \cdot O_q^{res_i} \leq \Gamma_i$, where $i = A, B, C$; $\forall y$
4. Waste volume constraint for landfills, where $W_{l,y}^s$ and W_l are vectors of size L

   $$\sum_{y=1}^{Y}\sum_{s=1}^{S} W_{l,y}^s \leq W_l$$
5. Waste volume constraint for cities

   $$\sum_{s=1}^{S} w_{n,y}^s \leq w_n^y \; ; \; \forall y, \forall n$$
6. Non-negativity constraints

   $J_{y,s,q} \geq 0$; $W_{l,y}^s \geq 0$; $W_{n,y}^s \geq 0$ for $\forall y, \forall s, \forall q, \forall l, \forall n$
7. Integer constraints

   $J_{y,s,q} = \text{int}$; $\forall y, \forall s, \forall q$

The total number of constraints in equal to $Y\left[S\left[2+2Q+L+N\right]+3+N\right]+L$, which in the above considered example of a problem with 20 potential locations for factories, 100 years, 3 technologies, 5 possible capacities, 10 landfills, and 10 cities, results in 57310 constraints.

8.5 Joint objective function

Expressing damage in monetary terms allows for combining the two above-considered objective functions of profit and environmental damage into one. It requires defining a price for one unit of damage. As it has been previously discussed it is possible to use the EPS2000 indicators which are calculated in Euros as damage coefficients, or to employ Eco-Indicators'99 which can also be converted to monetary units, by multiplication by the factor $\alpha = 2689\ EUR/mPt$. In order to simplify the expression we define ζ_q as a constant for technology q, related to the variable costs.

$$\zeta_q = v_q - \Delta_q^{GHG} P_{GHG} + O_q(\alpha D^{coeff} - \alpha D_{altern}^{coeff} - P)$$

The coefficient α is used for converting the non-monetary damage coefficients into monetary terms.

Combining both expressions together results in a following objective function that has to be minimized:

$$\sum_{y=0}^{Y}(1+r)^{-y}\left[\begin{array}{l}\sum_{s=1}^{S}\left[\begin{array}{l}I^T W_{l,y}^s(p_w + c_{ton}) - I^T W_{n,y}^s(p_m - c_{ton}) + 2\left(D_l^s W_{l,y}^s + D_n^s W_{n,y}^s\right)\cdot\left(c_{km} + \alpha D_{km}\right)\\ +\sum_{q=1}^{Q}\left[\begin{array}{l}J_{y,s,q}\left(\Psi_q + F_q E(\theta_{y,s})\right) - H\left(\phi_{y,s,q}\cdot O_q^h - B_{y,s}\right)\cdot B_{y,s}P_h\\ +\phi_{y,s,q}\left[\zeta_q - H(B_{y,s} - \phi_{y,s,q}\cdot O_q^h)\cdot O_q^h P_h\right]\end{array}\right]\end{array}\right]\\ +\alpha\sum_{l=1}^{L}\left[\left[w_l - \sum_{x=0}^{y}\sum_{s=1}^{S} w_{l,x}^s\right]\cdot D(T_l^0 + y)\right]\\ +\alpha I^T\left[W_n^y - \sum_{s=1}^{S} W_{n,y}^s\right]\cdot\int_0^\infty D(t)e^{-rt}dt\\ +kA_l^T \times H\left(W_l - \sum_{x=0}^{y}\sum_{s=1}^{S} W_{l,x}^s\right)\end{array}\right] + (1+r)^{-Y}\alpha\cdot\sum_{l=1}^{L}\left[\left[w_l - \sum_{y=0}^{Y}\sum_{s=1}^{S} w_{l,y}^s\right]\cdot\int_{T_l^0+Y}^{\infty} D(t)e^{-rt}dt\right]$$

9 CONCLUSIONS

1) The paper has covered the major methodological aspects of modeling a waste management system. It has included an assessment of the damage created by waste mismanagement, as well as the question of expressing environmental damage in monetary terms.

2) One of the achievements of this work is the expression of Eco-Indicators'99 used in Life Cycle Analysis (LCA) in monetary terms with the help of simple calculation and employment of the Value of Statistical Life (VSL) concept.

3) The developed solution method addresses a question of an optimal planning horizon definition, which has not been found in the previous contributions.

4) The capacity of plants is calculated in modules; which brings the calculations closer to the practical needs.

5) It has been shown on the Beijing example that application of a model that solves both the problems of treating waste generated by cities and the problem of processing the waste stored at unmanaged landfills increases profits. In the case of Beijing, this amounted to 2%.

6) The paper proposes that an additional research on scale effects for the different technologies and waste management systems in general should be conducted in cooperation with the equipment producers. This information is necessary for enabling practical application of the developed model. However, it should be noted, that the model can be easily degraded to a case without scale effects.

7) One of the most interesting technical approaches used in the model is the substitution of the non-linear functions with the sets of vectors, which allows

for the incorporation of non-linear effects into a linear model. The only non-linear elements of the developed model are the Heaviside function and possibly the function of economies of scale for fixed costs.

8) Aside from the above-mentioned features, the model allows for the choice between the waste management technologies and for the simultaneous implementation of multiple technological solutions. Factors such as local demand for heat, economies of scale, space restrictions, and equipment lifetime have been incorporated into the model, which makes it possible that one technology can be more effective in one location in comparison to different ones.

9) The model is supposed to be in particular useful for planning state-of-the-art waste management systems in the countries where modern waste management practices have not yet been applied.

10) The model does not explicitly allow for the optimization of multi-stage processes and does not address the question of uncertainty. These points can be taken as topics for a further research, as well as incorporation of LCA of the waste treatment facilities.

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APPENDIX I: NOTATIONS

Variables

y – periods $[0; Y]$

s – potential locations for plants $[1; S]$

l – landfills $[1; L]$

n – cities $[1; N]$

q – technologies $[1; Q]$

Z_q - a vector of possible module capacities for a technology q

$J_{y,s,q}$ - a vector of numbers of modules of each possible capacity constructed in period y at a site s according to a technology q

$W_{l,y}^{s}$ - a vector of quantities delivered to location s in period y from all landfills

$W_{n,y}^{s}$ - a vector of quantities delivered to location s in period y from all cities

P_q - a vector of land requirements for different module sizes for technology q

M_q - a vector of NPVs of maintenance costs for different module sizes for technology q

Δ_q^{GHG} - a difference in GHG emissions per one ton of waste between unmanaged landfill and a treatment process q. Methane emissions should be fully counted because methane produced by a treatment process is useful and not emitted to the atmosphere.

P_{GHG} - a vector of prices of GHG permits

F_q - a vector of NPVs of fixed costs for different module sizes for technology q

X_q - a vector of NPVs of terminal values for module q of different capacities

D_l^s - a vector of distances between a location s and all landfills

D_n^s - a vector of distances between a location s and all cities

W_l - a vector of quantities of waste stored at landfills

W_n^y - a vector of quantities of waste produced by cities in period y

A_l - a vector of land areas occupied by the landfills

C_q - a vector of construction costs for technology q

σ_s - price of land in location s. If price is equal in all locations than $\sigma_s = \sigma; \forall s$

Ω_s - area restriction in location s

$H(x)$ – Heaviside step function

$\theta_{y,s}$ - total capacity installed in location s in period y

$\theta_{y,s,q}$ - capacity of modules built according to technology q in location s in period y

$\Theta_{y,s,q}$ - a share of capacity functioning according to technology q in location s in period y

ξ - arbitrary small number

$E(\theta_{y,s})$ - economies of scale factor for location s which depends on total installed capacity in location s in a period y

v_q - variable cost for treating one ton of MSW with technology q

$\phi_{y,s,q}$ - amount of waste treated at location s in year y by technology q

P – price vector

O_q - output vector for technology q

O_q^h - heat output coefficient for technology q

P_h - price for heat

$B_{y,s}$ - demand for heat in location s in period y

$\gamma_{y,i}$ - total quantity of residue of type i produced by waste processing in period y; $i = A, B, C$

$O_q^{res_i}$ - output coefficient for technology q for residue type i; $i = A, B, C$

Γ_i - maximal allowed quantity of residue of type i (an optional constraint)

c_{km} - a cost of transporting one ton of waste to a one kilometer distance

c_{ton} - a fixed cost per ton for transporting waste (e.g. cost of loading and unloading)

p_w - price paid per ton of waste from a landfill

p_m - municipal payment for treating one ton of waste transported from a city

I^T - a transpose of a unit vector

k - revenue from renting out one square kilometer of land for one year

$D(t)$ – environmental damage from unmanaged landfill as a function of a landfill age

T_l^0 - an age of a landfill l in period 0

D^{coeff} - a vector of damage coefficients, which has the same size as the output vector

D_{altern}^{coeff} - a vector of aggregate damage coefficients for production of useful outputs (the same as obtained from waste) by conventional methods (avoided damage)

D_{km} - environmental damage created by transportation of one ton to one kilometer

$\Psi_q = C_q + M_q + \mathrm{P}_q \sigma + \mathrm{X}_q$ - a sum of vectors of module fixed costs for technology q

$\zeta_q = v_q - \Delta_q^{GHG} P_{GHG} + O_q(\alpha D^{coeff} - \alpha D_{altern}^{coeff} - P)$ - a constant related to variable costs for technology q

VSL – value of statistical life

d_l – a quantity of damage, measured in some relative damage units, that has a lethal effect on a statistical person

α – a price for a unit of damage

Vectors

$$J_{y,s,q}=\begin{bmatrix} j_{y,s,q,z_{\min}} \\ j_{y,s,q,z_2} \\ j_{y,s,q,z_3} \\ . \\ j_{y,s,q,z_{\max}} \end{bmatrix};\ W^s_{l,y}=\begin{bmatrix} w^s_{l_1,y} \\ w^s_{l_2,y} \\ w^s_{l_3,y} \\ . \\ w^s_{l_L,y} \end{bmatrix};\ W^s_{n,y}=\begin{bmatrix} w^s_{n_1,y} \\ w^s_{n_2,y} \\ w^s_{n_3,y} \\ . \\ w^s_{n_N,y} \end{bmatrix};\ \mathrm{P}_q=\begin{bmatrix} \rho_{q,z_{\min}} \\ \rho_{q,z_2} \\ \rho_{q,z_3} \\ . \\ \rho_{q,z_{\max}} \end{bmatrix};\ M_q=\begin{bmatrix} NPV(m_{q,z_{\min}}) \\ NPV(m_{q,z_2}) \\ NPV(m_{q,z_3}) \\ . \\ NPV(m_{q,z_{\max}}) \end{bmatrix}$$

$$\Delta^{GHG}_q=\begin{bmatrix} O^{methane}_{ldf} \\ O^{CO_2}_{ldf}-O^{CO_2}_q \\ O^{NO_x}_{ldf}-O^{NO_x}_q \\ . \\ O^{GHG}_{ldf}-O^{GHG}_q \end{bmatrix};\quad P_{GHG}=\begin{bmatrix} p^{methane} \\ p^{CO_2} \\ p^{NO_x} \\ . \\ p^{GHG} \end{bmatrix};\quad F_q=\begin{bmatrix} NPV(f_{q,z_{\min}}) \\ NPV(f_{q,z_2}) \\ NPV(f_{q,z_3}) \\ . \\ NPV(f_{q,z_{\max}}) \end{bmatrix};\quad Z_q=\begin{bmatrix} z_{q,\min} \\ z_{q,2} \\ z_{q,3} \\ . \\ z_{q,\max} \end{bmatrix};$$

$$\mathrm{X}_q=\begin{bmatrix} NPV\chi_{q,z_{\min}} \\ NPV\chi_{q,z_2} \\ NPV\chi_{q,z_3} \\ . \\ NPV\chi_{q,z_{\max}} \end{bmatrix};\quad D^s_l=\begin{bmatrix} d^{s_i}_{l_1} \\ d^{s_i}_{l_2} \\ d^{s_i}_{l_3} \\ . \\ d^{s_i}_{l_L} \end{bmatrix};\quad D^s_n=\begin{bmatrix} d^{s_i}_{n_1} \\ d^{s_i}_{n_2} \\ d^{s_i}_{n_3} \\ . \\ d^{s_i}_{n_N} \end{bmatrix};\quad W_l=\begin{bmatrix} w_{l_1} \\ w_{l_2} \\ w_{l_3} \\ . \\ w_{l_L} \end{bmatrix};\quad W^y_n=\begin{bmatrix} w^y_{n_1} \\ w^y_{n_2} \\ w^y_{n_3} \\ . \\ w^y_{n_N} \end{bmatrix};\quad A_l=\begin{bmatrix} a_{l_1} \\ a_{l_2} \\ a_{l_3} \\ . \\ a_{l_L} \end{bmatrix}$$

APPENDIX II: EMISSIONS FROM LANDFILLS

The appendix consists of six tables with data for emissions from landfills adopted from Obersteiner et al. (2007). The first three tables correspond to the leachate composition, whereas the last three correspond to the gaseous emissions to air.

In cases when values reported in the literature exceeded legal limit values, the legal limit values were used. These values are marked in grey.

Table 14: Leachate concentration for different landfill types during operational period I (year 1–5)

Landfill type		Open dump		Sanitary landfill		MBP landfill		MSWI landfill	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max
pH-value		73	8.7		8.5	8.07	8.50	8.50	8.50
TOC	mg/l	1235	7725	20	20	20	20	4	110
BOD5	mg/l	2285	16,000	10	10	10	10		
COD	mg/l	3810	22,700	50	50	50	50	25	25
NH_4–N	mg/l	405	7000	10	10	10	10	39	10
NO_2–N	mg/l	0.06	0.30	0.06	0.30	2	2		
NO_3–N	mg/l	3.6	26.0	3.6	26.0	35	35		
SO_4	mg/l	98	400	98	400	547	1358	1470	3100
SO_3	mg/l	5.60	21.00	5.60	21.00				
Cd	mg/l	0.01	0.05	0.01	0.05			0.10	0.10
Fe	mg/l	50	550	2	2	2	2	2	2
Zn	mg/l	1.10	24.00	0.50	0.50	0.50	0.50	0.42	0.50
AOX	mg/l	2.77	7500	0.50	0.50	0.40	0.50		
Na	mg/l	815	2200	815	2200	414	586	4044	9300
K	mg/l	1220	2200	1220	2200	193	403	2489	6900
Ca	mg/l	375	2290	375	2290	147	366	124	16,000
Mg	mg/l	290	612	290	612			14	26
Mn	mg/l	3.90	43	3.90	43	0.34	0.88	0.01	0.02
Pb	mg/l	0.16	0.92	0.16	0.50	0.05	0.17	0.04	0.50
Cu	mg/l	0.71	40	0.50	0.50	0.04	0.10	0.27	0.50
Ni	mg/l	0.20	1.40	0.20	0.50	0.26	0.40	0	0
Cr	mg/l	0.16	0.48	0.16	0.48	0.50	0.50	0.02	0.03
Hg	mg/l				0.01	0.01	0.01	0	0
As	mg/l	0.02	0.03	0.02	0.03			0.10	0.10
Al	mg/l			2	2	1.53	2	2	2
Sb	mg/l							0.03	0.06
B	mg/l	5.90	15.00	5.90				2.64	3.73
Ba	mg/l				5				
Co	mg/l				1				
Mo	mg/l							0.73	1.31
Si	mg/l							4.22	0
V	mg/l							0.03	0.05

Table 15: Leachate concentration for different landfill types during active aftercare period II (year 6–30)

Landfill type		Open dump		Sanitary landfill		MBP landfill		MSWI landfill	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max
pH-value		7.60	9	7.60	8.5	8.38	8.80	7.30	8.50
TOC	mg/l	613	1120	20	20	12	12	4	110
BOD5	mg/l	443	1100	10	10	10	10		
COD	mg/l	2002	8300	50	50	50	50	25	25
NH_4–N	mg/l	637	1650	10	10	10	10	3.90	10
NO_2–N	mg/l	0.67	7.18	0.67	2	2	2		
NO_3–N	mg/l	9.50	64	9.50	64	35	35		
SO_4	mg/l	174	2500	174	2500	248	950	2.560	3.100
SO_3	mg/l	3.07	4.80	3.07	4.80				
Cd	mg/l	0.02	0.53	0.02	0.10			0.10	0.10
Fe	mg/l	22	189	2	2	2	2	2	2
Zn	mg/l	0.73	9	0.50	0.50	0.19	0.50	0.50	0.50
AOX	mg/l	1.62	5.60	0.50	0.50	0.40	0.50		
Na	mg/l	1021	6800	1.021	6800	414	586	5300	9300
K	mg/l	807	1750	807	1750	193	403	2740	6900
Ca	mg/l	258	1100	258	1100	80	85	5786	16,000
Mg	mg/l	153	300	153	300			14	26
Mn	mg/l	1.75	12.00	1.75	12.00	0.15	0.30	0.01	0.02
Pb	mg/l	0.11	0.40	0.11	0.40	0.04	0.10	0.07	0.14
Cu	mg/l	0.08	0.56	0.08	0.50	0.10	0.50	0.31	0.50
Ni	mg/l	0.18	1.00	0.18	0.50	0.13	0.29		0
Cr	mg/l	0.17	1.62	0.17	0.50	0.35	0.50	0.03	0.03
Hg	mg/l	0.00	0.03	0.00	0.01	0.00	0.01		0
As	mg/l	0.03	0.18	0.03	0.10			0.10	0.10
Al	mg/l					0.74	2.00	2.00	2.00
Sb	mg/l							0.03	0.06
B	mg/l	6.90	58.00	6.90	58.00			2.64	3.73
Ba	mg/l							0	0
Co	mg/l							0	0
Mo	mg/l							0.73	1.31
Si	mg/l							4.22	0
V	mg/l							0.03	0.05

Table 16: Leachate concentration for different landfill types during foreseeable period III (year 31–100)

Landfill type		Open dump	Sanitary landfill	MBP landfill	MSWI landfill
		Mean	Mean	Mean	Mean
pH-value		7.70	7.70	7.70	7.60
TOC	mg/l	500	500	500	
BOD5	mg/l	300	300	300	
COD	mg/l	1200	1200	1200	
NH_4–N	mg/l	120	120	120	
NO_2–N	mg/l	0.84	0.84	0.84	
NO_3–N	mg/l	10.00	10.00	10	
SO_4	mg/l	80	80	80	2.900
SO_3	mg/l	1.1	1.1	1	
Cd	mg/l	0.0028	0.0028	0.0028	0.0027
Fe	mg/l	12.50	12.50	13	0.09
Zn	mg/l	0.54	0.54	0.54	0.13
AOX	mg/l	1.13	1.13	1	
Na	mg/l	600	600	600	500
K	mg/l	600	600	600	200
Ca	mg/l	200	200	200	600
Mg	mg/l	100	100	100	400
Mn	mg/l	0.91	0.91	1	0.07
Pb	mg/l	0.03	0.03	0.03	0.0027
Cu	mg/l	0.04	0.04	0.04	0.03
Ni	mg/l	0.12	0.12	0.12	0.03
Cr	mg/l	0.18	0.18	0.18	0.01
Hg	mg/l				0.0004
As	mg/l	0.04	0.04	0.04	0.0047
Al	mg/l				0.05
Sb	mg/l				0.03
B	mg/l	10.00	10.00	10	3.27
Ba	mg/l				0.03
Co	mg/l				0.0017
Mo	mg/l				0.26
Si	mg/l				4
V	mg/l				0.0043

Table 17: Landfill gas concentration for different landfill types during operational period I (year 1-5)

Landfill type			Open dump		Sanitary landfill		MBP landfill
Landfill gas potential	m^3/ton		120		120		15.6
Proportion year 1–5	%		22%		22%		30%
Landfill gas potential year 1–5	m^3/ton		26.4		26.4		4.68
CH_4	Vol%		60		60		60
CO_2	Vol%		40		40		40
CH_4	m^3/ton		15.8		15.8		2.8
CO_2	m^3/ton		10.6		10.6		1.9
		Min	Max	Min	Max	Min	Max
CH_4	g/t	11,339	11,339	11,339	11,339	2010	2010
CO_2	g/t	20,738	20,738	20,738	20,738	3676	3676
Benzene	mg/ton	0.26	2508	0.3	2508	0.9	3.7
Toluene	mg/ton	0.53	16,236	0.5	16,236	0.1	13.5
o-Xylol	mg/ton	5.28	185	5.3	185	0.1	12.6
p/*m* Xylol	mg/ton	0	9926	0	9926	0.3	32.5
Dichloromethane	mg/ton	0	6600	0	6600	0.017	0.327
Trichloromethane	mg/ton	0	52.8	0	52.8	0.002	0.006
Tetrachloromethane	mg/ton	0	15.8	0	15.8	0.002	0.002
1,1,1-Trichloroethane	mg/ton	0.013	726.0	0.013	726.0	0.003	0.042
Trichloroethene	mg/ton	0	4804.8	0	4804.8	0.014	0.050
Tetrachloroethene	mg/ton	0.003	3748.8	0.003	3748.8	0.005	0.032

Table 18: Landfill gas concentration for different landfill types during active aftercare period II (year 6-30)

Landfill type		Open dump		Sanitary landfill		MBP landfill	
Landfill gas potential	m^3/ton	120		120		15.6	
Proportion year 6–30	%	75%		75%		60%	
Landfill gas potential year 6–30	m^3/ton	90		90		9.36	
Active gas collection	%			45%			
Gas used for energy production	m^3/ton			40.5			
Landfill gas emissions year 6–30	m^3/ton	90		49.5		9.36	
CH_4	Vol%	60		60		60	
CO_2	Vol%	40		40		40	
CH_4	m^3/ton	54		29.7		5.62	
CO_2	m^3/ton %	36		90 19.8		90 3.74	
Methane oxidation	%						
CH_4-emissions	m^3/ton	54		2.97		0.562	
CO_2-emissions	m^3/ton	36		46.53		8.798	
		Min	Max	Min	Max	Min	Max
CH_4	g/ton	38,657	38,657	2126	2126	402	402
CO_2	g/ton	70,698	70,698	91,378	91,378	17,279	17,279
Benzene	mg/ton	0.9	8550	0.495	4703	1.760	7.413
Toluene	mg/ton	1.8	55,350	0.99	30,443	0.140	26.947
o-Xylol	mg/ton	18	630	9.9	347	0.197	25.132
p/*m* Xylol	mg/ton		33,840		18,612	0.599	64.977
Dichloromethane	mg/ton		22,500		12,375	0.034	0.654
Trichloromethane	mg/ton		180		99	0.004	0.012
Tetrachloromethane	mg/ton		54		30	0.003	0.003
1,1,1-Trichloroethane	mg/ton	0.045	2475	0.025	1361	0.007	0.083
Trichloroethene	mg/ton		16380		9009	0.028	0.099
Tetrachloroethene	mg/ton	0.009	12,780	0.005	7029	0.010	0.065

Table 19: Landfill gas concentration for different landfill types during foreseeable period III (year 31-100)

Landfill type		Open dump		Sanitary landfill		MBP landfill	
Landfill gas potential	m^3/ton	120		120		15.6	
Proportion year 30–100	%	3%		3%		10%	
Landfill gas potential year 6–30	m^3/ton	3.6		3.6		1.56	
CH_4	Vol%	60		60		60	
CO_2	Vol%	40		40		40	
CH_4	m^3/ton	2.16		2.16		0.936	
CO_2	m^3/ton %	0 1.44		90 1.44		90 0.624	
Methane Oxidation	%	0		90		90	
CH_4-emissions	m^3/ton	2.16		0.216		0.094	
CO_2-emissions	m^3/ton	1.44		3.384		1.466	
		Min	Max	Min	Max	Min	Max
CH_4	g/ton	1546	1546	155	155	67	67
CO_2	g/ton	2828	2828	6646	6646	2880	2880
Benzene	mg/ton	0.036	342	0.036	342	0.293	1.236
Toluene	mg/ton	0.072	2214	0.072	2214	0.023	4.491
o-Xylol	mg/ton	0.72	25.2	0.72	25.2	0.033	4.189
p/*m* Xylol	mg/ton	0	1354	0	1354	0.100	10.830
Dichloromethane	mg/ton	0	900	0	900	0.006	0.109
Trichloromethane	mg/ton	0	7.2	0	7.2	0.001	0.002
Tetrachloromethane	mg/ton	0	2.16	0	2.16	0.001	0.001
1,1,1-Trichloroethane	mg/ton	0.002	99	0.002	99	0.001	0.014
Trichloroethene	mg/ton	0	655	0	655	0.005	0.017
Tetrachloroethene	mg/ton	0.0004	511	0.0004	511	0.002	0.011

APPENDIX III: MONETARY VALUATION OF DAMAGE FROM OPEN DUMPS

The appendix includes the tables that are also available in MS Excel format under the following link:

https://docs.google.com/file/d/0B0J-JwC4EVi5VWczc3RmSWEtcGc/edit?usp=sharing

The data on emissions has been taken from Obersteiner et al. (2007) and can also be found in Appendix II.

The values for the EPS2000 indicators have been taken from (Chalmers, n.d.).

The published list of indicators was rather incomplete; therefore, the values for some substances have been substituted with the values for some similar substances, which indeed does not guarantee that the caused damage is identical. Aside from that, if the values for emissions to some compartments were unavailable, the values for different compartments have been used. The list of substitutions can be found below:

1. NH3 to air instead of NH4
2. NOx to air instead of NO3 and NO2
3. Fe resource consumption impact instead of emissions impact
4. Zn resource consumption impact instead of emissions impact
5. SO2 to air instead of SO3 and SO4
6. K resource consumption impact instead of emissions impact
7. Mn resource consumption impact instead of emissions impact
8. Pb to air instead of Pb to soil
9. Cu to water instead of Cu to soil
10. Ni resource consumption impact instead of emissions impact
11. Cr to air instead of Cr to soil
12. As to air instead of As to soil
13. B resource consumption impact instead of emissions impact
14. P-Xylol instead of p/m-Xylol

Table 20: Annual damage from leachate caused between the first and the fifth year after disposal

Leachate, 1-5 year				
Substance	**Mean, Mg/l**	**Mean, kg/ton**	**ELU/kg**	**Damage, ELU**
TOC	1235.00	80.275		0.000
BOD5	2285.00	148.525	0.002	0.299
COD	3810.00	247.650	0.001	0.250
NH4-N	405.00	26.325	1.963	51.669
NO2-N	0.06	0.004	2.030	0.008
NO3-N	3.60	0.234	2.030	0.475
SO4	98.00	6.370	3.268	20.816
SO3	5.60	0.364	3.268	1.189
Cd	0.01	0.001	5.000	0.003
Fe	50.00	3.250	0.961	3.123
Zn	1.10	0.072	57.100	4.083
AOX	2.77	0.180		0.000
Na	815.00	52.975		0.000
K	1220.00	79.300	0.010	0.793
Ca	375.00	24.375		0.000
Mg	290.00	18.850		0.000
Mn	3.90	0.254	5.640	1.430
Pb	0.16	0.010	2910.000	30.264
Cu	0.71	0.046	0.000	0.000
Ni	0.20	0.013	160.000	2.080
Cr	0.16	0.010	20.045	0.208
Hg		0.000	61.424	0.000
As	0.20	0.013	103.299	1.343
Al		0.000		0.000
Sb		0.000		0.000
B	5.90	0.384	0.050	0.019
Ba		0.000		0.000
Co		0.000		0.000
Mo		0.000		0.000
Si		0.000		0.000
V		0.000		0.000
Total				**118.05**
Total for 5 years				**590.27**

(Own table, based on Obersteiner, et al. (2007))

Table 21: Annual damage from gaseous emissions caused between the first and the fifth year after disposal

Gas, 1-5 year				
Substance	**Mean, Mg/ton, 5 years**	**Mean, kg/ton, 1 year**	**ELU/kg**	**Damage, ELU**
CH4	11339000.00	2.26780	27.71985	62.86306
CO2	20738000.00	4.14760	1.10913	4.60025
Benzene	1254.13	0.00025	3.65033	0.00092
Toluene	8118.27	0.00162	1.95108	0.00317
o-Xylol	95.14	0.00002	1.91063	0.00004
p/m Xylol	4963.00	0.00099	2.19763	0.00218
Dichloromethane	3300.00	0.00066		0.00000
Trichloromethane	26.40	0.00001		0.00000
Tetrachloromethane	7.90	0.00000		0.00000
1,1,1-Trichloroethane	363.01	0.00007		0.00000
Trichloroethane	2402.40	0.00048		0.00000
Tetrachloroethane	1874.40	0.00037		0.00000
Total				**67.47**
Total for 5 years				**337.35**

(Own table, based on Obersteiner, et al. (2007))

The calculations for the second (year 6-30) and the third (year 31-100) periods have been conducted in the same way and the tables can be downloaded via the mentioned link.

The next table presents the summary of the results for all three periods.

Table 22: Total damage caused by emissions from one ton of waste disposed at open dump in the first 100 years

	Period I, annual	**Period I, total**	**Period II, annual**	**Period II, total**	**Period III, annual**	**Period III, total**	**Total damage for 100 years**
Leachate	€ 118.05	€ 590.27	€ 148.79	€ 3,719.74	€ 45.05	€ 3,153.60	€ 7,463.61
Gas	€ 67.47	€ 337.35	€ 46.00	€ 1,150.09	€ 0.66	€ 46.00	€ 1,533.43
Total, annual	€ 185.52		€ 194.79		€ 45.71		
Total per period		€ 927.61		€ 4,869.83		€ 3,199.60	**€ 8,997.04**

(Own table, based on Obersteiner, et al. (2007))

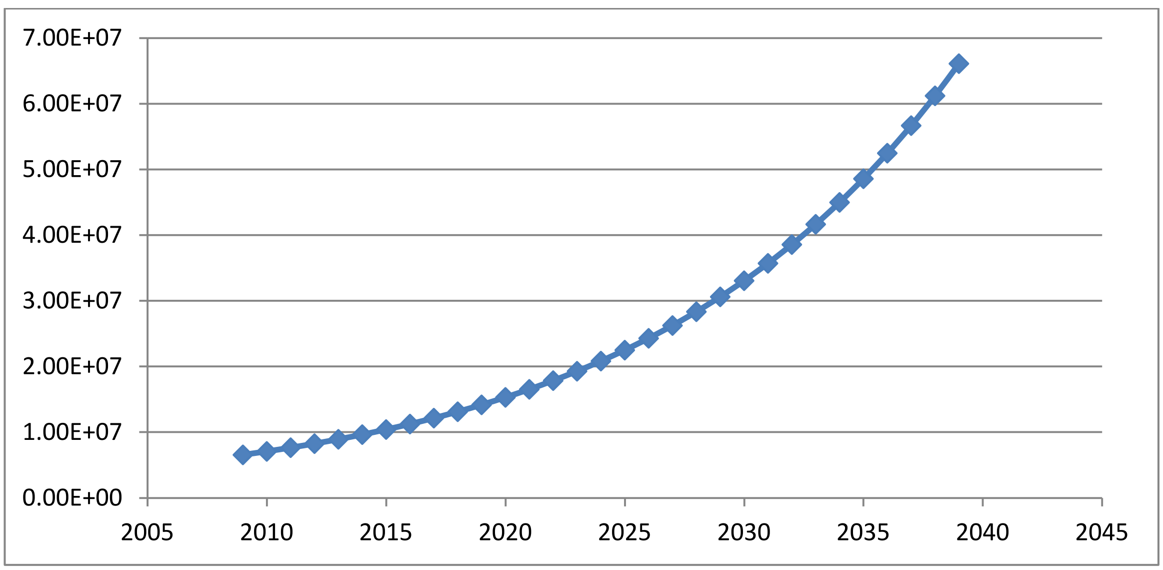
Discounting the annual damages by 1% yields the value for discounted damage caused in the first 100 years by one ton of waste disposed at open dump. It is equal to €6683 (estimated with the help of EPS2000 indicators).

APPENDIX IV: ECONOMIC BENEFITS OF THE DEVELOPED APPROACH, EXAMPLE OF BEIJING

This example shows the benefits of solving the problem of existing unmanaged open dumps and the problem of continuously generated MSW in one optimization problem.

According to China Daily Beijing was generating 18000 tons of trash daily in 2009 and the quantity was growing by 8% per annum (Qian, 2009), which means that the annual waste generation rate was $6.57 * 10^6$ tons and in 30 years after 2009 it should be equal to $66.1 * 10^6$ tons per year.

Figure 16: Forecasted annual waste generation in Beijing, tons



(Own figure, based on Qian (2009))

In the excel spreadsheet which can be found via the below-inserted link it is shown, that under certain assumptions regarding the employed waste treatment technology, interest rate, environmental damage valuation, and age of the existing landfills, the discussed approach yields a 2% profit increase for the Beijing case.

https://docs.google.com/file/d/0B0J-JwC4EVi5N2hscmRRTjZ6YlE/edit?usp=sharing

In this example, following the general idea of the developed model, the net present value of a project is calculated as the sum of monetary and environmental benefits.

It is assumed that there is one waste processing plant type that can incinerate 5000000 tons of waste yearly. The economic and technical parameters have been adopted form the Spokane WtE facility (Spokane Waste to Energy, 2010?), as it has been analyzed in the chapter devoted to the calculation of the optimal planning horizon, but in this case the values were multiplied by a factor of 20, in order to consider one large plant that can serve the current Beijing needs. It is also worth mentioning that the considered technological solution is by far not the most efficient one, because the Spokane plant has been built in 1991. Moreover, all the employed parameters were calculated for Spokane, which implies certain waste composition, labor costs, and electricity prices that can vary from those in China in a noticeable way.

The interest rate is assumed to be 1%. The values for environmental damage are based on EPS2000 indicators.

Table 23: Example assumptions

Parameter	Value
Cost of module, EUR	4421700000
Variable cost per ton (without damage), EUR	52
Damage from one ton of waste per year, EUR	90
Capacity of a module (average thru-put), tons	5000000
Damage from 1 kg of CO2, ELU	1.1
Annual Greenhouse Gas Production, pounds of CO2	12000000000
Annual Greenhouse Gas Production, tons of CO2	5443100
GHG production per ton of waste, tons of CO2	1.04
Environmental damage per ton treated, ELU (EUR)	1141
Variable cost per ton (incl. damage)	1193
Fixed costs (in the present example are already	
included in variable costs per ton)	0
Environmental damage per not treated ton, ELU (EUR)	6684
Interest rate, %	1

(Own table, partially based on Spokane Waste to Energy (2010?))

This example assumes that if the waste is not processed immediately after being produced and is disposed at an open dump landfill, it will never be processed and will cause environmental damage for the next 100 years.

Regarding the existing landfills it is assumed that the average age of waste is equal to 30 years; therefore, the opportunity cost of not processing this waste is calculated as a discounted sum of damages caused from the 31^{st} year to the 100^{th} year. The question of total volume of waste stored at Beijing landfills has not been considered in this example and it is assumed that the landfill waste is available in any requested quantities.

Table 24 presents NPV of a waste management project for Beijing. The total value of a project includes the benefits of avoided environmental damage as well as the damage caused by processing waste.

The second column shows how much waste is generated in a respective year, whereas the forth column shows how many plants of a standard size should be functioning in the respective period in order to cover the demand. The fifth column shows an excess capacity that exists in a respective period. The sixth column shows how many plants are added to the system in a considered period. It is assumed that the plants are instantly erected in a beginning of a period. The calculations show that the NPV of a project equals to 3.58E+12 Euros.

Following this, the example is recalculated with using the excess capacity for treating the waste from unmanaged landfills. It increases variable costs and adds an additional term to consider avoided environmental damage. As previously mentioned, it is assumed that the average age of waste at landfills is equal to 30 years; therefore, the avoided damage is calculated for the rest of a 100 year period.

The new NPV of a project rises to 3.66E+12 Euros, which can be estimated as a 2% efficiency increase. It is proposed that the similar positive effect will take place when using the developed model for solving the two waste management problems jointly.

Table 24: NPV calculation for WtE project of processing currently generated municipal solid waste

Year	Waste, tons	Modules	Modules roundup	Excess capacity, tons	Modules added	Excess capacity, %	Investment	Operations cost	Env. Damage treatment	Avoided Env. Damage	Total
2009	6.57E+06	1.3	2	3.43E+06	2	34%	8.84E+09	-3.42E+08	7.50E+09	4.39E+10	2.72E+10
2010	7.10E+06	1.4	2	2.90E+06	0	29%	0.00E+00	-3.69E+08	8.10E+09	4.74E+10	3.86E+10
2011	7.66E+06	1.5	2	2.34E+06	0	23%	0.00E+00	-3.98E+08	8.74E+09	5.12E+10	4.12E+10
2012	8.28E+06	1.7	2	1.72E+06	0	17%	0.00E+00	-4.30E+08	9.44E+09	5.53E+10	4.41E+10
2013	8.94E+06	1.8	2	1.06E+06	0	11%	0.00E+00	-4.65E+08	1.02E+10	5.97E+10	4.72E+10
2014	9.65E+06	1.9	2	3.47E+05	0	3%	0.00E+00	-5.02E+08	1.10E+10	6.45E+10	5.04E+10
2015	1.04E+07	2.1	3	4.57E+06	1	30%	4.42E+09	-5.42E+08	1.19E+10	6.97E+10	4.98E+10
2016	1.13E+07	2.3	3	3.74E+06	0	25%	0.00E+00	-5.86E+08	1.28E+10	7.53E+10	5.77E+10
2017	1.22E+07	2.4	3	2.84E+06	0	19%	0.00E+00	-6.32E+08	1.39E+10	8.13E+10	6.17E+10
2018	1.31E+07	2.6	3	1.87E+06	0	12%	0.00E+00	-6.83E+08	1.50E+10	8.78E+10	6.59E+10
2019	1.42E+07	2.8	3	8.16E+05	0	5%	0.00E+00	-7.38E+08	1.62E+10	9.48E+10	7.05E+10
2020	1.53E+07	3.1	4	4.68E+06	1	23%	4.42E+09	-7.97E+08	1.75E+10	1.02E+11	7.14E+10
2021	1.65E+07	3.3	4	3.46E+06	0	17%	0.00E+00	-8.60E+08	1.89E+10	1.11E+11	8.06E+10
2022	1.79E+07	3.6	4	2.13E+06	0	11%	0.00E+00	-9.29E+08	2.04E+10	1.19E+11	8.62E+10
2023	1.93E+07	3.9	4	7.03E+05	0	4%	0.00E+00	-1.00E+09	2.20E+10	1.29E+11	9.22E+10
2024	2.08E+07	4.2	5	4.16E+06	1	17%	4.42E+09	-1.08E+09	2.38E+10	1.39E+11	9.48E+10
2025	2.25E+07	4.5	5	2.49E+06	0	10%	0.00E+00	-1.17E+09	2.57E+10	1.50E+11	1.05E+11
2026	2.43E+07	4.9	5	6.91E+05	0	3%	0.00E+00	-1.26E+09	2.77E+10	1.62E+11	1.13E+11
2027	2.63E+07	5.3	6	3.75E+06	1	12%	4.42E+09	-1.37E+09	3.00E+10	1.75E+11	1.17E+11
2028	2.84E+07	5.7	6	1.65E+06	0	5%	0.00E+00	-1.47E+09	3.24E+10	1.90E+11	1.29E+11
2029	3.06E+07	6.1	7	4.38E+06	1	13%	4.42E+09	-1.59E+09	3.49E+10	2.05E+11	1.34E+11
2030	3.31E+07	6.6	7	1.93E+06	0	6%	0.00E+00	-1.72E+09	3.77E+10	2.21E+11	1.47E+11
2031	3.57E+07	7.1	8	4.28E+06	1	11%	4.42E+09	-1.86E+09	4.08E+10	2.39E+11	1.54E+11
2032	3.86E+07	7.7	8	1.42E+06	0	4%	0.00E+00	-2.01E+09	4.40E+10	2.58E+11	1.68E+11
2033	4.17E+07	8.3	9	3.34E+06	1	7%	4.42E+09	-2.17E+09	4.75E+10	2.78E+11	1.77E+11
2034	4.50E+07	9.0	9	5.52E+03	0	0%	0.00E+00	-2.34E+09	5.13E+10	3.01E+11	1.93E+11
2035	4.86E+07	9.7	10	1.41E+06	1	3%	4.42E+09	-2.53E+09	5.54E+10	3.25E+11	2.03E+11
2036	5.25E+07	10.5	11	2.52E+06	1	5%	4.42E+09	-2.73E+09	5.99E+10	3.51E+11	2.17E+11
2037	5.67E+07	11.3	12	3.32E+06	1	6%	4.42E+09	-2.95E+09	6.47E+10	3.79E+11	2.32E+11
2038	6.12E+07	12.2	13	3.79E+06	1	6%	4.42E+09	-3.18E+09	6.98E+10	4.09E+11	2.49E+11
2039	6.61E+07	13.2	14	3.89E+06	1	6%	4.42E+09	-3.44E+09	7.54E+10	4.42E+11	2.66E+11
Total				**7.96E+07**	**14**		**6.19E+10**	**-4.21E+10**	**9.25E+11**	**5.42E+12**	**3.58E+12**

(Own table)

APPENDIX V: CV

Daniil Shulman **linkedin.com/in/shulmand**

English – Fluent
German – Upper Intermediate
Russian – Native
Hebrew – Intermediate

Academic background

2011 – 2013	**MSc, International Business Administration, specialization in Energy & Environmental Management, University of Vienna** Master thesis: **Optimization model for the planning of a regional waste management system**
2007 – 2010	**BA, Intercultural Business Administration, specialization in Marketing, Lauder Business School, Vienna** Bachelor works: **1) Market potential of Passive House technology in Austria** **2) Applications of carbon-containing matter gasification technologies**
2004 – 2006	**Audiovisual Equipment Engineering, St. Petersburg State University of Cinema and Television, Russia** Major courses: Mathematical analysis, probability theory, physics, electronics, circuit theory
2003 – 2004	**Gymnasium “Migdal Or”, St. Petersburg, Russia**

Work experience

Oct 2010 – current	**Online store operations manager (part-time)**, M. Liska&Co GmbH
July - August 2009	**Company representative (internship in CRM)**, Unifin Holding GmbH
2006 – 2008	**Web design team project manager**, Russia/Austria
2006 – 2007	**System administrator**, Interform Ltd, St. Petersburg, Russia

Additional Information

<u>Skills:</u>	**MS Office (ECDL); MS Project; Dynamics; SPSS; Photoshop; Corel Draw, Google Ad-Words** Driving License (B) Other skills: Project Management, Communication, Analytical thinking