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Analysing efficiency of Waste to Energy Systems: Using Data Envelopment Analysis in Municipal Solid Waste Management

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Abstract

In our day-to-day living, a simple underlying principle is to consume resources in one form or another. This consumption generates waste, which needs to be dealt with in a responsible, efficient and effective manner. Waste is mostly collected and disposed by municipalities. This presents a challenge for these municipalities in dealing with ever increasing amounts of waste to be managed. This is particularly critical in cities, where the demand for these services is increasing. Management of municipal solid waste (MSW) continues to be one of the top priorities for human communities in the 21st century. The model of integrated solid waste management, reduction of waste right at the source points before it enters the chain of waste stream, reuse of generated wastes for recovery by recycling, and disposal through environmentally sound combustion facilities and landfills that meet policy standards are being used by communities as they evolve. Solid waste management is known to be an important contributor to various environmental problems, for example climate change (e.g. greenhouse gas emissions from landfills), disturbing multiple ecosystems (e.g. heavy metal emissions into air, soil and surface water), and improper use of resources leading to depletion (e.g. inexistent or inefficient recycling processing methods for a few particular key minerals or metals) among others. The formidable rise in solid waste generation require suitable management systems, which methodically handle these environmental issues and eventually contribute to move towards a more environmentally sustainable society. This paper presents a method based on Data Envelopment Analysis to analyse the efficiency of Waste to Energy systems, looking not only at maximising the positive outputs (e.g. Energy), but also minimising the negative ones (e.g. emissions). The results provide a benchmark for municipalities to aim in the operation of their Municipal Solid Waste Management (MSWM).

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Keywords: Waste to Energy; Data Envelopement Analysis; Municipal Solid Waste.

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1. Introduction

It is estimated that the annual worldwide solid waste generation will be increased to 27 billion tons in 2050 from 13 billion tons in the year 1990 (Beede and Bloom, 1995). In 2009, the annual total solid waste generation was approximately 17 billion tons (Chattopadhyay et al., 2009), of which about 1.3 billion tonnes are from cities, and are estimated to generate up to 2.2 billion tonnes by 2025 predominantly due to rise in the population, amassed urbanization and socio-economic development in low income (as well as in middle income as well) countries (Hoornweg & Bhada-Tata, 2012). Global generation of MSW in 1997 was 0.49 billion tons. While, estimated to have a 3.2–4.5% and 2–3% annual growth rate in developed nations, developing nations respectively (Suocheng et al., 2001).

Usually MSW physical composition has organic material, paper, plastic, glass, metals, and other refuse collected by local authorities, principally from homes, offices, institutions, and commercial institutions. Typically MSW doesn't envelop waste collected outside of proper municipal programs, rural wastes, sewage, industrial waste, or construction waste generated through cities. MSW is measured before disposal, and statistical data corresponding to it often include collected material that is sorted for recycling in the later stages of processing. MSW tends to be generated in large quantities from economically rich parts of the world.

The Organization for Economic Co-operation and Development (OECD), a group of 34 industrialized nations as its members, are leaders in MSW generation, producing about 1.6 million tons per day, while, sub-Saharan Africa produces less than one eighth as much (~200,000 tons per day). We intend to work with one of the four developing nations viz a viz (Mexico, India, China and Brazil) which are also listed in the top 10 MSW-generating countries, although size of their urban populations is a major factor in part their urban residents are progressing while adopting to high-consumption lifestyles. The current annual Municipal Solid Waste (MSW) generation is estimated to 1.9 billion tonnes while almost 30% of it is being predicted to be remained uncollected. As for the collected MSW, 70% is taken to landfills and dumpsites, 19% is reused or recycled and the rest (a mere 11%) is being turned over to energy recovery facilities. Although the United States leads the world in MSW output at 621,000 tons per day, China is a relatively close second, at 521,000 tons. Due to this and the fact that it is a developing nation, China is the prime focus in this paper.

1.1 Research Gap

Being a rapidly developing country with a large population, which increased from 963 million in 1978 to 1361 million in 2013, of which urban communities increased from 17.4 to 53.7% (National Bureau of Statistics of China, 2013), a severe need for improvements in both the standards of living and the surrounding ecosystems pose multiple environmental challenges in China. MSW management is one of the major problems that affect China's environmental quality and the sustainable development of its cities. In a short span of 15 years (1996-2011) MSW generated in China has grown from 108.25 million tons to 163.95 million tons (National Bureau of Statistics of China, 2012) Severe environmental issues have aroused due to improper and inefficient disposal of MSW (Tai et al., 2011).

The traditional methods, like landfill, are facing a crisis of shortage in land (Dong et al., 2003). At the same time, waste to energy (WTE) methods such as incineration and gasification are the two primary WTE technologies that have been used successfully throughout the world (Liu and Liu, 2005). It is estimated that about 181 million tonnes of MSW are combusted annually in over 600 WTE facilities worldwide, while 2.9% of MSW treated was incinerated in 2001, this fraction increased to 13.2% in 2006(Cheng and Hu, 2010) producing electricity and steam for district heating and recovered metals for recycling (Themelis, 2003). WTE incineration has been accepted as a more preferred solid waste management option, complementing composting and landfilling (American Society of Mechanical Engineers, 2008, and United Nations Environment Programme, 1996). Incineration of MSW in WTE facilities prevents the possible aqueous and gaseous pollution associated with landfilling and provides a source of consistent renewable energy. Being a proven, environmentally sound technology for disposal of waste to our advantage, WTE has been deployed widely in Europe and developed countries in Asia i.e. Singapore & Japan (American Society of Mechanical Engineers, 2008).

Currently there is an unparalleled demand for sustainable urban growth in China, dealing with the increasing volume of MSW generated as an outcome of increasing urban population and the improving life style of the people, presenting a formidable challenge (Cheng et al., 2007 and Cheng and Hu, 2009). Simultaneously, China, being the world's second largest consumer of energy and the third largest importer of oil (Energy Information Administration, 2009), also faces a massive demand for energy to enable its economic growth. MSW is a viable energy source for electricity generation in a carbon-restrained world (Kaplan et al., 2009), thus a MSW management technology with the benefits of recovering energy from a source that needs disposal is a secure alternative with potential for solving the MSW disposal problem in China. WTE is gaining increasing popularity in China predominantly for its ability to reduce the volume of MSW that requires landfill. It also reduces the nation's dependency on fossil fuels and greenhouse gas emissions. The overall MSW treatment rate in China was approximately 62% (i.e. 14.35 million tons/year) in 2007. In 2007, there were 460 facilities, including 366 landfill sites, 17 composing plants, and 66 incineration plants.

Since incineration based WTE plants being a mature and simpler technology compared to others (Nie, 2008, Xu and Liu, 2007 and Yuan et al., 2008), they are leading in operation all over China. A typical incinerator processes heterogeneous waste that has been collected as input materials, and primarily treats them into more homogeneous residues (flue gas, fly ash, and bottom ash) with the primary benefit of reduction in weight (up to 75%) and volume (up to 90%). As a secondary benefit, the heat generated is collected through steam generation, which is subsequently used for power generation and/or heating an additional recovery of heat (i.e., cogeneration) from the used steam is also in practice.
In summary, incineration based WTE plants consists of two production activities:

1) Waste treatment
2) Energy recovery (electricity and/or heat generation).

1.2 MSW Incineration facility:

In the waste treatment process line, the operator deploys human resources, incineration equipment, and incurs other costs to sort and homogenize the feed before entering the incineration process so as handle efficiently the non-homogeneous solid waste. The hot air and gasses exiting the incineration of MSW in a combustion chamber or a gasifier carries heat, which in turn is used by the energy recovery equipment (steam produced from generated heat integrated with turbine-generator, waste heat recovery systems for used steam), resources and other operating costs to produce electric power as a secondary output to the power grid.

Solid residues are sent to landfills or cleaned up and used off-site for certain construction purposes (Cheng et al., 2007 and Wei et al., 1990). Considering the source and nature of the MSW incinerated, flue gases emitted may contain significant amounts of particulate matter, sulfur dioxide, hydrochloric acid, dioxins, and heavy metals. Dioxins are considered a serious environmental concern associated with MSW incineration (Vogg et al., 1987). Although, with technological advancement in the design of incinerators and emissions handling due to regulations enforced dioxins are under control in developed countries (American Society of Mechanical Engineers, 2008 and Themelis, 2003), the total amount of PCDD/Fs emitted from MSW incinerators to the atmosphere in China was estimated to 19.64 g TEQ per year in 2006. However China has a regulation of 10 times the EU standard of dioxin emission 0.1 ng TEQ/Nm3. The incinerators are continuously being retrofitted with better emission treatment apparatus to deal with adverse public reaction against all WTE facilities. Despite the relatively high capital cost, the central government of China has put forth encouraging policies aiming to increasing WTE capacity such as provided a credit of about $30 per MWh of electricity generated, which being a byproduct of the incinerator operation, partially compensates the incineration costs. With the exception of some small-scale (100–200 t/d) furnaces (integrated models), the rest of the MSW incineration facilities in China have the ability of electricity generation (Nie, 2008 and Xu and Liu, 2007). Although in earlier years, WTE plants were designed to handle less than 725 tonnes of MSW per day, in recent years WTE plants are designed to handle typically 907 tonnes of MSW per day, i.e. a single process line within a plant has increased from 181 tonnes/day in early years to over 453 tonnes/day in recent years.

With the increasing importance of the development of sustainable waste management systems, an up-to-date status on current knowledge and practices is required. So we propose to address it by conducting a comprehensive, review of a few major MSW incineration systems that have been reported in scientific literature and public reports. We aim to:

(1) Provide a methodology for assessing performance of MSW Incineration systems
(2) Draw on this performance assessment to provide a contextual analysis that:
   a) Addresses the assessed types of waste and waste management systems in perception to the worldwide context of solid waste management.
   b) Reviews the quality of the MSW feed based on an energy content evaluation and classification scheme developed for this purpose
(3) Reviews the material capacity of incinerators and investigates the feasibility of future investments in developing new MSW incineration projects
(4) Based on the review and suggesting a few integrations that can be applied in practice to develop the quality of MSW feed, and provide guidance to ensure a robust application of proposed methodology.
(5)
(6) This paper describes the methodology used for conducting a performance review and addresses the above objectives (1) and (2). It is aimed to provide a useful performance review methodology to all the stakeholders involved in management of solid waste, but also decision- and policy-makers.

2. Literature Review

2.1 China in relation to MSW Incineration industry:

Cheng et. al, 2010 provides an extensive overview of the WTE industry, studying the major challenges in intensifying WTE incineration in China, viz a viz high capital and operational costs, corrosion of equipment, emission of pollutants, and disposal of fly ash. Demanding prospects from research and technology development focusing on above challenges along with beneficial reuse of residues for making MSW as a renewable energy source in China is presented. Cheng et. al, 2010 describe the advantages and disadvantages of 3 largest ways for MSW treatment namely Landfill, Composting and Incineration.. Different authors have highlighted the fact that that due to absence of effective leachate collection and treatment systems, a serious threat of contamination to surface water and groundwater sources in many landfill sites was found in over half of the existing landfills (Ministry of Construction of China, 2006 and Yan and Wu, 2003) as severe limitations in the availability of land space for construction of new lined landfills in many cities due to rapid urbanization. While emphasis is made upon how distinct compositional characteristics of MSW in China compared to those in developed countries in terms of organic components (~50%), moisture content (typically around 50% vs. 20–30% in the U.S. and European countries) and the calorific values (3000–6700 kJ/kg for Chinese MSW which is less than half of MSW produced from the west i.e. 8400–17,000 kJ/kg) has a direct influence on productivity levels in WTE plants, such similar efforts have been made analyzing the compositional characteristics of municipal solid waste in south China by (Zhang et. al., 2015). Valuable contributions are made by summarizing the need for development in WTE technologies to deal with the low quality MSW that is being generated in China, whilst providing analysis of the advancements made in a few WTE plants of china by technical upgrades. A detailed comparison in performances of stoke grate and fluidized bed MSW incinerators has been provided including assessments based on pre-treatment practices, auxiliary fuel, feeding methods, slag and fly ash production, startup and shutdown convenience and maintenance procedures. An unique observation comparing Stoke grate technology which is typically used in the economically more developed cities which rely predominantly on imported equipment because of their high costs and the heat content requirement (provided externally through burning fuel) for the MSW (>6000–6500 kJ/kg) (Nie, 2008 and Xu and Liu, 2007) with Fluidized bed incinerators which are based entirely on domestic technologies for much lower capital and operating capital and allow co-firing of MSW with coal (abundant low quality energy resource in China with relatively less costs than supplementing petroleum fuels) with ease conveying that a dynamic shift towards WTE incineration facilities based on domestic fluidized bed technologies in small and mid-sized urban epicenters, and the large cities in the middle and western parts of China (Nie, 2008 and Xu and Liu, 2007). However promising fluidized bed technology of co-firing MSW with coal faces a challenge in terms of treatment capacities currently limited to a small range of 100 t/d –500 t/d when compared to medium (500 t/d) or large (1000 t/d) capacities of Stoke grate furnaces.

Tai et. al., 2011 provides an overview of different methods of collection, transportation, and treatment of MSW of 8 cities, in addition to making a comparative analysis of MSW source-separated collection in China, the quantity and composition information of MSW showed that the characteristics of MSW are similar, which are low calorific value, high moisture content and high proportion of organics. While Beijing and Shanghai exhibited a relatively effective result demonstrating benefits in the deploying MSW source-separated collection, the six remaining cities result in poor performance. They also identified the urgent need in an integrated MSWM, mentioning that source-separated collection should be a key priority considering the current status of MSWM and is necessary for a wider range of cities should participate in this program instead of merely the eight pilot cities and also addressed problematic issues like improvement in legislation, coordination mechanisms and public education to encourage recyclable separation at the source.

Previous literature on incineration plants envelops technical, environmental, industrial, socio-economic, public health and political issues because of its multitudinous nature. Nevertheless, most studies consider MSW incinerators as WTE plants and emphasis on improving their performance on energy recovery or to evaluate pollution control efficiency from an technical or scientific perspective (Autret et al., 2007; Yang et al., 2007; Morselli et al., 2007; Kuo et al., 2008; Liamsanguan and Gheewala, 2007; Pai et al., 2008; Sharifah et al., 2008; Tsai and Chou, 2006; Huang et al., 2006); Estimating extent of the recycling volume would change following the introduction of an incineration tax (Sahlin et al., 2007). Most research does not consider utilizing the fact that WTE plants are also production decision making units (DMUs) providing the services of waste treatment and electricity, emitting undesirable pollutants like ash and dioxins, in addition to being waste treatment facilities. A sample perspective of motive can be, to improve the performance of any existing inefficiency, through classifying emissions of toxic wastes and pollutants as undesirable outputs while operating the DMU to generate desirable outputs viz a viz waste treatment and electricity services.

2.2 Data Envelopment Analysis in MSW

Data Envelopment Analysis has been extensively used to estimate the scale and technical efficiency in energy sector industries (e.g. Raczka, 2001; Pacudan and de Guzman, 2002; Vaninsky, 2006; Pombo and Taborda, 2006). Multiple literature findings have been made for its application in the waste sector, several of them employ the DEA technique to analyze MSW service efficiencies. Simoes et al. (2010) investigated the efficiency of the Portuguese urban solid waste services by using 29 samples of solid waste utilities based on DEA approach. The analysis results support that the relationship between service efficiencies and environmental context is significant. A huge effort has been made encompassing the attributed for characterizing the operational environmental context viz a viz GDP per capita, population density, distance to treatment facilities, incineration services. Gallardo et al. (2010) calculated the efficiency of various collection systems employed in Spanish cities based on several indexes defined by the authors. Marques and Simões (2010) conveyed the immense opportunity present in improving the performance of solid waste management services by attempting to examine the effects of Portuguese regulatory policy on the solid waste utilities' performance. Thereby using DEA tool, the efficiency of the Portuguese solid waste management services is assessed and the impacts of the environmental context on the operational efficiency is analyzed. Bosch et al. (2001 ????? 2000) analyzed the technical and cost efficiencies of the garbage collection services by applying a modified DEA model for the data of 73 municipalities of Catalonia.

Attempts towards implementing DEA for studying MSW incinerators have been made by Chen and Chang, (2012)??? Chen et al??? where multi-activity network data envelopment analysis has been used to appraise how incineration plants in Taiwan perform through examining the trade-offs between efficiency enhancement and pollution abatement, efficiencies of the waste treatment and electricity generation suggesting that efficiency of waste treatment activity takes priority over improving electricity generation activity to enhance the overall performance of

Taiwan’s incinerators.

(Chen and Chen, 2011) contributed towards comparing the relative efficiency across MSW incineration facilities under the three operating modes namely, government-owned government-operated (GOO), government-owned private-operated (GOPO), and private-owned private-operated (POPO) by using DEA to examine the factors affecting the efficiency variation showing that the technical efficiency scores are in an increasing order for GOO, GOPO and POPO.

2.3 Life Cycle Energy Analysis.

Life cycle energy analysis (LCEA) is a methodology accounting all energy inputs to a product. An earlier term for the approach was energy analysis. While disposed waste is incinerated gas produces more greenhouse gas emissions than landfilling, so the waste plants are retrofitted with filters to minimize this negative impact. Liamsanguan, C. (2009) developed a decision support tool for environmental assessment of MSW management systems and concluded that incineration is superior, with the exception of landfill gas being recovered for electricity production while comparing energy consumption and greenhouse gas emissions from landfilling (without energy recovery) against incineration (with energy recovery). A number of reviews have studied the application of LCEA to the field of solid waste management limiting their heir focus to specific types of waste or waste management systems or specific methodological aspects. Villanueva and Wenzel (2007), reviewed 9 LCEA studies assessing the management of paper and cardboard waste; Cleary (2009), made a comprehensive analysis of methodological conduct and findings of 20 studies assessing the management of municipal waste; Lazarevic et al. (2010) analyzed 10 LCEA studies assessing the management of post-consumer plastic waste in Europe; Gentil et al. (2010) and Björklund et al. (2011) provided overviews of existing models of LCEA applied to solid waste; and Morris et al. (2013) performed a meta-analysis of 82 studies assessing the management of organic waste. Just about all these reviews had shown interest towards a selection of high quality LCA studies, occasionally missing out on the explicit description of the selection criteria.

3. Methodology developed for analyzing performance

The methodology that will be used in this paper, in order to evaluate the performance of Chinese incineration plants, is Data Envelopment Analysis (DEA hereafter). Applying DEA an assumption is made that there are some inputs where though a production process are transformed into outputs. In this methodology each incineration plant is treated as a Decision Making Unit (DMU hereafter); it is assumed that $j=1,...,n$ DMUs consume $i=1,...,m$ inputs ($x_{i,j}$) in order to produce $r=1,...,s$ inputs ($y_{r,j}$). For each LP model solved, the reference set is constructed with λ_j, also called peers of DMU j. The efficiency of each DMU is derived by free variable θ. For each DMU the following Linear Programming model is solved:

$$
\begin{aligned}
&\min\ \theta \\
&s.t. \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot x_{i,j} \leq \theta \cdot x_{i,j_0},\ i=1,..,m \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot y_{r,j} \geq y_{r,j_0},\ r=1,..,s \\
&\quad \lambda_j \geq 0,\ j=1,..,n \\
&\quad \theta\ free
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
&\min\ \theta \\
&s.t. \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot x_{i,j} \le \theta \cdot x_{i,j_0},\ i = 1,..,m \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot y_{r,j} \ge y_{r,j_0},\ r = 1,..,s \\
&\quad \sum_{j=1}^{n} \lambda_j = 1 \\
&\quad \lambda_j \ge 0,\ j = 1,..,n \\
&\quad \theta\ free
\end{aligned} \tag{2}
$$

3.1 Measuring performance under exogenously fixed input variables

LP formulation (1) represents a Constant Returns to Scale (CRS) whereas LP formulation (2) represents a Variable Returns to Scale (VRS) input oriented DEA model, assuming that in order to improve the operations that are conducted through that production process, a reduction in the inputs must be considered. However, when dealing with DMUs with not only desirable, but undesirable outputs as well, a different formulation to (1), (2) must be taken into account. The extension of the "basic" DEA formulations is represented as follows:

$$
\begin{aligned}
&\min\ \hat{\theta} \\
&s.t. \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot x^{nf}_{i_1,j} \le \hat{\theta} \cdot x^{nf}_{i_1,j_0},\ i_1 = 1,..,m_1 \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot x^{f}_{i_2,j} \le \sum_{j=1}^{n} \lambda_j x^{f}_{i_2,j_0} \cdot,\ i_2 = 1,..,m_2 \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot y_{r,j} \ge y_{r,j_0},\ r = 1,..,s \\
&\quad \lambda_j \ge 0,\ j = 1,..,n \\
&\quad \hat{\theta}\ free
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
&\min\ \hat{\theta} \\
&s.t. \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot x^{nf}_{i_1,j} \le \hat{\theta} \cdot x^{nf}_{i_1,j_0},\ i_1 = 1,..,m_1 \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot x^{f}_{i_2,j} \le x^{f}_{i_2,j_0},\ i_2 = 1,..,m_2 \\
&\quad \sum_{j=1}^{n} \lambda_j \cdot y_{r,j} \ge y_{r,j_0},\ r = 1,..,s \\
&\quad \sum_{j=1}^{n} \lambda_j = 1 \\
&\quad \lambda_j \ge 0,\ j = 1,..,n \\
&\quad \hat{\theta}\ free
\end{aligned} \tag{4}
$$

LP formulations (3) and (4) extend basic LP formulations (1) and (2) considering exogenous inputs along with fixed inputs. The exogenous inputs as can be seen are not associated with variable $\hat{\theta}$ and potential reductions to exogenously fixed inputs are not captured by model; $x_{i_1,j}^{nf}$ are considered to be under managerial control. Model (3) is a CRS model whereas model (4) a VRS model. In order to utilise the information from both models, scale efficiency measure is considered and formulated as follows:

$$SE = \frac{\theta^{CRS}}{\theta^{VRS}} \tag{5}$$

When dealing with incineration plants, the consumption of inputs does not provide only desirable but undesirable outputs as well. The fixed inputs in this case can be labor, investment cost etc, which can be easily handled and controlled however, as during incineration the waste does not have a consistent composure the emissions cannot be controlled.

3.2 Measuring performance with the use of categorical variables

In the presence of categorical variables, the following LP formulations are adopted:

$$\begin{aligned}
&\min \ \overline{\theta} \\
&s.t. \\
&\qquad \sum_{j \in \bigcup_{j=1}^{p} S_j}^{n} \lambda_j \cdot x_{i_1,j}^{nf} \le \overline{\theta} \cdot x_{i_1,j_0}^{nf}, \ i_1 = 1,..,m_1 \\
&\qquad \sum_{j \in \bigcup_{j=1}^{p} S_j}^{n} \lambda_j \cdot x_{i_2,j}^{f} \le \sum_{j \in \bigcup_{j=1}^{p} S_j}^{n} \lambda_j x_{i_2,j_0}^{f} \cdot, \ i_2 = 1,..,m_2 \\
&\qquad \sum_{j \in \bigcup_{j=1}^{p} S_j}^{n} \lambda_j \cdot y_{r,j} \ge y_{r,j_0}, \ r = 1,..,s \\
&\qquad \lambda_j \ge 0, \ j = 1,..,n \\
&\qquad \overline{\theta} \ free
\end{aligned} \tag{6}$$

$$\begin{aligned}
&\min \ \overline{\theta} \\
&s.t. \\
&\qquad \sum_{j \in \bigcup_{j=1}^{p} S_j}^{n} \lambda_j \cdot x_{i_1,j}^{nf} \le \overline{\theta} \cdot x_{i_1,j_0}^{nf}, \ i_1 = 1,..,m_1 \\
&\qquad \sum_{j \in \bigcup_{j=1}^{p} S_j}^{n} \lambda_j \cdot x_{i_2,j}^{f} \le x_{i_2,j_0}^{f}, \ i_2 = 1,..,m_2 \\
&\qquad \sum_{j \in \bigcup_{j=1}^{p} S_j}^{n} \lambda_j \cdot y_{r,j} \ge y_{r,j_0}, \ r = 1,..,s \\
&\qquad \sum_{j \in \bigcup_{j=1}^{p} S_j}^{n} \lambda_j = 1 \\
&\qquad \lambda_j \ge 0, \ j = 1,..,n \\
&\qquad \overline{\theta} \ free
\end{aligned} \tag{7}$$

In LP formulations (6) and (7), the summation of the models is conducted upon a categorical variable. The sets that is assumed in this case (S_j), splits the incineration plants based on their technical characteristics. In this paper, four categories have been examined based on the technologies used. These categories were CFB Reactor (1), Multistage Grate Furnace (2), Martin Grate Furnace (3) and SITY 2000 Grate (4).

4. Application of the model

4.1 Input Data

The data that are used for this methodology are given in Table 1. The columns for Capacity and Investment serve as controllable inputs whereas LHV and non- combustible as exogenously fixed inputs. The reason behind that is that the quantity and LHV values cannot be controlled, as the municipal waste incinerated has no specific composure. Finally the output that is produced by incineration is electricity (sixth column of Table 1). In the last column of Table 1, the categorization of each incineration plant is presented.

Based on their characteristics the following incineration plants belong to the first category, S_1 ={INC1,INC2,INC8,INC12}, the following in the second category, S_2 ={INC4,INC7,INC9,INC11,INC14,INC16,INC20}, the following in the third category, S_3 ={INC3,INC6,INC13,INC14,INC15,INC17,INC18} and finally in the fourth category S_4={INC5,INC10,INC19}. Thus, four categories have been considered in this paper; based on those sets, the summation in LP formulations (6) and (7) are performed in Table 2.

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Table 1. Data of Chinese incineration plants

	Capacity	Investment	Non combustibles	LHV	Electricity Generated	Category
INC1	309375	100	6	10722.21	17	1
INC2	495000	139.68	6.5	16353.833	24	1
INC3	346500	63.33	19.3	5437	12	3
INC4	148500	34.13	31.335	4793.5	7	2
INC5	363000	45.4	13	7754	12	4
INC6	396000	63.49	13	7754	9	3
INC7	148500	36.51	13	7754	6	2
INC8	264000	68.57	13	7754	12	1
INC9	1095000	245	13	7754	18	2

	Capacity	Investment	Non combustibles	LHV	Electricity Generated	Category
INC10	396000	50	4.5	10788.58	24	4
INC11	396000	85.71	27.9	13325.758	24	2
INC12	330000	100	7.74	16092.579	15	1
INC13	547500	99.21	1.915	9889.9475	27	3
INC14	132000	31.75	25.5	11866.484	6	2
INC15	330000	57.94	37.39	11276.163	16	3
INC16	528000	119.05	30	12.655	14696.4695	2
INC17	396000	76.19	24	17	13897.91	3
INC18	264000	52.38	27	39.14	3007	3
INC19	171600	25.4	6	11.27	3030.23502	4
INC20	660000	153.49	40	7.74	16092.579	2

Table 2: Sets for summation in LP formulations (6) and (7)

	Set
1	$S_1 = \{INC1, INC2, INC8, INC12\}$
2	$\bigcup_{j=1}^{2} S_j = \{INC1, INC2, INC8, INC12\} \cup \{INC4, INC7, INC9, INC11, INC14, INC16, INC20\}$ $= \{INC1, INC2, INC4, INC7, INC8, INC9, INC11, INC12, INC14, INC16, INC20\}$
3	$\bigcup_{j=1}^{3} S_j = \{INC1, INC2, INC8, INC12\} \cup \{INC4, INC7, INC9, INC11, INC14, INC16, INC20\} \cup$ $\{INC3, INC6, INC13, INC14, INC15, INC17, INC18\} =$ $\left\{\begin{matrix} INC1, INC2, INC3, INC4, INC6, INC7, INC8, INC9, INC11, INC12, INC13, INC14, INC15, \\ INC16, INC17, INC18, INC20 \end{matrix}\right\}$
4	$\bigcup_{j=1}^{4} S_j = \{INC1, \ldots, INC20\}$

In this section the results of the analysis will be presented. In Table 3, the results derived from models (3) and (4) are presented along with Scale Efficiency. It can be seen that incinerations 10, 13 18 and 19 make full use of the inputs whereas the rest of the incinerators underperform.

Table 3. Results for Efficiency (CRS, VRS) and Scale Efficiency

	$\hat{\theta}^{CRS}$	$\hat{\theta}^{VRS}$	**Scale Efficiency (SE)**
INC1	0.888769	1	0.888768933
INC2	0.778982	0.780586114	0.997944425
INC3	0.495066	0.561159999	0.88221962
INC4	0.521899	1	0.521898757
INC5	0.569371	0.735865468	0.773743998
INC6	0.348384	0.488117838	0.713728837
INC7	0.619349	1	0.619348936
INC8	0.696768	0.827372576	0.842144849

	$\hat{\theta}_{CRS}$	$\hat{\theta}_{VRS}$	**Scale Efficiency (SE)**
INC9	0.251982	0.263335818	0.956883468
INC10	**1**	**1**	**1**
INC11	0.714495	0.716071924	0.99779764
INC12	0.718219	0.841315385	0.853686317
INC13	**1**	**1**	**1**
INC14	0.556286	1	0.556286059
INC15	0.537514	0.660124595	0.814261576
INC16	0.839234	0.867401565	0.967526583
INC17	0.841747	0.848329019	0.99224079
INC18	**1**	**1**	**1**
INC19	**1**	**1**	**1**
INC20	0.957626	1	0.95762591

The results for efficiency (CRS, VRS) and Scale Efficiency, based on formulation (7) are presented below in Tables 4 – 7.

Table 4. CRS efficiency for each of the categories examined (S)

S / *j*	**1**	**2**	**3**	**4**
INC1	1	1	1	0.888769
INC2	1	0.842259	0.828275	0.778982
INC3			1	0.495066
INC4		1	0.521899	0.521899
INC5				0.569371
INC6			0.460354	0.348384
INC7		0.939058	0.713442	0.619349
INC8	1	1	0.802623	0.696768
INC9		0.419816	0.290264	0.251982
INC10				1
INC11		1	0.722193	0.714495
INC12	0.876356	0.75	0.75	0.718219
INC13			1	1
INC14		0.764638	0.567208	0.556286
INC15			0.553691	0.537514
INC16		0.965253	0.903003	0.839234
INC17			0.960534	0.841747
INC18			1	1
INC19				1
INC20		1	1	0.957626

Table 5. CRS efficiency for each of the categories examined (S)

S / *j*	**1**	**2**	**3**	**4**
INC1	1	1	1	1
INC2	1	1	0.841637	0.780586
INC3			1	0.56116
INC4		1	1	1
INC5				0.735865
INC6			0.688189	0.488118
INC7		1	1	1
INC8	1	1	0.915345	0.827373
INC9		1	0.305755	0.263336
INC10				1
INC11		1	0.747133	0.716072
INC12	0.921874	0.861948	0.853225	0.841315
INC13			1	1
INC14		1	1	1
INC15			0.717532	0.660125
INC16		0.979922	0.920807	0.867402
INC17			0.974226	0.848329
INC18			1	1
INC19				1
INC20		1	1	1

Table 6: Scale efficiency for each of the categories examined (S)

S / *j*	**1**	**2**	**3**	**4**
INC1	1	1	1	0.888769
INC2	1	0.842259	0.984125	0.997944
INC3			1	0.88222
INC4			0.521899	0.521899
INC5				0.773744
INC6			0.668936	0.713729
INC7		0.939058	0.713442	0.619349
INC8	1	1	0.876853	0.842145
INC9		0.419816	0.949333	0.956883
INC10				**1**
INC11		1	0.966619	0.997798
INC12	0.950625	0.870123	0.879018	0.853686
INC13			**1**	**1**
INC14		0.764638	0.567208	0.556286
INC15			0.77166	0.814262

S / *j*	1	2	3	4
INC16		0.985031	0.980665	0.967527
INC17			0.985946	0.992241
INC18			**1**	**1**
INC19				**1**
INC20		1	1	0.957626

5. Conclusions

The proposed DEA approach is designed in order to provide assess the performance of incineration plants. The efficiency of 20 incineration plants have been evaluated based on inputs and outputs regarding operational aspect. For each plant the scale efficiency has been computed. A meta analysis of the plants has been performed grouping the plants into four major categories based on the technology used. From the analysis it has been reported that incineration plants 10, 13, 18 and 19 are scale efficient.

The proposed methodology provides insight to environmental authorities and can be a valuable policy tool for decision makers on the performance of incineration plants.

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