Designing a Sustainable Waste Management System: The Strategic Planning Model and Related Sustainability Issues

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Abstract: Developing countries have been suffering the most of uncontrollable waste dumping where current waste management systems are neither efficient nor sufficient. This paper discusses and presents a milestone in the design and operation of a sustainable waste management system for cities in developing economies wishing to improve their waste management practices. It discusses the fundamental process steps for the development of a strategic plan for waste management system integrating sustainability in its design and operations.

Keywords: sustainable waste management systems, cost benefit analysis, strategic planning and developing cities.

1 Introduction

The current consumption patterns worldwide, particularly in fast growing economies, generate an amount of wastes that cannot anymore be treated and processed in an unorganized and economically inefficient manner. Consumption has grown dramatically over the five past decades. In goods purchased, the increase between 1960 to 2006 represents 622% (in 2008, units in $). Of course a part of this increase can be explained by the rise in the world's population, however population only increased by 220% from 1996 to 2006, [1]. As a consequence, this excessive consumption impacts detrimentally different components of the environment such as air, water, soil, fossils and natural resources. The importance of these impacts is reflected in the amount of wastes generated and how these wastes are managed. Yet, while these consumption patterns seem natural they are neither sustainable nor inborn. They have been developed over time and actively being spread and reinforced to developing countries with low awareness levels.

To mitigate the impact of this consumerism two parallel lines of action should be put forward. First, the dominant habits in consumer cultures has to be changed. Transforming cultural habits takes decades of effort to happen. A key to this change is to direct the fundamental cultural institutions such as education, business, government and media towards sustainability [2]. Second, focusing on utilizing solid waste management drivers, frame works, performance indicators that could catalyze the transfer to a more sustainable system. The development of waste management drivers have been investigated by Wilson et al. and Marshall and Farahbakhsh [3, 4]. Different waste management frameworks were also proposed and can be found in [5-7]. While performance and sustainability indicators have been discussed in [8-13]. Models and Methodologies for solving the waste management problem will be further discussed in later sections of this paper.

The performance of the waste management system assessment process in a city is dependent on the degree of success in integrating assessment findings into decision-making during the planning and implementation process. The linkages between appraisal and decision making are not well researched and understood, particularly in less developed countries and countries in transition. The current work highlights the development process of a decision support tool that would aid decision makers during the strategic planning phase. The main aim of waste management is to treat, reuse, recycle and recover energy whenever possible[14]. In the available literature on waste management, it is common to find research work tackling any of the sub-systems involved in waste management. Some papers compare different recycling techniques, others different energy recovery alternatives, and others different composting methodologies [15-17]. The current paper investigates the waste management problem as whole. It tackles different sub-systems concurrently and attempts to model the relationship relating these sub-systems.

The development of a sustainable waste management system, particularly for rapidly growing cities in developing economies, entails designing a sustainable system which must quickly become effective while generating a revenue that could guarantee its sustainability. The main objectives of the system is drastically reducing open dumping and uncontrolled burning practices. Educating citizens to abandon these practices, that have damaging impacts both on their environment and their health, in developing economies is certainly fundamental. Designing a system which is capable of providing incentives to deviate from these harmful practices is a strategy that is likely to guarantee sustainability. The proposed strategic model is the first step towards the development of such a system which utilizes the general framework proposed by Elsaid and Aghezzaf [7] as the fundamental basis.

The main streams in a municipal waste management system - organic wastes, recyclables and non- recyclable- are often collected in a mixed spectrum from households in developing countries. A sorting process takes place to obtain as much as possible of recyclables. We propose a model for the design phase that help cities selecting the appropriate treatments and their corresponding capacities. Before starting the modelling step at the strategic level, it is imperative to understand and discuss the various types of solid waste and their treatment and output possibilities. Section 3 presents the bases for the strategic model, some solution methods and governing equations.

2. System Breakdown Structure

2.1 Recycling

Collected wastes are either sorted or unsorted at source. Unsorted wastes will have to go through a sorting process to separate recoverable materials. Paper, glass, plastic and metal are recyclable materials that can be either reused or recycled. Paper enters the municipal solid waste stream in different forms (e.g., newspaper, cardboard, fine paper, etc.). The paper recycling process involves several steps. The paper are sorted according to color, then repulped into very small pieces. The repulped paper is mixed with water to produce a slurry. The slurry is pressed to produce recycled paper which could be bleached to obtain white paper if required.

Glass is mostly found in municipal solid wastes in the form of beverages or food containers. Glass is first cleaned to remove impurities then sorted according to color. Glass is broken into small pieces then melted in a furnace, which can be used for the production of new bottles. Unlike paper, once the impurities are removed there will be no quality loss in recycled glass of the same color.

Plastics are found in MSW usually comprise a wide range of polymers that are mainly used in food and drink containers, and accordingly have a very short life cycle span. The most common form of plastics are the polyethylene in its different forms (HDPE, LDPE and LLDPE) and polyethylene terephthalate (PET). Other plastics such as polyvinyl chloride (PVC), polystyrene (PS) as well as other resins are also found in smaller quantities [18]. A separation phase takes place to separate different plastics according to resin type. Plastics are compacted and washed and shredded. The shredded plastics are extruded into rods which can then be used as a raw material for new products. The recycling process is not an emissions free process; Hanandeh and El-Zein presented a list of tables including the emissions resulting from different recycling processes [18].

Metals are sorted according to material. The metals found in municipal solid wastes are mainly iron and aluminum. Metals are cleaned to remove organic wastes attached. Painting and coating are also removed. Metals are separated according to type then molten in a furnace to generate new products.

2.2 Composting

Composting is one of the oldest practices in waste utilization [19]. Composting is an aerobic biological process, in which the organic fraction is broken up by microorganisms into a biologically stable substance. The decomposition process results in a stabilized product that can not degrade further and can be used as natural soil fertilizer. The process of composting occur in the presence of oxygen, and can be either natural or controlled. The commercially sold compost is a result of controlled composting where the organic wastes are cut into small pieces and piled. Under favorable oxygen and water conditions, microorganisms find their way to the organic piles producing compost. In some cases such as worm composting (vermicomposting), warms are introduced to the pile intentionally. The composting process can take any time between one month and one year depending on the composting process used. The compost is sieved to remove impurities such as small glass, plastic pieces or big organic parts that have not decomposed fully.

2.3 Waste to Energy (WTE)

Energy generated from wastes has become an economic alternative as well as a way to get rid of wastes [16]. There are different alternatives for obtaining energy in terms of expenses and technologies used to generate energy from wastes. Such variety imply substantial investment and operating cost as well as efficiencies and environmental implications. There are two main categories of energy generation from wastes:

1- Transforming wastes to electric or heat energy by incineration, gasification or pyrolysis.

Incineration is the most widely used waste to energy technique for example Taiwan incinerates 53% of its wastes while Denmark, incinerates 48% of its MSW, Switzerland and Sweden with 49%, the Netherlands at 39% and Germany at 34% (data from 2009) [16] . Incineration uses municipal wastes (with or without sorting) as a fuel to generate energy through burning them in large incinerators at high temperature (above 800 C), and the heat generated is then used in a steam power generation cycle to produce electricity. There is also waste generated from incineration which is mainly ash. This ash could be further utilized in some road construction applications or possibly landfilled depending on the composition of the original wastes incinerated.

Similar to incineration gasification and pyrolysis are other WTE techniques that are characterized by a heavy investment and a high operating cost. The U.S. Environmental Protection Agency (EPA) named WTE technology as one of the cleanest sources of energy due to the steadily diminishing levels of dioxin, furan, mercury, and other volatile metal emissions over the last 20 years [16]. However WTE technologies are not emission free processes. Burning wastes in massive incinerators destroys chemical compounds and bacteria but also generates carbon dioxide, nitrogen oxides and sulphur dioxide which are all environment pollutants [17].

2- Collecting methane from landfills or biogas from anaerobic digestion

Methane is continuously released mainly during landfill operation, but can also extend long after landfill closure; methane generation is uncontrollable because it is produced by the anaerobic microbiological activity within the landfill material due to the closed nature of landfills which prevents aeration. Because methane is a greenhouse gas with commercial value, effort has to be made to capture and use it as a source of energy [16].

A similar in concept process is anaerobic digestion which consist of air proof digesters where organic wastes are fed in to a digester in the absence of oxygen.

Anaerobic microorganisms degrade the wastes releasing methane, which is collected and used as an energy source. Another bi-product of anaerobic digestion is a digestate, which is rich in nutritious compounds.

2.4 Landfilling

Landfilling is the most common practice of MSW management. Landfilling is a way to store wastes under safe conditions and in a lot of cases it is the only affordable solution. Modern landfills are highly engineered facilities that are specifically designed to stabilize the waste and minimize its hazards to the public and environment. Landfills are constructed by digging deep pitches and with special liners that cover the bottom and sides of the landfill to make sure that waste material will not contaminate the soil and underground water. Wastes are introduced to the landfill in thin layers that are then compacted and covered with isolating substances. A leachate collection system is designed to remove leachate generated from waste decomposition. A methane collection system could be possibly installed to collect methane. Several countries around the world have issued directives to minimize the amount of waste sent to landfills. Nevertheless, it is impossible to eliminate the need for landfills because some materials are thermodynamically impossible to recycle [18]. However, landfills need to be well designed, maintained and operated to ensure environmental sustainability.

3. A Strategic Planning Model Toward development

3.1 Integrating Economic and Environmental Models

The current research links the economic and environmental models underlying the waste management problem. Figure 1 shows the supply chain within the waste management system. Both an example of a reverse supply chain and a forward supply chain are presented. In the case of reverse supply chain the municipal solid wastes represent the raw materials (provided by a supplier) which go through a treatment process (manufacturing process) resulting in energy, compost and secondary products. The secondary products act as raw material for the forward supply chain that end in a product. Thus, clarifying the closed loop process that could be attainable.

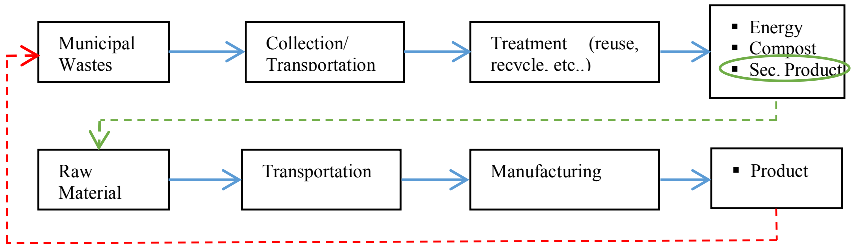

Figure 1: supply chain within a waste management system.

3.2 A brief literature review on existing models and solution methods

The municipal solid waste management problem has been widely tackled in literature due to its importance. In this section we will give a briefing of the solution methods encountered, however the current research approaches the problem from a different perspective. The aim of the current contribution is the development of a long term strategic plan for a sustainable waste management system for developing cities where the capacities and technologies are still undetermined. Chang et al 2011 classified solution methods for waste management problem in two broad spectrums. (I) systems engineering methods and (II) system assessment tools [20].

(I) System engineering methods include cost benefit analysis (CBA), forecasting models (FM), simulation models (SM), optimization models (OM), multi criteria decision models (MCDM) and integrated modelling systems (IMS). Results obtained from cost benefit analysis along with simulation and forecasting models can be utilized in designing Integrated management system or a multi criteria decision method.

Earliest attempts to solve waste management related problems utilized Linear programming which has been widely used to solve regional planning models and the related cost accounting [21, 22]. Solano et al. presented a linear programing optimization model for integrated solid waste management that recognizes alternative strategies that meet cost, energy and environmental emissions objectives [23, 24] . Mixed-integer linear programming (MILP) has been used to solve a dynamic, multi-period investment model for regional solid waste management [25]. Vadenbo et al. presented a MILP model that combines material flow analysis, process models of waste treatments and other industrial processes, and mathematical optimization techniques within a unified framework [26]. Minciardi et al. developed a nonlinear multi-objective model to optimize the flow of waste to alternative treatment plants [27]. Another approach is Multi-Criteria Decision Making (MCDM) methods. MCDM is a sub discipline of operations research that deals with complex problems involving conflicting constrains. Due to the multi-dimensional nature of the problem of waste management which require the consideration of a significant number of usually conflicting criteria (technical, economic, environmental and social aspects), MCDM has been frequently used in order to come up with the optimal solution among alternative scenarios [21]. In the presence of multiple criteria, a unique optimal decision for the problem does not exist but rather many or even infinitely many decisions are suitable. There is no one optimal solution in MCDA, criteria are selected and weighted , evaluated and finally aggregated [22].

(II) System assessment tools include decision support systems (DSS), expert systems (ES), and management information system (MIS). Such systems can utilize results from systems engineering methods or could be based on heuristic approaches. System assessment tools also entails more comprehensive types of assessments such as scenario development, material flow analysis, life cycle assessment, risk assessment, environmental impact assessment, strategic environmental assessment, socioeconomic assessment, and sustainable assessment. [23].

The most famous among the system analysis tools in literature is Life cycle assessment. Since most mathematical models cannot grasp the interaction between processes and stages of the waste management system. With the rise of the concept of integrated waste management, Life cycle assessment has emerged as an effective methodology for incorporating environmental draining within integrated waste management. Several papers utilized LCA to compare between different alternatives while foreseeing the environmental impact of these alternatives [24-27].

3.3 System Design's Strategic Planning Model

Let W be the set of all possible waste types and Q_w be the total amount of waste type w that is generated on a yearly basis. α_w is the at source unsorted fraction of the total amount Q_w. The amount $\alpha_w Q_w$ can either go to a Separator S or can directly go to treatment facilities without sorting as seen in figure 2.

There are four possible treatment categories in the current model; recycling R, organic composting C, waste to energy W and Landfilling L. Within each category different technologies could exist which are not determined at this level. For example different waste to energy technologies could be incineration, pyrolysis and gasification.

At the strategic planning phase of the waste management system's design, the treatment categories are variables that would be decided on, by solving the model. Hence depending on the chosen treatment technology at each facility, some wastes could be generated and internally transferred to a facility in the system where it could be best treated as shown in figure 2.

Accordingly α_w, Q_w are input parameters that describe the current waste management practices of a given city. $QUX_w, QUE_w, QUL_w, QXR_w, QXC_w, QXE_w, QXL_w, QSR_w, QSC_w, QSE_w, QSL_w$ are the amounts of wastes going between different facilities and are independent variables assigned by the model as an output. QRE, QRL, QCE, QCL, QEL are wastes generated from different treatment facilities and are dependent variables which are also outputs of the model. REC, SEC, COM, WTE, LTW stand for the amount of recycled material, secondary products, compost, energy, and biogas from landfill consecutively.

Choosing the treatment technology depends on the waste composition of the city and the amount of investments they are willing to make in the system. For example, different alternatives of treating wastes are proposed such as incineration, gasification and recycling but choosing on whether to use the three technologies simultaneously or choose among them and with which capacities are all decision variables that would be obtained by solving a specific problem. It is inevitable to have a landfill since there will always be some inert materials that could not be treated and hence, landfilled.

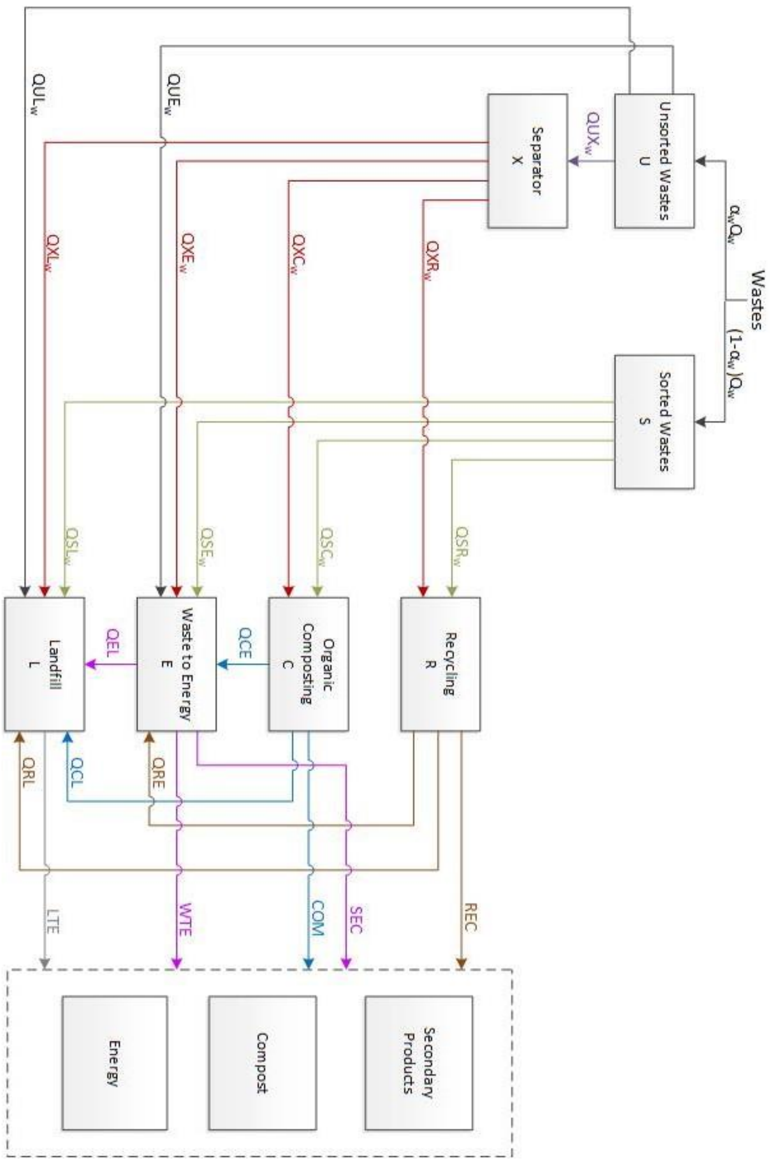

Figure 2: A diagram representing the flow of wastes and the different treatment categories for a city waste management system.

3.4 The Generic Strategic Planning Model

The system design is based on a cost benefit analysis which compares the gains and the losses related to each decision. The model is meant to provide a solution which takes into account the proper characteristics in terms of waste generated and the economic development. All fundamental benefits and losses must be measured and with the same units to be able to compare. The purpose is to help decision makers find an appropriate strategic plan for a sustainable waste management system.

The objective function of the model is to reach sustainability where the benefits from selling the system outputs balances or exceeds the costs of running the system. Therefore, the objectives becomes to maximize benefits.

Maximize:

$$ValR(REC) + ValS(SEC) + ValC(COM) + ValE(WTE) + ValL(LTE) - \Bigg[\sum_{w}^{W} Sepacost(QUX_w) + [Recycost \sum_{w}^{W}(QSR_w + QXR_w)] + [Compcost \sum_{w}^{W}(QSC_w + QXC_w)] + [Enrgcost(QCE + QRE + \sum_{w}^{W}(QSE_w + QXE_w + QUE_w)] + [Lanfcost(QEL + QCL + QRL + \sum_{w}^{W}(QSL_w + QXL_w + QUL_w)\Bigg]$$

Where ValR, ValS, ValC, ValE, ValL are unit sale price from selling the recycled materials, secondary products, compost, energy and biogas. Sepacost, Recycost, Compcost, Enrgcost, Lanfcost are costs incurred from sorting, recycling, composting, waste to energy and landfilling processes.

Subject to:

Mass flow constraints:

For Unsorted wastes

$$\sum_{w}^{W} \alpha_w Q_w = \sum_{w}^{W}(QUX_w + QUE_w + QUL_w)$$

Separator

$$\sum_{w}^{W} QUX_w = \sum_{w}^{W} (QXR_w + QXC_w + QXE_w + QXL_w)$$

Sorted Wastes

$$\sum_{w}^{W} (1-\alpha_w) Q_w = \sum_{w}^{W} (QSR_w + QSC_w + QSE_w + QSL_w)$$

<u>Output wastes:</u>

Recycling

$$QRE + QRL = R_r \sum_{w}^{W} (QSR_w + QXR_w)$$

Composting

$$QCE + QCL = R_c \sum_{w}^{W} (QSC_w + QXC_w)$$

Waste to Energy

$$QEL = R_e \left[QRE + QCE + \sum_{w}^{W} (QSE_w + QXE_w + QUE_w) \right]$$

where R_r, R_c, R_e are reduction ratios for wastes coming out from recycling, composting, waste to energy by mass.

<u>Output products and energy constraints:</u>

Recycling

$$REC = \eta_r \sum_{w}^{W} (QSR_w + QXR_w)$$

Composting

$$COM = \eta_c \sum_{w}^{W} (QSC_w + QXC_w)$$

Waste to Energy

$$WTE = \eta_{e1} \left[QRE + QCE + \sum_{w}^{W} (QSE_w + QXE_w + QUE_w) \right]$$

$$SEC = \eta_{e2} \left[QRE + QCE + \sum_{w}^{W} (QSE_w + QXE_w + QUE_w) \right]$$

Landfill

$$LTE = \eta_l \left[QRL + QCL + QEL + \sum_{w}^{W} (QSL_w + QXL_w + QUL_w) \right]$$

Where $\eta_r, \eta_c, \eta_{e1}, \eta_{e2}, \eta_l$ are correlation factors between amount of input waste and amount of recycled products, compost, energy, secondary products, landfill gas generated

Non negativity constrains:

$$QUX_w, QUE_w, QUL_w, QXR_w, QXC_w, QXE_w, QXL_w, QSR_w, QSC_w, QSE_w, QSL_w,$$
$$QRE, QRL, QCE, QCL, QEL, REC, SEC, COM, WTE, LTW \geq 0$$

Capacity Constraints:

Separator

$$\beta_s\, CapSL \leq \sum_{w}^{W} QUX_w \leq \beta_s\, CapSU$$

Recycling

$$\beta_r\, CapRL \leq \sum_{w}^{W} (QSR_w + QXR_w) \leq \beta_r\, CapRU$$

Composting

$$\beta_c\, CapCL \leq \sum_{w}^{W} (QSC_w + QXC_w) \leq \beta_c\, CapCU$$

Waste to Energy

$$\beta_e\, CapEL \leq QRE + QCE + \sum_{w}^{W} (QSE_w + QXE_w + QUE_w) \leq \beta_e\, CapEU$$

Landfill

$$\beta_l\, CapLL \leq QRL + QCL + QEL + \sum_{w}^{W} (QSL_w + QXL_w + QUL_w) \leq \beta_l\, CapLU$$

$\beta_s, \beta_r, \beta_c, \beta_e, \beta_l,$ are binary decision variables that determine if this method is used

$CapSL, CapRL, CapCL, CapEL, CapLL$ are lower bound capacities for separator, recycling, composting, waste to energy and landfill.

$CapSU, CapRU, CapCU, CapEU, CapLU$ are upper bound capacities for separator, recycling, composting, waste to energy and landfill.

The current model requires that the technology functions $\eta_r, \eta_c, \eta_{e1}, \eta_{e2}, \eta_l$, reduction ratios R_r, R_c, R_e and capacities be specified. The application of cost benefit analysis to environmental problems in developing countries must take into account that the problems taking place are very different from that taking place in industrialized countries [28]. Hence to obtain a fully sustainable system economic, social and environmental factors need to be incorporated. Accordingly the current generic model is only a milestone is the process of development of such sustainable system.

Conclusions and Remarks

The problem of managing waste is one of the major problems that each urban community is and will be facing in future. It is even one of the severe problems for the communities in developing countries. The aim of the current work is to propose a design tool that can help decision makers develop sustainable solutions for waste management in their developing cities. As a first step in this direction, a strategic planning model underlying the tool is presented as a milestone for the current research.

The proposed model attempts to address questions such as whether it is better to do sorting after collection or use waste treatment technologies that do not require sorting, what type of treatments could be combined with landfilling to assure sustainability of the system, and many others. Furthermore, the model could also demonstrate the benefits of sorting at source as an economically proven strategy, and therefore developing cities may be encouraged to consider at source sorting plans. The model provides thus, a customized tentative solution for cities wishing to improve their waste management system while considering the specific constraints to the developing communities and economies.

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