Applications of Systems Thinking in Integrated Solid Waste Management Planning for African Cities: The case of Nairobi, Kenya

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Declaration

I know the meaning of plagiarism and declare that all the work in this document, save for that which is properly acknowledged, is my own.

Allison Kasozi ..... Date: .....

Acknowledgements

I come to the start of a road I have not figured out completely, but a road I hope will have many great returns as it is enjoyable. I prefer to call this work not a completion or the end of a phase, but rather simply a step in my journey of intellectual curiosity and application, and hopefully a similar step for many others. For learning never stops, if it did we would not be here to enjoy the many pleasantries that scientific discovery and enterprise have benefited us.

It is sometimes difficult to express the full gratitude one would like to extend to those that have helped them get where they are, but I hope I can try to even a little here. This work is dedicated to my parents, Dr. Stuart Kasozi & Mrs. Miriam Kasozi, who have worked tirelessly to teach me the values of hard work, perseverance and love, values I hope my life can one day reflect more fully. I am deeply indebted to you, for all your sacrifice, motivation, and support. I also want to express my love and gratitude to my sister, Aida, and brother, Nsubuga, for being the supportive and inspiring people you are. They say you don't choose your family, but am certain somewhere in the heavenly lottery I won in getting you two! Thank you Porogo, thank you for who you are; for always loving, always supporting, and always smiling at life, and yeiih we'll still be smiling at 80!☺ Thank you Ms. Stella Kasozi and Ms. Aida Kasozi for pushing and continually supporting me in my studies, what a journey it's been and still is! I hope you all see some reflection of your inspiration and love in this work.

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Allison Kasozi
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Synopsis

The majority of solid waste generated by urban living cannot be assimilated in the city environment, and initial improvements in urban cleanliness and health were only realized when organized waste collection and disposal outside of city limits was introduced in Europe in the late 19th century. Sanitary landfills were later invented to reduce the environmental effects of large unsecured dumpsites, it is now however increasingly being shown that this too as a waste management strategy offers a worse environmental footprint than material and energy recovery and recycling (Cherubini *et al.*, 2009). Modern approaches to solid waste management, collectively referred to as Integrated Solid Waste Management (ISWM), therefore increasingly incorporate strategies to reduce waste generation and to encourage re-use and recycling of materials, and recovery of energy; with land filling as a last option for residual waste. This represents a shift in waste management paradigms from a focus on collection for disposal, to an increasing integrated interest in the entire waste chain from waste generation to material and energy recovery and recycling, and to safe residual treatment and disposal. The increasing acceptance of Mebratu's (1998) cosmic interdependence model as a more realistic conceptualisation of our world and how its natural, social, and economic spheres interact however implies that sustainable waste management design needs to take a further leap into a systems discourse, and cannot be considered in isolation of a rigorous understanding of the systemic interactions of the social and economic circumstances unique to particular areas. This calls for a greater understanding of how ISWM principles fit within the social and economic contexts of given areas; an analytical gap that can be filled through the use of systems thinking and systems-based tools to multi-dimensionally investigate, and articulate the structures and relationships that often underlie complex situations. While systems thinking has found wide application in the sustainability sciences as a prerequisite to building truly sustainable systems (for example Capra, 2002 and Hjorth & Bagheri, 2006), it has as yet found little application in waste management analysis and designs, which have evolved from simple problem-oriented to "integrated" engineering methods.

In response to dire solid waste conditions in Nairobi, the government of Kenya agreed in 2009 to collaborate with UNEP to develop an ISWM Strategy for Nairobi. The project was initiated in March 2009, and a National Task Team was established to oversee the development of the plan along with a team from the University of Cape Town, of which the author was part. The core elements of the resulting Nairobi City ISWM Strategy (CCN & UNEP, 2010) were finalised in April 2010 and included, alongside the formal use of the UNEP ISWM planning methodology, some application of systems analysis. These systems analyses could however only be partially developed due to project delivery time constraints, and this dissertation extends these analyses to completion and explores their implications for ISWM in Nairobi.

Systems based tools from the research area of system dynamics were applied to systematically structure the waste problem and situation in Nairobi, and to develop conceptual causal loop models articulating the solid waste system in Nairobi as a whole. This enabled the highlighting of inherent waste system strengths and weaknesses in Nairobi, system drivers, leverage points, behavioural archetypes, and resulting implications for ISWM planning in Nairobi. The insights generated were used to inform an examination of whether the intervention strategies finally developed in the Nairobi ISWM Strategy Plan (CCN & UNEP, 2010) were adequate at a fundamental level and sufficiently relevant. It was also determined that the bulk of Nairobi's solid waste is organic, and that the material recycling and reuse capacity in the city is a key system driver in its waste management

towards ISWM, of which organic waste valorization comprises a significant part. It was therefore of interest to determine the current capacity, and potential for expansion of organic waste valorization in the city towards amplifying material recycling as a system driver towards ISWM.

The application of a systems based analysis of Nairobi's waste management identified the presence of ten system drivers of varying nature and flexibility, through which to influence the achievement of ISWM objectives in the city. Potential system leverage points in Nairobi's waste sector were also identified and allowed the development of additional systemic interventions through which large waste sector changes towards ISWM may be achieved with relatively small inputs. The solid waste management scene in Nairobi was also found to involve a combination of two systems archetypes as defined by Braun (2002): a '*Success to the successful*' trend of private waste collection relative to the City Council, embedded within a larger '*Tragedy of the Commons*' trend – the commons being the city's economic, human, and natural capital; and implicitly its potential revenue base for collection service providers, whose tragic diminishing for all will be the inevitable result if the current operation and disposal practices of both the private collectors and the City Council continue. The interventions proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010) were found to have targeted many of the fundamental causes leading to the current solid waste situation in Nairobi, due in part to the partial use of systems analysis in their development by the author; additional insights were however generated from the completed systems analysis discussed in this dissertation. These highlight a need for the development of policy consistent with eight extra systemic interventions, six of which may be considered critical to the success of ISWM efforts in Nairobi.

The latter focus on the potential of organic waste valorization to amplify Nairobi's material recycling capacity as a waste system driver towards ISWM revealed that there is a leakage of 14% to 23% of all waste in the city due to organic waste degradation at open dumps or collection points. There is a current interest in the use of such organic wastes as animal feed in Nairobi City, and this use represents a promising but seemingly under tapped organic waste valorisation potential that is likely to gain in importance in future. Bulk compost production from organic waste is uneconomical under the present market conditions in the city, and does not currently offer a rational option for the bulk valorisation of organic wastes in Nairobi. The anaerobic digestion of organic waste for energy however shows potential to achieve radically improved organic waste valorisation levels in the city, and from techno-economic modelling undertaken of potential medium scale biogas-to-energy plant investments, seems feasible at the current biogas energy feed-in tariffs of 6 KShs/kWh (≈ 8 US Cents/kWh) with a requirement of a small tipping fee of KShs. 1/kg organic waste treated; and yields a fair pay-back period of ≈ 8 years. An energy feed-in-tariff target of about 13-14 KShs/kWh electricity (≈17-19 US Cents/kWh) and an organic waste tipping fee of KShs. 1/kg organic waste treated, is recommended to achieve more attractive investment payback periods of under five years for especially private investors, and generally agrees with feed-in tariff recommendations by Fischer *et al.* (2010) of 18.05 US Cents/kWh electricity for combined heat and power CSTR-type biogas facilities in Kenya.

Overall, the application of systems thinking based tools and techniques in planning for ISWM shows a great potential to add value to the formal UNEP ISWM methodology by enabling a simple but powerful, structured synthesis of waste management observations derived from data collection across different disciplines. The application of systems based tools also shows potential to enhance stakeholder ownership of the intervention actions finally proposed in an ISWM Plan derived with the application of these techniques, building on UNEP's participatory stakeholder approach. Findings on

organic waste valorisation practice in Nairobi strongly suggest that in order to successfully develop organic waste valorisation in developing African cities as drivers towards ISWM, there is a need for strong, visionary, and enterprising government support structures to provide a conducive investment environment for potential investors. The valorisation of organic waste, especially through anaerobic digestion for biogas-to-energy at the small to medium scale, shows promising potential to contribute radically to waste diversion from landfill in developing African cities and to achieve systemic ISWM goals.

Recommendations are made for revisions and additions to the Nairobi ISWM strategy (CCN & UNEP, 2010), for the formal application of systems thinking based techniques and tools in UNEP's ISWM planning methodology, and finally for the realisation of greater organic waste valorisation levels in Nairobi.

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Abbreviations

CBO – Community Based Organisation

CBD – Central Business District

CCN – City Council of Nairobi

CCN DoE – City Council of Nairobi Department of Environment

CLD – Causal Loop Diagram

ERC – Electricity Regulatory Commission

GHG – Green House Gases

GTZ – Gesellschaft für Technische Zusammenarbeit (German Technical Cooperation Agency)

ISWM – Integrated Solid Waste Management

ITDG – Intermediate Technology Development Group, now Practical Action

JICA – Japan International Cooperation Agency

Kengen – Kenya Energy Generation Company

KNCPC – Kenya National Cleaner Production Centre

KOAN – Kenya Organic Agriculture Network

KPLC – Kenya Power and Lighting Company

KShs. – Kenya Shillings

LA – Local Authority

MEMR – Ministry of Environment and Mineral Resources

MOLG – Ministry of Local Government

MoNMD – Ministry of Nairobi Metropolitan Development

MoPHS – Ministry of Public Health and Sanitation

MSW – Municipal Solid Waste

NEMA – National Environmental Management Authority

NGO – Non-Governmental Organisation

NTT – National Task Team (Multi-Public/Private Stakeholder team commissioned to oversee the execution and implementation of the UNEP/CCN Nairobi ISWM Project)

RA – Resident Association

OECD – Organisation for Economic Cooperation and Development

SWM – Solid Waste Management

UNEP – United Nations Environmental Program

UN-Habitat – United Nations Human Settlements Programme

UNDP – United Nations Development Programme

UN-OCHA – United Nations Office for the Coordination of Humanitarian Affairs

1 Introduction

1.1 Background

Urban living generates a variety of solid wastes that cannot be assimilated in the city environment. Large improvements in urban cleanliness and health were realized when organized solid waste collection and disposal outside of city limits was introduced in Europe in the late 19th century. Sanitary land-filling was later invented to prevent environmental degradation arising from large dumpsites. More recently, it has been shown that sanitary land-filling as a waste management strategy offers a worse environmental footprint than material and energy recovery and recycling (Cherubini *et al.*, 2009). It has also always been true that one person's waste can be another person's resource. Modern approaches to solid waste management therefore incorporate strategies to reduce waste generation and to encourage re-use and recycling of materials, and recovery of energy; with land-filling as a last option for waste that cannot be absorbed alternatively. The emergence of these approaches, codified in the ethos of Integrated Solid Waste Management (ISWM), represents an improvement in waste management paradigms with a shift from a focus on collection for disposal, to an interest in the entire waste chain from generation to material and energy recovery and recycling, and lastly to safe treatment and disposal.

The increasing acceptance of Mebratu's (1998) cosmic interdependence model as a conceptualisation of our world and how its natural, social, and economic spheres interact, however, implies that sustainable waste management design, in pursuit of greater levels of sustainable development, cannot be considered in isolation of social and economic influences. This calls for a greater understanding of how ISWM principles can fit within the social and economic contexts of particular areas; a framework of analysis which is amenable to systems thinking – a research area which seeks to investigate and articulate the structures and relationships that often underlie complex situations in a multi-dimensional manner. Indeed, while systems' thinking has found wide application in the sustainability sciences as a prerequisite to building truly sustainable systems (see for example Capra, 2002 and Hjorth & Bagheri, 2006), it has as yet little application in waste management analysis and design.

Developing cities, especially in Africa, are often characterised by high population growth and urbanisation rates coupled to slower economic growth. This has resulted in rapidly increasing solid waste volumes, and low waste collection and safe disposal levels due to the prevalent lower economic growth conditions. This has led to an increasing public waste service provision backlog, with this vacuum increasingly being taken up by private collectors, community based organisations, and actors in informal waste recovery and recycling. These circumstances render idealised traditional command and control waste management strategies in developing African cities largely untenable, and further favour systems thinking based analyses to understand present causalities and interrelationships in waste management more holistically, and to highlight opportunities for the realisation of ISWM in the context of the developing African city.

1.2 Thesis Origins

Nairobi city, the capital of Kenya, has experienced four decades of exponential population growth, much of it in slum urbanisation. This has translated into significant volumes of solid waste generation that neither the inhabitants nor the local government structures can deal with. Current official waste management policy, which is largely waste collection to disposal at dumpsite/landfill, cannot be sustained in the longer term due to increasing disposal costs with waste volumes, increasing scarcity of landfill space and the environmental risks of landfill schemes. The official dumpsite at Dandora has been

shown to be directly responsible for extensive environmental pollution into surrounding areas including the Nairobi River, resulting in public health hazards (Kimani, 2007). In addition, it has reached capacity and the end of its service life is on the horizon. While a decision has been reached by the municipal authorities to move to a new engineered sanitary landfill at Ruai in future, there remains an urgent need for a holistic solution to the bigger waste challenge. This needs to be in the form of an Integrated Solid Waste Management (ISWM) system with emphasis on waste reduction, recovery, reuse and recycling efforts; with waste treatment and landfill disposal as the last management options for preferably residual wastes. The Kenyan government agreed in 2009 to collaborate with the United Nations Environment Program to develop an Integrated Solid Waste Management (ISWM) Strategy for Nairobi City, dealing with the entire waste chain. The core elements of this strategy were finalised in April 2010 (CCN & UNEP, 2010), and this work contributed to their development.

1.3 Problem statement

The provision of solid waste management services in Nairobi currently involves a multiplicity of actors in the formal economy and informal sectors, with the majority operating informally or to some degree in semi-formal fashion. These actors are motivated by different factors, face different constraints, and operate via different mechanisms. The ISWM Plan developed had to be implementable under these conditions of semi-formality, or risk failure if it failed to build on these existing systems. The development of an ISWM Strategy for the city therefore, over and above the formal integrated approach recommended by UNEP; required a rigorous all encompassing understanding of the waste system across the city as a whole, of the placement and contributions of its various actors, and of the resulting implications of this for ISWM planning in the city. Investigation was also necessary later to determine the feasibility and potential contribution, which the expansion of a promising subsystem or activity within Nairobi's waste system could play in helping the city achieve ISWM goals. This work formed part of the development process of the ISWM Strategy for Nairobi City (CCN & UNEP, 2010), and in developing intervention strategies for Nairobi sought to uncover not just the current waste management situation but also the fundamental underlying causal relationships leading to this situation using soft systems analyses, with an aim to developing waste management interventions that tackle these causes. The investigation and analysis of these relationships however during the development of the Nairobi ISWM Strategy, could only be done partially due to project delivery time constraints.

1.4 Thesis Objectives, Research Questions and Scope

This dissertation extends the systems analyses initiated in the Nairobi ISWM planning process, and examines the adequacy of the interventions finally proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010) to achieve ISWM goals in the city. The objectives of this thesis are therefore:

1) To investigate the fundamental underlying causal relationships and patterns that have led to the current solid waste management situation in Nairobi using 'soft systems' modelling and approaches, and to utilise the knowledge generated to gain strategic insights on how to achieve ISWM goals in the city by targeting the fundamental causes, and not merely the symptoms.
2) To re-examine the recommendation of the Nairobi ISWM Strategy (CCN & UNEP, 2010) in light of the recommendations from the systems analysis application.
3) Given the high prevalence of organic waste and the high promise of its valorisation as a system driver in Nairobi's waste management; to investigate current organic waste valorisation practice, and the subsequent techno-economic feasibility of expanding its contribution to the city's material recycling capacity towards achieving ISWM.

1.4.1 Key Questions

In order to meet the thesis objectives, this work seeks to answer the following derived key questions:

- Can systems thinking as an analytical framework adequately capture the current waste situation and aid the generation of valuable insights into its causes, patterns and intervention recommendations?
- Following the systems insights generated, do the interventions proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010) adequately target the fundamental causes?
- What are the current organic waste valorisation practices in Nairobi and how effective are they? What alternatives are available if current practice is inadequate? What is the techno-economic feasibility of expanding the most promising organic waste valorisation practices to increase the city's material recycling capacity and achieve ISWM goals?

This work focuses on the use of 'soft-systems' thinking and analyses which do not venture into mathematical reductions and simulation. The application of systems thinking in waste management planning especially for developing African cities does not seem amenable to mechanistic mathematical modelling, but rather appears more valuable as a tool to systematically structure the waste problem/situation and to develop conceptual models and analyses articulating the solid waste system or arrangement in a given area as a whole. The conceptual modelling and analyses done can then be used to highlight prevalent behavioural patterns, inherent system strengths and weaknesses, and to provide guidance to appropriate system interventions for ISWM.

1.5 Plan of development

This document begins by discussing in Chapter 2 the pertinent literature that informed the core theory and methodology employed in this work. Pertinent literature includes an exploration of the significance of sustainable development and the role of solid waste management in its pursuit, comparisons of municipal solid waste character and management strategies globally, the emergence of ISWM as a more holistic waste management strategy, the status quo of waste management in the developing world, and a brief description of the current situation in Nairobi. An overview of the UNEP ISWM planning methodology is presented afterwards, with an elaboration of the technical requirements necessary in the solid waste surveys that inform a sizable part of this planning. Systems thinking is then introduced as a potential tool to aid strategy development in such a planning process, followed by a description of the role organic waste valorisation currently plays globally as a driver in waste management systems.

The specific motivation for this work is drawn in Chapter 3 building from the literature, followed by a description of the system data collection, systems mapping and modelling, and the methodology employed for systems analysis. The methodology employed in investigating the potential that organic waste valorisation could play as a waste system driver in helping Nairobi achieve ISWM goals, is also described.

A systems analysis of Nairobi's current solid waste system is presented in Chapter 4, first illustrating the relevant system data collected, followed by the development of a causal loop map of Nairobi's waste system and its explicit description. Discernable behavioural patterns, system drivers, leverage points, and system archetypes from the causal loop map are discussed. A synthesis is then presented of the appropriate intervention recommendations towards ISWM observable from the systems analysis, followed by a re-examination of the adequacy of the interventions that were proposed in the final Nairobi ISWM Strategy (CCN & UNEP, 2010).

The dissertation ends with the identification of organic waste valorisation as a promising solid waste management sub-activity building on existing local systems in Nairobi. The potential of organic waste valorisation in Nairobi is explored in general, followed by a detailed investigation of the techno-economic feasibility and potential that the anaerobic digestion of organic waste for biogas-to-energy, could play as a waste system driver in helping Nairobi achieve its ISWM goals.

2 Literature Review

2.1 The pursuit of Sustainability and the role of Solid Waste Management

Sustainable development was originally defined by the Brundtland commission as development which meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). Goodland and Daly (1996) presented a more specific analysis of the "universal and non-negotiable" importance of environmental limits, re-defining sustainable development as "development without growth in throughput of matter and energy beyond the regenerative and absorptive capacities of the environment". The work of these and many others have made it abundantly clear that the dominant paradigm of economic growth (leading to social welfare) is unsustainable, as it destroys environmental health upon which countless "ecosystem services" depend. While the dominant conceptualisation has been to view the economic, social, and environmental spheres as independent of each other (Figure 1) - with efforts towards sustainability seeking to find a harmonious intersection between the three, Mebratu (1998) captures the world as we experientially know it more realistically with his 'cosmic interdependence' model as in Figure 1.

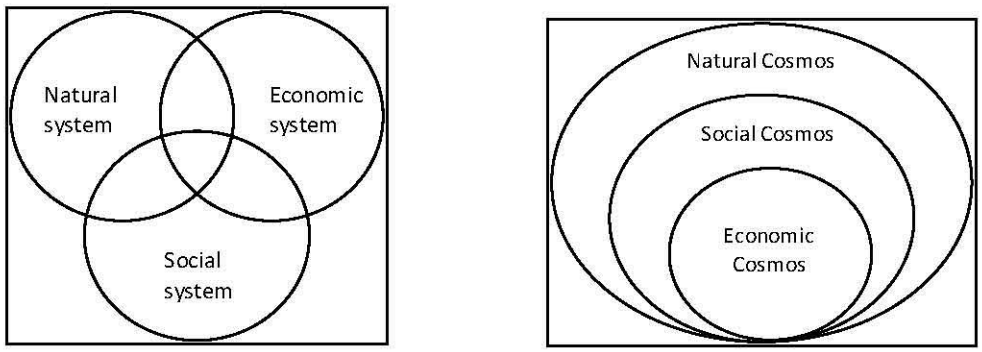

Figure 1: The dominant model (left), and cosmic interdependence model (right) - conceptualisations of the world (adapted from Mebratu, 1998)

Mebratu's (1998) model makes explicit the reality that while the natural environment can exist without human social and economic systems, the reverse is not true; with the existence and health of the economy dependant on that of the social structures and the natural environment, and that of society dependant on the health and provisional capacity of the natural systems. The pursuit of sustainable development in this scenario then is not an option to integrate three independent spheres, but a subservient imperative for our existence and health as a species. The role of solid waste management in this pursuit is to safely handle and treat the wastes arising from the social and economic spheres in such a way as not to impair the natural environment's regenerative and absorptive capacities, and thereby its ability to healthily support these spheres. This is exemplified in solid waste expert estimations that global GHG emissions could be reduced by up to 10% at comparably low cost, if sustainable waste management systems were established, particularly in developing and emerging countries (KfW, 2010).

One key resulting implication of the adoption of Mebratu's (1998) cosmic interdependence model, is that in order to pursue sustainable development, an understanding of the systemic influences and inter-relationships between the natural, social and economic spheres is crucial in designing for human activity and systems. This implies a need for the use of systems thinking and systems-based

tools for all aspects of sustainable development, including waste management. In this regard, while engineering planning methods in waste management have evolved from simple problem-oriented to "integrated" approaches, they have not yet adequately made the leap into a systems-based discourse.

2.2 Global Trends in Solid Waste Management

Urban living generates a variety of solid wastes that cannot be assimilated in the city environment. Large improvements in urban cleanliness and health were realized when organized collection of solid waste and its disposal outside of city limits was introduced in Europe in the late 19th century. To prevent environmental degradation arising from large dumpsites, the practice of sanitary land-filling was invented. More recently it has been realized that state-of-the-art waste incineration, whilst more costly to operate, and material and energy recovery and recycling; offer even lower environmental footprints as waste management strategies (Cherubini *et al.*, 2009). It has also always been true that one person's waste can be another person's resource. Modern approaches to solid waste management therefore incorporate strategies to reduce waste generation and to encourage re-use and recycling of materials, and recovery of energy; with land filling as a last option for waste that cannot be absorbed alternatively.

2.2.1 Municipal Solid Waste Composition & Generation: Global Comparisons

Troschinetz & Mihelcic (2008) in a survey of 19 developing countries in the global south (with case studies from Asia, South America, and Botswana and Mauritius from Africa), observed an average 55% organic waste content relative to an average of only 30% organic waste in the developed world (EU and USA). Achankeng (2003) in general agreement with Troschinetz & Mihelcic's (2008) findings, reports the presence of a typically rich organic content, as high as 70%, in African solid wastes as found by other researchers. The high organic waste content for developing countries has been attributed by some to be due to the low proportion of high income households relative to the developed world, which generate more inorganic material from packaging waste; whereas low income households - as in developing nations, produce more organic material due to preparing food from base ingredients (Wells, 1994).

Troschinetz & Mihelcic (2008) in their survey found a waste generation range 0.3 – 1.44 kg/person/day to be typical of developing countries. Achankeng's (2003) work on Africa reports a similar range, with 23 out of 24 cities across Africa outside of South Africa having a generation range of 0.3 – 1.4 kg/person/day; and 20 of these cities showing generation rates ≤ 1 kg/person/day. In comparison developed countries typically generated 1.43 – 2.08 kg/person/day, an observation broadly attributed to increasing income levels, although this influence decreases markedly in the highest income countries (Troschinetz & Mihelcic, 2008).

2.2.2 Global Waste Management Efforts

Globally, efforts to manage solid waste take on different forms. The main waste management strategies employed include direct thermal treatment through incineration with or without energy recovery; material recovery and recycling/reuse - with or without energy recovery in the form of refuse derived fuel from inorganic wastes and anaerobic digestion or composting of organic waste; or bulk waste land filing (Masters & Ela, 2008).

2.2.2.1 Waste Recovery, Recycling, Reuse, and Land-filling

Developed countries typically utilize kerbside recycling programs to collect and sort wastes for recycling and re-processing; while developing countries mostly use the informal sector, also known as scavengers, to handle such activities; with the materials subsequently sold on to recycling shops, middlemen, or exporters. Troschinetz & Mihelcic (2008) observed that municipal solid waste (MSW) recovery rates in their work broadly fell between 5 – 20% of total MSW in developing countries in the global south, with Brazil however showing exceptional recovery levels at 41% of total MSW - likely due to the emergence of 'Participatory Solid Waste Management' (described in Section 2.2.3.2). Waste Recycling rates in developed countries average about 30% in the US and ≈ 18% in the European Union (Troschinetz & Mihelcic, 2008), with some EU member states - most notably Germany, Belgium, Sweden, Ireland and Netherlands, achieving recycling rates of up to 30 - 48% of MSW (WtERT, 2010).

The composting of organic waste also plays an important role in waste recovery and reuse in the developed world, with about 15% of the estimated total recoverable organic waste in Europe treated biologically (Barth, 2001). Countries such as Austria, Italy, Netherlands and Belgium comfortably compost up to 25 – 40 % of their MSW. The last 15 years in Europe have begun to see the emergence of small to medium-scale anaerobic digestion of municipal organic waste, due to the added attraction of energy recovery from the organic waste fraction; Germany is currently considered one of the world leaders in this sector. Similar organic waste reuse efforts in the developing world have not been as widespread due to a number of reasons elaborated in Section 2.5.3.3.

Bulk land filling or dumping of waste still plays a significant role in waste management in many countries especially in the developing world.

2.2.2.2 Thermal Waste Treatment

Estimates for waste incineration in the EU put total waste incineration at about 20% of all EU waste, with some member states such as Denmark and Sweden incinerating as much as 50% of their waste (WtERT, 2010). Direct thermal waste treatment with or without energy recovery, coupled to incineration or otherwise; generally does not play a significant role in MSW management in Africa due to the relatively high fraction of food wastes and moisture in African MSW, the lack of appropriately skilled manpower, and the technical infrastructure and high capital costs involved (Bahri, 2005; Achankeng, 2003). Achankeng (2003) additionally attributes failed waste incineration efforts in Tanzania and Nigeria to high capital and operational costs, and argues that the process in Africa is a net energy consumer rather than a net energy generator due to the typically high organic and moisture content of African MSW.

2.2.2.3 Integrated Solid Waste Management (ISWM)

Integrated Solid Waste Management (ISWM), an approach to managing waste via avoidance and reduction at source, reuse, recycling and treatment or landfill disposal - in order of preference; offers a more holistic approach to waste management from generation to residual disposal, with a focus on waste volume reduction to landfill. The guiding principles of ISWM can be summarised as shown in Figure 2.

Figure 2: Principles of Integrated Solid Waste Management (Source: Markel *et al.*, 2008)

Within the ISWM framework; reduction of waste at source might include the use of less packaging in consumer goods, direct product reuse, production of more durable goods and onsite mulching and composting. Reuse and Recycling of waste materials could include the collection and processing of recyclable materials, encouraging the use of recycled materials in products, and composting. Final disposal options include combustion of materials with energy recovery, direct land filling, and incineration without energy recovery (Masters & Ela, 2008).

The benefits of an integrated approach to waste management are evident in countries such as the United States that have had such policies in place for a considerable time. In spite of a 50% population increase in the US between 1960 and 2005, the volumes of waste to disposal at landfill have stabilized since 1985 (see dotted line in Figure 3 below), and have even been observed to decrease slightly since the early 90's due to the promotion of source reduction, reuse, recycling and extensive composting efforts (Masters & Ela, 2008). This is illustrated in Figure 3 below.

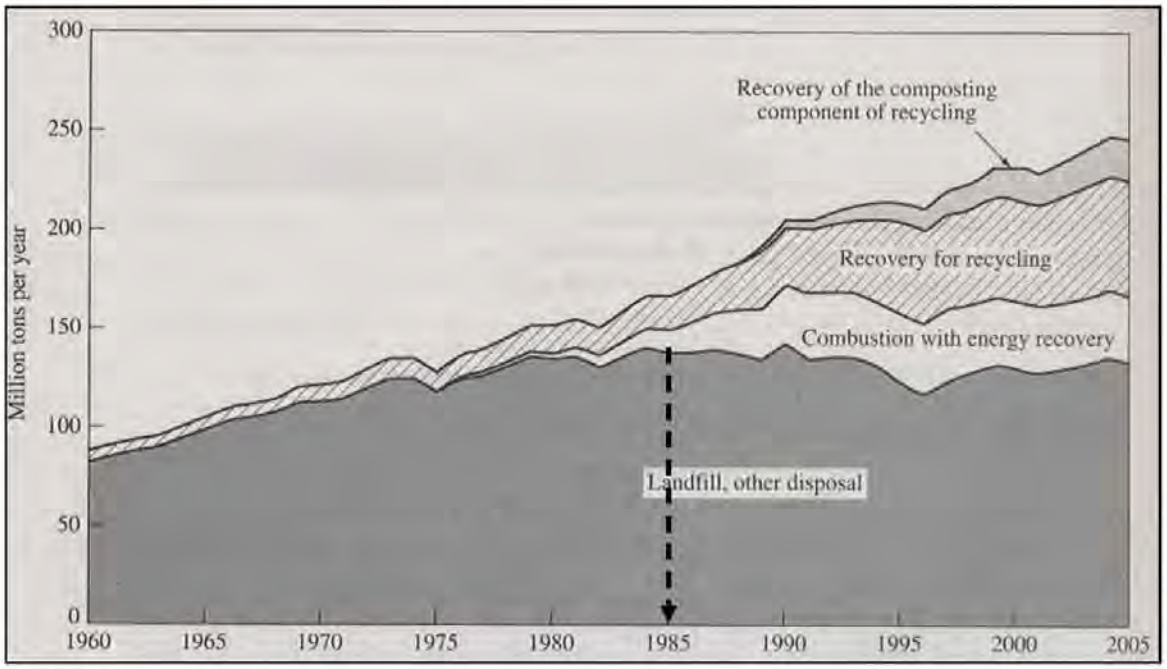

Figure 3: Impact of ISWM practices on US municipal solid waste generation, recovery, and disposal from 1960- 2005 (Source: Masters & Ela, 2008)

2.2.3 Solid Waste Management in Africa and the Developing world

2.2.3.1 Status Quo

Developing cities in the developing world, and especially in Africa, are often characterised by high population growth and urbanisation rates coupled to slower economic growth. This has resulted in rapidly increasing solid waste volumes, and low solid waste collection and safe disposal levels due to the prevalent lower economic growth rates. Population statistics and projections for the period 2005 - 2020 estimate that African population growth will average 2% per annum, doubling average world population growth over the same period at an average of 1 % per annum (UN Population Division, 2008). Africa is currently ≈ 40% urban, and is experiencing the world's most rapid urbanisation rates at 3.4% per annum, much higher than the world average of 1.9%, with these levels of urbanisation expected to persist above 3% till 2020 (UN Dept. of Economic & Social Affairs, 2009). GDP per capita growth on the other hand for the period 1990 – 2007 in Sub-Saharan Africa stood at a slower average of 1.3% (UNICEF, 2009). The pressures from these high population and urban growth rates, coupled to relatively slower economic growth indicators, mean that residents and municipal solid waste authorities in developing cities in Africa are faced with the problem of rapidly increasing waste volumes from growing populations but little financial means to cope with them, thereby constraining the ability of the public sector to effectively deliver waste collection and management services. This is evidenced by average waste collection levels of only 46% of total generated waste across 24 African cities outside of South Africa (Achankeng, 2003). Illegal and indiscriminate waste dumping as a result is widespread in African cities. This situation is often compounded by the traditional approach common in African cities; where municipal authorities attempt to monopolise waste management, ignore other stakeholders, use command-and-rule strategies as well as ill-adapted imported technologies and approaches; all the while overlooking local initiatives, techniques, and stakeholders (Achankeng, 2003).

2.2.3.2 Emerging Trends

There is growing evidence of the success of bringing traditionally peripheral actors in waste management, often referred to as the informal resource recovery and recycling sector or waste scavengers, into the formal solid waste management systems in developing countries to fill the vacuum left by low public sector waste service delivery.

'Participatory Solid Waste Management'- defined as 'solid waste recovery, reuse and recycling practices within organized and empowered recycling co-ops supported with public policies, embedded in solidarity economy, and targeting social equity and environmental sustainability, combines environmental and social issues such as employment creation, increased income generation, improved occupational health and the promotion of human development opportunities and environmental health in general (Gutberlet, 2010). Gutberlet (2010) cites the example of the success of Participatory or Inclusive Waste Management in the organized Recyclers' Movement in Brazil, officially created in 2001 during the 1st National Recyclers' Congress in Brasilia, with the participation of more than 1700 recyclers from across Brazil. The resulting "Brasilia document" expresses the needs of the people who make a living from recovering recyclables. The first Latin American Congress of recyclers was held in Caxias do Sul where the "Caxias document" was produced; disseminating the conditions of recyclers in various countries in Latin America. The movement has gone on to gain momentum through strengthening regional networks, and would

seem to be one of the prime drivers of the high municipal solid waste recovery rates in Brazil (see Section 2.2.2.1).

2.2.4 Solid Waste Situation in Nairobi City, Kenya

The Nairobi and Athi Rivers, two of Nairobi's main water bodies, were found to be polluted 2,000 times above the WHO water body standards (Kuria, 2008). The Nairobi River Basin Project, a multi-partner effort, was launched in response by the UNEP and UN-Habitat in 1999, with a vision to rehabilitate and maintain good water quality of the river system passing through Nairobi, and in the process reduce environmental health risks to the urban population. The project, executed in collaboration with the City Council of Nairobi (CCN) and the Ministry of Water Resources Management and Development, is directed at addressing problems including pollution, waste management, legislation and public participation and awareness as they relate to the Nairobi River Basin system. One of the biggest contributions to the pollution of Nairobi's rivers has been the inadequate nature of solid waste management in Nairobi (Baud et al, 2004), whose goals are largely 'waste to disposal' at the official but non-sanitary Dandora dumpsite located next to the Nairobi river. The dire condition of the Dandora dumpsite is elaborated below.

2.2.4.1 Current state of the official Dandora dumpsite, and problems arising

The CCN currently has only one official dumpsite, Dandora, which has reached the end of its service life (JICA, 1998). The Dandora dumpsite, an open and un-engineered landfill, is located 7.5 km south east of Nairobi and covers an area of 26.5 hectares containing 1.3 million cubic metres of waste after 14 years of service (Baud et al, 2004). No facilities exist to prevent secondary pollution at the site and controls to prevent entry of hazardous and toxic waste are ineffective (JICA, 1998). The dumpsite borders a densely populated low income residential area, the Dandora Housing Estate, and the risk of spread of diseases, contamination, and water/air pollution is especially high due to the mixed hazardous substances deposited there and the presence of open burning and rodents. Due to secondary pollution, residents of the dumpsite area protested against the continued use of the dumpsite in 2001 (Baud et al, 2004). A 2006 study commissioned by UNEP to determine the environmental and pollution effects of the dumpsite showed that soil samples collected from the site recorded high levels of lead and other heavy metals compared with international standards. According to the study, medical records obtained from the Catholic Church dispensary at Kariobangi near the dump showed that an average 9,121 people were treated for respiratory tract-related problems in 2003-2006. Cases of skin disorders, abdominal problems and eye infections were also common among those tested (IRIN, 2009).

In 2001 a decision was made by the City Council of Nairobi to move the dumpsite to a new sanitary landfill site, Ruai, on the recommendation of JICA (1998). A number of problems however surround Ruai's use as a landfill site. Although the land is the property of the CCN, a dispute over ownership of the land with private parties ensued (Bahri, 2005). Aviation authorities from the nearby Jomo Kenyatta International Airport also filed objections claiming birds from the site will interfere with airport operations. Bahri (2005) also notes the resistance of local residents to the opening of the proposed new landfill site, as well as encroachment on the land by illegal settlers.

2.2.4.2 The need for environmentally responsible ISWM in Nairobi

In spite of the needed decision to move to a new engineered landfill at Ruai as part of its future ISWM effort, the use of landfills and a 'waste to disposal' approach in Nairobi and many African cities raises a number of sustainability problems in the longer term. The use of landfills in the future will be limited by the lack of space, growing restrictions on the siting of these dumps, and increased financial costs owing to higher waste volumes and longer travel distances to appropriate landfill spaces away from commercial land; all of which issues are illustrated in Section 2.2.4.1 above. Additionally the generation of potent greenhouse gases, especially of methane which is 21 times as potent as carbon dioxide with respect to global warming, at landfills as a result of uncontrolled anaerobic conditions, negatively impacts local and global climate. Engineered and sanitary landfills also continue to run the risk of environmental and ecological pollution and associated public health hazards, due to the waste leachates generated at these facilities which can sip through slits, cracks, or other failure of the containment structures. Life Cycle Assessments of sanitary land filling are also beginning to show it as the worst waste management option relative to material and energy recovery and recycling, and even direct incineration (Cherubini *et al.*, 2009).

The broad environmental and economic implications of bulk waste to landfill therefore make it desirable only as a last waste management option in Nairobi's ISWM Strategy. Waste disposal via incineration - with or without energy recovery; with is its high capital costs, environmental and social health risks if poorly operated, and less positive energy balance than material transformation via recycling (Oliveira & Rosa, 2003), also does not offer a ready waste disposal solution in most developing communities. Nairobi is better served in beginning a journey that moves higher up the ISWM hierarchy (see Section 2.2.2.3), from simply disposing of waste at landfill/dumpsite in bulk, and progresses towards viewing waste as a resource with potential useful outputs through the encouragement of active material reduction at source, material recovery, recycling and reuse activities, and potentially of non-thermal energy recovery through strategies like anaerobic digestion of organic waste. This direction offers a more environmentally and economically sustainable future; decreasing waste volumes left for final disposal, and providing opportunities for social empowerment through the economic activity generated by the application of the ISWM hierarchy.

2.3 Planning for ISWM: Plan development and Waste Surveys

2.3.1 Overview of UNEP ISWM Planning Methodology

Following an increasing global acknowledgement of the need for, and challenges faced by especially developing countries in managing their solid waste, UNEP developed an ISWM plan development program for national governments that includes support for capacity development and technology transfer for ISWM (UNEP-IETC, 2009). The steps typically undertaken in the UNEP ISWM planning and development process include (Memon, 2009):

1) Waste quantification and characterization of all waste types – municipal, industrial etc, via solid waste quantification and characterization surveys.
2) Assessments of the prevailing waste management situation (Situation Analyses) including; assessments of existing institutional and stakeholder frameworks for waste management in the area of interest; national and local government solid waste legislation; locally available technology, infrastructure and solid waste practices; and available waste financing

mechanisms. These assessments may be accomplished through literature surveys and reviews, workshops, field visits and interviews.

3) Gap analysis and identification of issues of concern through Stakeholder Consultation Workshops.
4) Development of draft ISWM Plan (including all waste streams, all aspects of ISWM chain and technologies).
5) Stakeholder consultation on draft ISWM Plan.
6) Development of final ISWM Plan.
7) Awareness raising and training.
8) Implementation of Plan.

One of the key technical areas necessary for the development of an ISWM plan is a good knowledge of waste generation volumes, compositions, and characteristics in the area of interest. In order to determine solid waste characteristics, and effectively map solid waste trends and quantities from different generators and plan for these effectively in an ISWM plan, solid waste surveys are often necessary.

2.3.2 Waste Characterisation & Quantification Surveys

There are broadly three ways to determine the quantities, nature and characteristics of Municipal Solid Waste:

- **Using the Material Flows Approach**; this assumes that by analysing products sold, predictions can be made as to what was thrown away to create space for the products being bought. While the characterisation percentages from this approach can approximate local percentages, it fails to account for wide variations that may result from different locations, seasons and different generators. (Martin, Collins & and Diener, 1995).
- **Site specific sampling or Direct Waste Analysis**; solid waste samples are taken from either points of generation, waste transportation vehicles, waste processing facilities or at final disposal points and sorted to determine waste quantities and composition. Physical analysis such as moisture content, and chemical analysis may also be conducted. Waste composition (characterisation) can be determined through manual hand sorting of different waste components, or visually - although this is not recommended unless the load is fairly homogeneous such as saw dust, agricultural chaff, and construction and demolition debris. The Direct Waste Analysis approach is the traditional method of waste characterisation and provides more suitable data for local municipal solid waste planning. (Martin, Collins & and Diener, 1995).
- **Questionnaire surveys**; these are normally restricted to collection of data at point of generation. They involve the preparation and pre-testing of a questionnaire, sample selection and administration of the questionnaire to various waste generators through mail outs, interviews or telephone surveys. Questionnaire surveys and Direct Waste Analysis have been shown to result in fairly similar waste flow quantifications; however the questionnaire approach performs poorly in tracking waste composition (Yu & Maclaren, 1995).

Waste characterisation surveys serve two main purposes; the quantification of waste amounts generated in an area, and the determination of the composition of generated waste. Methods to determine waste quantities generated and composition are detailed in the sections following.

2.3.2.1 Waste Quantification

Waste amounts can be quantified through measurements or examination of records at points of generation, use of a vehicle survey, or through examination of records at disposal facilities;

- **Measurements at Point of Generation** – This is done through visits to or contacting waste generators such as business and housing complexes, and measuring or observing the amounts of waste disposed over a period of time. Due to the variability of waste generated from different entities and over time, the collection of data from many points results in a more representative average for waste generated by a certain sector. (UNEP - IETC, 2006).
- **Quantification through Vehicle Surveys and records at Disposal Facilities** – This approach quantifies waste arriving at disposal facilities through vehicles. Interviews of the waste haulers, drivers and vehicle waste records can be used to ascertain the origin of the waste, waste types and estimate quantities. A random or targeted selection of trucks for sorting over the period of sampling may be done to achieve representativeness. (Cerrato, 1993). Where transaction records for waste brought for disposal exist at the disposal facility, these can be used to determine waste quantities, geographical origin and generators (UNEP - IETC, 2006).

2.3.2.2 Waste Characterisation/Composition Analysis

The composition of waste generated in an area can be determined from:

- **Waste generators** – waste samples are obtained at the point of generation such as bins, communal disposal areas, business or building waste containers. Waste composition data obtained from this approach can be used to determine correlations for waste composition with respect to specific generators such as business, industry, family residences (UNEP - IETC, 2006).
- **Disposal facility** – Waste at disposal facilities is sampled for analysis of composition. This approach can produce very accurate waste characterisation data and is particularly suited for waste that comprises numerous components (UNEP-IETC, 2006).

2.3.2.3 Number of samples required for representative solid waste characterisation & quantification

Following a decision on the waste material categories generally present in the waste stream, the number of samples required for characterisation will vary according to the material type and accuracy required. Typical categories of waste material of interest in MSW include: paper, plant debris, wood, plastics, glass, metals, putrescibles (food wastes and materials contaminated with food), rock (e.g. from construction and demolition works), directly reusable goods (books, tools etc), textiles, leather, chemicals, soils (Martin, Collins & and Diener, 1995). These may be subdivided into micro-components, such as plastics into PET, PVC, HDPE and others, depending on the desired level of detail or possible for the study. A confidence level of 80% or 90% is considered sufficient for MSW data sampling (UNEP-IETC, 2006).

- **Sampling at disposal sites, waste processing and conversion facilities, or transfer stations**

The number of samples required to achieve representativeness at a given accuracy from landfill sites, waste processing and conversion facilities, and transfer stations varies with material type, and can be determined using a standard test and sampling protocol devised by the American Society for Testing and Materials (ASTM D 5231 - 92) for these types of sampling sites. The required sample number, n, is determined using Equation 1 below via an iterative procedure described in the protocol;

$$n = \left(\frac{t * s}{e * x}\right)^2$$

Equation 1

where t^* is the student t characteristic that corresponds to the desired level of confidence, s is the estimated standard deviation, e is the standard sampling error or precision, and x is the estimated mean % of the waste component of interest, usually determined from previous work in the generation area of interest or similar areas. The waste component compositions in this protocol are assumed to follow a normal distribution.

- **Sampling at waste generation source**

The number of waste samples required to achieve representativeness in waste characterisation at immediate waste source can be determined using a household waste sampling protocol based on the central limit theorem after Qdais *et al* (1997) and Gomez et al (2007), using Equation 2;

$$n = \left(\frac{z * SD}{R}\right)^2$$

Equation 2

where n is the minimum number of samples, z is the score determined from t Student statistical tables for standard normal distribution at the desired confidence interval, SD is standard deviation of population, equal to the standard deviation of a sufficient number of samples (usually n > 30 ; Qdais *et al*, 1997)) and R is the standard sampling error.

2.3.2.4 Retrieving waste samples for characterisation

As described in Section 2.3, manual sorting is more accurate than visual methods for determining waste composition. When doing manual sorting of MSW for characterisation, it is necessary to remove a manageable portion of the waste load that is representative of the entire collection/discharge vehicle or point of generation. This may be done using one of two methods;

- **Mixing and quartering** – the entire load (from discharge vehicle, point of generation or disposal) is mixed thoroughly and levelled into a continuous pile. A quarter of this is removed and placed separate from the rest of the waste. This portion is remixed and one quarter removed again. The procedure is repeated until the remaining quarter is 200-300lb (91 – 136kg) (Cerrato, 1993).
- **Longitudinal retrieval from a discharged load** – in this method, instead of mixing the entire load prior to sample removal, a sample is removed longitudinally along one entire side of the discharged load. The sample should be approximately 1000lb (454kg). This is then thoroughly mixed, and one quarter of it selected for manual sorting. This method requires less time and the results are consistent with those of the first (Cerrato, 1993).

Only one sample may be retrieved from each collection vehicle or waste load. The retrieved samples are then manually sorted into the various waste components/materials as decided prior to characterisation. Sorted materials are placed into pre-weighed empty buckets which are reweighed at the end of sorting; with the difference in weight equal to the mass of the waste component placed in the bucket (Cerrato, 1993).

2.3.2.5 Accounting for Seasonal and Geographical Variations

The quantities of waste generated and disposed are bound to vary day to day, seasonally and with location, resulting in fluctuations over time and geography. Solid waste characterisation studies are usually done on a seasonal basis with analyses during different times of the year. Week-long programmes are considered the minimum requirement for characterisation (Cerrato, 1993). Geographical variation in waste composition and quantities due to socio-economic and other factors can also be minimised by evenly distributing the sampling points (Cerrato, 1993).

2.3.2.6 Laboratory Analysis

Laboratory analyses of the waste may be done to determine the chemical and physical properties of the waste, typically to determine suitability for waste to energy projects, composting or environmental considerations. Typical laboratory tests conducted include Cerrato (1993):

- *Heating Value*: to determine the energy content of the waste available through burning it.
- *Proximate Analysis*: to determine total moisture content, volatile matter, fixed carbon and ash content.
- *Ultimate Analysis*: to determine contents of ash, carbon, hydrogen, sulphur, oxygen, nitrogen and chlorine in the waste.
- *Elemental Analysis*: to determine a broad range of chemical properties including acidity, herbicides, asbestos and dioxin.

2.3.2.7 Analysis of Variance (Anova) as a tool to discern statistical disparities

Analysis of Variance (ANOVA) is a statistical procedure that tests to determine whether differences exist between two or more population means (Keller, 2006). The technique analyses the variance of the data from which the population means have been derived to determine whether it can be inferred that the population means actually differ, or can be assumed to be equal based on the data variance.

ANOVA tests may be done to assess the significant effects of one factor (one-way ANOVA), e.g. of 'geographical location' between two or more populations; or to simultaneously assess the effects of two factors (two-way ANOVA), e.g. of 'geographical location' and 'income level' simultaneously between two or more populations. Two-way ANOVA tests can also be used to assess if there are interactions between the factors in bringing about certain effects in the population means.

2.3.2.8 Projecting Solid Waste Generation into the future

In order to plan for ISWM goals such as waste reduction, recovery, recycling and safe disposal, a reasonable idea of future waste growth is necessary. The prediction of MSW growth however is not a trivial pursuit and various studies have attempted to determine correlations between waste generation and demographic factors such as average education per household, number of residents per household, average household age and income per household (Johnstone & Labonne, 2004). Many of these models however tend to require several empirical data inputs which may not easily be obtainable especially in developing countries where previous waste generation and other specific data is mostly scarce and often unreliable. The results of such models are also to be handled with caution due to the different social, economic, and cultural circumstances of the areas in which they are developed.

The best insights to the behaviour of future solid waste generation are drawn from trend analyses of previous waste data. Where such data is not available, as is the case in many developing nations, estimations of waste generated may be made at a more fundamental level using some reasonable assumptions. With growth in population and GDP, both the quantity and quality of waste can be expected to change (Datar, 2007), with population having the most direct influence on waste volumes. Correlations have also generally shown that increases in GDP lead to increase in per capita waste generated (Barton et al., 2007; Chandak, 2008), although this influence decreases markedly in the highest income countries (Troschinetz & Mihelcic, 2008).

Human populations are usually projected using population age structures (Masters & Ela, 2008); however assumptions of logistic growth – where population growth is limited by the amount of resources such as land or food available in the surrounding environment (the 'environmental carrying capacity'), are a fair approximation. Evidence for this is illustrated in the typical population growth pattern of biological organisms as in Figure 4, compared to that of two of the world's largest cities – New York and London since 1800 as shown in Figure 5 .

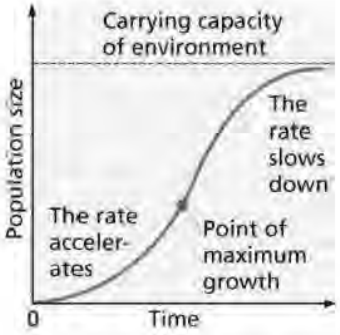

Figure 4: Typical logistic growth curve of biological organisms (Source: Farabee, 2001)

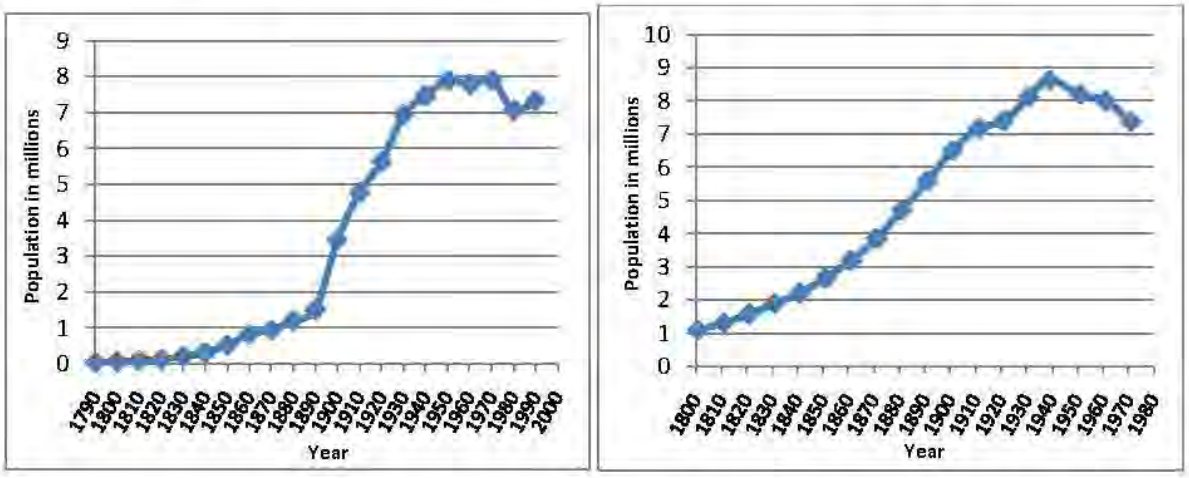

Figure 5: Population growth of New York - left (Source: Gibson & Jung, 2005) and London - right (Source: Wendell Cox Consultancy, 2001)

The logistic growth model is based on the assumption that there are various stages in population growth namely the exponential and lag phase. The lag phase occurs after a rapid population growth phase and represents the population levelling off to a certain value - the carrying capacity, and takes into account that there is a limitation to how much population grows. The maximum population

capacity (carrying capacity) of the city or interest area can be estimated. Logistic population growth is modelled mathematically as in Equation 3 (Masters & Ela, 2008);

$$P(t) = \frac{K(P_0)}{P_0 + (K - P_0)e^{-rt}}$$

Equation 3

where P_0 is the population at time, $t = 0$; K is the environmental carrying capacity; t is the age of the population; and r - the population growth rate constant is determined from Equation 4;

$$r = \frac{R_0}{1 - N_0/K}$$

Equation 4

where R_0 is the instantaneous growth rate at $t = 0$, assuming no limitations to population growth and exponential growth at this stage.

After the projection of population growth, the residential MSW generated can be determined from the product of the projected population and waste generation per capita (per person). Waste generation per capita increases with GDP, and can be estimated using a simple technique from JICA (JICA, 1998). The JICA (1998) solid waste study on Nairobi used waste generation and income statistics from the Tokyo Metropolitan Area between 1956 and 1968 - while it was still a developing economy with a GDP comparable to Kenya's, to project future waste flows for Nairobi. This extraction of information from the developing phase of a developed ('mature') economy provides an estimation method for the waste growth behaviour to be expected in a developing economy, more so as populations in developing nations are generally aspiring to the lifestyles of citizens in developed countries.

Using these statistics, JICA (1998) found the ratio of annual growth in waste discharged per capita (% increase) to annual increase in GDP per capita (% increase), also referred to as *discharge flexibility*, to be 0.51. Another study of similar data from Bangkok - Thailand between 1990 and 1995 found this ratio to be 0.52. JICA (1998) assumed a *discharge flexibility* of 0.5 for residential waste projections for Nairobi, and their projection in 1998 for solid waste generation in 2004 of 2140 tons/day MSW compared reasonably well with an ITDG study (Bahri, 2005) which put waste generation in Nairobi in 2004 at 2400 tons/day. From this observation, this approach is a useful way to estimate domestic waste projections. Combined with the usually known or estimable contribution of domestic waste to total waste in a city, the total MSW to be expected in an area can be estimated.

2.4 Systems Thinking as a tool to aid ISWM Strategy and Planning

2.4.1 The interrelated nature of systems: Systems Dynamics & Causal Loop Diagrams

Systems' thinking is a growing research area that seeks to investigate and articulate the structures that often underlie complex situations (Senge, 1990), and attempts to simplify planning by enabling organisations see the deeper patterns beneath events and details. One of the tools employed in systems' thinking, and in particular the 'systems dynamics' stream of systems' thinking, is Causal Loop Diagrams (CLDs) - which provide a visual and modelling language for articulating our understanding of the dynamic interconnected nature of our world (Kim, 1992). The underlying premise for systems dynamics is that the multitude of variables existing in complex systems become causally related in feedback loops that themselves interact (Jackson, 2008). The systemic interrelationships between feedback loops constitute the structure of the system, and it is this structure that is the prime determinant of system behaviour (Jackson, 2008). Causal Loop Diagrams may be thought of as sentences constructed by linking together key variables and indicating the causal relationships and feedback loops between them (Kim, 1992). A few researchers in solid waste management have previously employed systems thinking, and in particular causal loop modeling in the development of their work including Dezs (2001) and Anomanyo (2004). Previous work has however been largely limited to niche areas of waste management, and mostly prescriptive in nature.

2.4.2 Methodology for Analysing Systems Dynamics

Cavana & Maani (2000) plot the development of systems dynamics as a field of inquiry, and present a five phase methodology statement synthesizing the core steps in the application of systems dynamics as follows;

1) *Problem structuring* - the problem situation is defined and the scope and boundaries of the study are identified. This involves the establishment of the objectives of the investigation, and collection of information and data from media reports, historical and statistical records, policy documents, previous studies and stakeholder interviews to determine key concern areas and variables in the defined problem.
2) *Causal Loop modelling* - the conceptual models of the problem are created based on the identification of key variables in the system, charting of behaviour over time of these main variables, and articulation of the causal relationships and feedback mechanisms among the variables. From here the temporal behaviour of the dynamics implied by the causal loop diagrams are investigated, along with the possible identification of system archetypes that describe high level causal patterns and key leverage points in the system. A synthesis of the above then informs the development of intervention strategies.
3) *Dynamic modelling* – goes a step further than *causal loop modelling* and seeks to mathematically model and simulate the behaviour of the system based on the causal loops and stock-flow relationships.
4) *Scenario planning and modelling* – in this phase various strategies and policies may be tested on the models under varying external conditions to gain insights into potential future system behaviour.

5) *Implementation and organisation learning* – this phase is concerned with extending learning amongst relevant stakeholders through interactive management simulations based on the simulation models.

Cavana & Maani (2000) emphasize that not all the phases in the five step methodology need be undertaken for all problems - this need is dictated by the nature and context of the problem, nor should the phases be undertaken following a strict sequence as outlined.

While Cavana & Maani's (2000) methodology provides a useful and structured guide to the application of systems dynamics, its step (3) alludes to a presumption that all systems are reducible to mathematical relationships and thereby readily predictable, in other words that they are mechanistic. The nature of solid waste management however, especially in developing cities in Africa, incorporates a large non-mechanistic social component in the form of generator behaviour and the spectrum of actors involved in waste collection and recovery resulting from the waste service vacuum left by the public sector (Section 2.2.3). The ideal command and rule, top-down control of waste management is not a reality in developing African cities (Section 2.2.3). These different actors in the waste chain, being human agents, are free to exercise their free will regarding their actions as circumstances dictate and represent, to quote Meadows (2002), 'self-organising, non-linear, feedback systems that are inherently unpredictable'. In these circumstances, a model that seeks to go beyond the conceptual identification of major causal and feedback relationships and their influence on other system variables; to mathematically and precisely model current system behaviour, will produce results that are largely un-useful for long term planning. In other words the ability to observe, comprehend and conceptually map new arising dynamics, causalities and interactions in such systems is more useful for strategy planning than numerical solutions to individual, self-organising scenarios. The data input and hardware requirements of this step (3) are also a handicap for many municipal planning authorities in African cities, and further make its application and usefulness untenable in the African context. Steps (4) & (5) of Cavana & Maani (2000) can still be employed directly for organisational learning from (2).

Indeed Meadows (2002) focuses on the non-simulational or 'soft systems' aspects of systems dynamics (equivalent to steps (1) & (2), with the possibility to extend into steps (4) & (5) in Cavana & Maani (2000)) in describing the influencing of systems as analogous to "dancing with" them, and provides elegant insights on how systems thinking can help ISWM planning to integrate system wide interventions and goals with existing structures. Some of these pertinent insights are summarised below;

- *Get the beat of the system* - before you disturb the system, understand its behaviour, learn its history, and ask those who have been around what's happened. This enables focus on the facts, and not beliefs or theories, directing one to dynamic as opposed to static analysis. This also discourages the tendency to define a problem not by the system's actual behaviour, but by the lack of our favourite solution.
- *Listen to the wisdom of the system* - aid and encourage the forces and structures that help the system run itself. Do not rush to intervene and end up destroying the systems' own self-maintenance abilities.

- *Honour and protect information* – Decision-makers cannot respond to information they don't have; neither can they respond accurately to inaccurate information or in time to information that is late.
- *Locate responsibility in the system* – Look at how the system creates its behaviour. Pay attention to triggering events; if you cannot control them, increase intrinsic responsibility such that feed back about the consequences of decision making is directly, quickly and compellingly fed back to decision makers.
- *Pay attention to what is important, not just what is quantifiable* – An obsession with numbers should not overshadow the value of those things that cannot be measured or quantified.
- *Go for the good of the whole system* – Do not maximise parts of the system while ignoring the whole. Individual parts of an integrated system cannot survive without the whole.
- *Expand time horizons* – Watch for both the short and long term.
- *Expand thought horizons* – In spite of what your disciplinary strength is, follow a system wherever it leads, across different disciplines, and their unique vantage points, perspectives and incompleteness.
- *Expand the boundary of caring* – In an integrated world, it's not possible for your heart to succeed if your lungs fail, or for your company to succeed if your workers fail.
- *Celebrate Complexity* – The universe is messy, and often non-linear. This dynamic nature however has patterns that can not only be harnessed, but also celebrated.

In addition, Meadows (1999) from her professional and research experience also proposes a set of twelve 'leverage points' through which to influence the behavior of a system – points within a complex system at which small shifts can produce big changes. In a hierarchy of decreasing effectiveness, Meadows proposes 'changing the mindset or paradigm out of which the system arose - its goals, structure, rules, and delays', as one of the foremost leverage points at which to successfully influence and change the behavior of any system; and ranks the setting of exact 'parameters, constants and numbers' to work the system details last in the leverage points as these typically result from the mindset and goals of the system. The identification of these leverage points in a given system therefore provides an additional guide and layer of investigation in soft systems analysis, through which complementary system interventions can be developed and proposed towards a given set of goals. A summary is given below, in order of decreasing effectiveness, of Meadow's (1999) proposed system leverage points;

1. The power to transcend paradigms.
2. The mindset or paradigm out of which the system arose – its goals, structure, rules, delays, parameters.
3. The goals of the system.
4. The power to add, change, evolve, or self-organize system structure.
5. The rules of the system (e.g. incentives, punishments, constraints).
6. Structure of information flows (who has and doesn't access to what sorts of information)
7. The gain (amplifying effect) around positive loops.
8. The strength of negative feedback loops relative to what they're influencing.
9. The length of delays relative to rate of system change.
10. The structure of material stocks and flows (e.g. transport networks, population age structures).
11. The size of buffers and stabilizing stocks, relative to their flows.
12. Constants, parameters, numbers (e.g. subsidies, taxes, standards).

2.4.3 Visualising the interrelated nature of Systems: Causal Loop Modelling

Causal Loop Diagrams (CLDs) provide a visual and modelling language for articulating our understanding of the dynamic interconnected nature of our world (Kim, 1992). In a Causal Loop Diagram or map, a positive sign (+) at the arrow head between two variables A & B shows a positive correlation between the variables, while negative sign (-) shows a counter relationship between the variables. A loop of three or more interconnected variables A, B & C containing the same signs at the arrow heads creates a net reinforcing effect of that sign, while the presence of an odd number of negative signs in this chain creates a balancing loop, i.e. an odd number of U-turns moves you in the opposite direction. These effects are summarised in Figure 6.

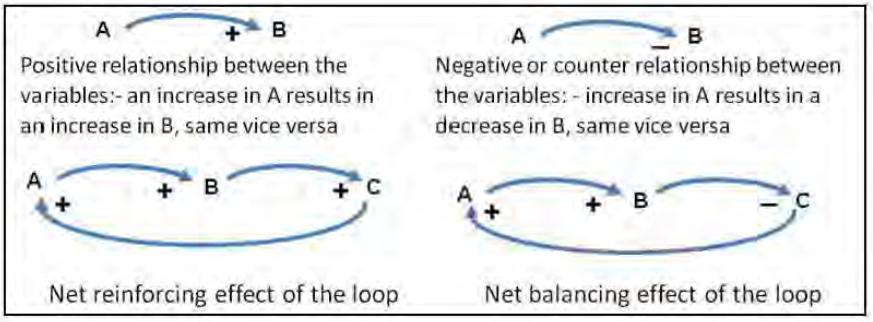

Figure 6: Relationships in causal loop diagrams

From combinations of causal arrows and loops, it is possible to decipher the 'drivers' (variables with more causal arrows or relationships leaving than arriving) and 'outcomes' (variables with more causal arrows arriving than leaving) that are present in the resulting system picture. These variables in turn become starting focal points for influencing the system towards set goals or objectives in systems analysis.

2.4.4 System Archetypes

Braun (2002) defines several System Archetypes which describe common patterns of behaviour in organisations or systems, and which may be used as high level diagnostic tools in soft systems analyses. System Archetypes provide a basic foundation for insight into the underlying structures from which temporal behaviour and discreet events emerge, and can alert observers to future unintended consequences. Braun (2002) identifies ten System Archetypes generally acknowledged as forming the set of tools that reveal behaviour patterns in systems. These are summarised below;

- **Limits to Growth** – based on the premise that growth cannot continue unabated in an unrestricted reinforcing fashion, and that reinforcing growth will encounter a balancing process as the limits of that system are approached.
- **Shifting the Burden** – an illustration of the tension between pursuing attractive (usually easy and low cost) solutions to visible symptoms, and pursuing fundamental solutions aimed at underlying causes for the long term
- **Eroding Goals** – the gap between goals and reality can be resolved by taking corrective action towards achieving the goal, or by lowering the goal itself. Lowering the goal will over time lead to diminishing overall performance.

- **Escalation** – this occurs when one party's actions are perceived as a threat by another; if the second party responds in a similar manner, this increases and reinforces the threat and leads to an escalation in threatening actions by both parties over time.
- **Success to the Successful** – if one group or party A has more resources than another equally capable group B, A has a higher likelihood of succeeding because A's initial success justifies devoting more resources to A. This in time widens the performance gap between the two parties
- **Tragedy of the Commons** – This archetype hypothesizes that if the total usage of a common resource becomes too great for the system to support, the commons will become depleted and everyone will experience diminished benefits.
- **Fixes that Fail** – a quick fix solution can have unintended consequences that exacerbate the problem. The problem symptom diminishes for a short while, only to return to previous or even worse levels later.
- **Growth and Underinvestment** – this applies when growth approaches a limit that can be overcome through capacity investments. The hypothesis here is that if a system is stretched beyond its limits, it will compensate by lowering performance standards, reducing the perceived need for investment. This leads to even lower performance which further justifies underinvestment over time.
- **Accidental adversaries** – when parties in a working relationship misinterpret each other's actions due to misunderstandings, unrealistic expectations or performance challenges, suspicion or mistrust, the mental models fuelling the deteriorating relationship ff left unchallenged may lead to all the parties losing the benefits of their synergy.
- **Attractiveness Principle** – the goals of a firm, which may be the result of a growing action or need, may be subject to multiple other slowing actions each of which represents an opportunity, at a specific opportunity cost. The interdependencies between the slowing actions can provide insights into deciding how best to allocate scarce resources to reduce or remove slowing actions.

2.5 Organic Waste Valorisation: Under-tapped opportunities in the developing world

As discussed in Section 2.2.1, the organic waste fraction is dominant in municipal solid waste in developing world cities. Alongside efforts towards greater waste recovery and recycling therefore, direct efforts towards building organic waste valorisation as a waste management driver would go a long way towards realising both ISWM and public health goals, as well as some measure of socio-economic development in developing cities.

Municipal or urban organic waste can be handled in one of three main ways; to produce fertiliser or soil improver from composting or co-composting with human excreta, as a source of energy through anaerobic digestion or briquetting, or as a source of food for animals for relatively fresh wastes (Rees, 2005). Sections 2.5.1 and 2.5.2 below elaborate on the composting and anaerobic digestion of organic waste as a resource oriented organic waste management strategy.

2.5.1 Organic Waste to Resource: Composting

Composting - the aerobic decomposition of organic material through the action of naturally occurring organisms like bacteria and fungi, has been one of main strategies for municipal organic waste handling globally to date and has several benefits including;

- The diversion of organic solid waste from landfill saving scarce space and possible contamination of land and water due to landfill leachate generation, as well as green house emissions in the form of uncontrolled anaerobic degradation.
- Composting provides a way to reclaim nutrients from organic refuse, and the resulting compost can be used as fertiliser in agriculture, helping to close the nutrient cycle.
- Compost improves the condition of soils i.e. texture, water retention capacity, pest inhibition, resulting in better crop yields over the long term.
- Composting operations are a potential source of employment and income generation for groups involved in composting and other related activities in the waste to compost chain.

Composting may be done at *backyard/household level* - where organic waste from the household is simply composted onsite in a heap or pit; *neighbourhood/community* or *centralised level* where several neighbourhoods, towns or municipalities compost their organic waste together as in much of the developed world (UNEP, 2009a; Favoino, 2001; US EPA, 1994); or through *co-composting* whereby organic household waste is mixed with human or animal excreta and composted. Compost may also be produced using the slurry product from anaerobic digestion.

2.5.2 Organic Waste to Resource: Anaerobic Digestion

2.5.2.1 Benefits

The anaerobic digestion of organic waste for biogas for energy use holds the added attraction of energy recovery from the organic waste fraction above and beyond the benefits of compost, which can also be produced using the digestion slurry product. Amigun & von Blottnitz (2007) summarise the added benefits of anaerobic digestion of organic waste for biogas as follows:

- Generates methane rich biogas which can be used as a fuel for thermal and electric energy generation at various scales.
- The components of biogas – carbondioxide and methane, can be used as industrial raw materials for specialised chemical applications.
- Direct reduction in green house gas emissions by controlling the anaerobic digestion of organic waste that would otherwise be emitted at landfill.

2.5.2.2 Process Dynamics

Anaerobic digestion is the biological breakdown of organic biodegradable matter by microorganisms in the absence of oxygen to produce 'biogas' consisting of 55-70% methane (CH_4) and 30-45% carbon dioxide (CO_2). Above 45% CH_4 content, biogas is flammable and can be used as a fuel (Deublein & Steinhauser, 2008). The process is complex, and can be broken up into four phases each carried out by different groups of microorganisms, with the first two and latter two phases closely inter-linked namely:

(i) Hydrolysis – undissolved compounds like cellulose, proteins and fats are cracked into monomers;

(ii) Acidogenesis – monomers formed in hydrolysis are reduced to short-chain organic acids (C1 – C5), CO_2 and H_2 ;

(iii) Acetogenesis – the products from acidogenesis are used as subtsrate for acetogenic bacteria which reduce CO_2 and H_2 to acetic acid and H_2O;

(iv) Methanation – Methanogenic bacterial species convert the acetate, methyl and CO_2 type substrates generated above into CH_4 which is flammable and usable as a fuel.

Biogas can in principle be obtained from any organic material, with actual biogas yields dependant on the feed stock properties and nature of digestion operation.

2.5.2.3 Technologies and Approaches

The anaerobic digestion of solid waste can be done in batch sequence, or as a continuous process at lower cost and greater use of reactor volume (Deublein & Steinhauser, 2008). The options for the continuous anaerobic digestion of organic waste material at scale can be classified according to the feed solids content. 'Wet' Systems are where the feedstock is diluted to 10-15% solids in the digester, while systems with a solids content of 20-40% are considered 'Dry' utilising less liquid dilution (Vazquez & Bagley, 2002). These systems may be single stage or two-stage separating the interlinked anaerobic digestion phases discussed in Section 2.5.2 for stability. Vazquez & Bagley (2002) reported that one phase systems can be as reliable as two-phase systems for the same kinds of waste if operational parameters are carefully adjusted, and that two-phase systems do not present higher biogas yields; other authors such as Burton *et al.* (2008) however argue that phase separation may lead to greater process efficiency. Anaerobic processes may be run under mesophilic (≈ 35°C) or thermophilic conditions (> 50°C).

Digesters of the Continuous Stirred Tank Reactor (CSTR) type, used historically with success in the agricultural sector, for sewage sludges in wastewater treatment and for industrial wastes; are primarily used for the wet anaerobic digestion of urban organic solid wastes, while digesting wastes in dry systems move via plug flow due to their higher viscosities. Vazquez and Bagley (2002) report that about 60% of all large-scale solid waste digestion plants in Europe operate under the one-phase dry scheme, with only limited application of the two phase scheme (about 10% of European facilities) due to their technical complexity and higher capital costs. The most successful low-tech anaerobic digestion plants for biodegradable organic solid wastes in developing countries are largely of the CSTR type, and tend to operate at relatively smaller scales and less sophistication (Muller, 2007).

2.5.3 Organic Waste-to-Resource: Global Experiences

2.5.3.1 Organic waste Experience in Europe

Currently, composting is the main organic waste handling method in Europe. Composting has a long history in Europe from the 1960's, and first caught on in countries such as Austria, Belgium (Flanders), Germany and the Netherlands. More recently, it has begun to spread out to other European countries including Denmark, Sweden, Italy, Spain -Catalunya, France and the UK (Favoino, 2001). Municipal composting operations in Europe are mostly highly mechanised from collection and transportation to central compost facilities. The collection of organic waste is usually done on a weekly basis, alternately with the rest of the MSW. Most composting is done aerobically, first in reactor systems, followed by composting in aerated piles. Windrow composting is not common (UNEP, 2009a).

Early attempts at composting used mixed MSW with extensive mechanical separation prior to composting. This however largely failed due to mixed compacted waste which resulted in high contamination of both the compost and recyclable material. This was followed by the introduction of 'Wet/Dry' waste collection which was abandoned due to poor definitions of what comprised 'wet' and 'dry' waste. The targeted collection of source-separated compostables as a separate stream, mostly limited to kitchen and garden waste, has proven to be the lasting collection model in Europe, producing clean compost (UNEP, 2009a). Compost products based on source separated organic waste show only 10-20% of the heavy metal content of mixed MSW compost, and can reach the same quality level as compost produced in private gardens (Barth, 2001). Certain municipalities in Europe (such as Monza, with large numbers of inhabitants well over 120,000 people) that have fully implemented composting and door-to-door collection of organic food waste, have reported total recovery/recycling rates as high as 50% of MSW (Favoino, 2001). Presently, about 15% of the estimated total recoverable organic waste in Europe is treated biologically (Barth, 2001).

The last 10-15 years in Europe have seen the emergence of small- to medium-scale anaerobic digestion of municipal organic wastes due to the added attraction of energy recovery from the organic waste fraction, and Germany is currently widely regarded as one of the global leaders in this sector.

2.5.3.2 Organic Waste Experience in North America

Organic waste in the US, comprising of food wastes and yard trimmings is handled largely through backyard composting (onsite) at households or via centralised municipal compost sites. The primary collection of these wastes, mandatorily source separated prior to collection, is through mechanised curbside collection (US EPA, 1994). Of 30 communities studied by the US EPA (1994), those with high composting rates typically provided frequent and convenient collection, targeted a wide range of organic materials, served a high percentage of households, promoted and encouraged backyard composting, and offered incentives to encourage residential, commercial, and institutional composting. High composting rates were observed for some municipalities such as Berlin Township, New Jersey (30% of MSW); Lincoln Park, New Jersey (30% MSW); West Linn, Oregon (20% MSW) and in turn these municipalities tended to show high total MSW recovery rates of up to 57%, 62% and 50% of MSW respectively. It was also observed that smaller communities tended to have higher recovery rates; 80% of municipalities studied with total recovery rates above 40% had populations less than 20,000, suggesting that more localised valorisation efforts are more effective.

In Canada, the City of Guelph started a better defined pilot Wet/Dry waste collection system in 1991 which was expanded citywide in 1993. 'Wet waste' material which includes food scraps, yard waste, soiled paper and disposable diapers, is composted while dry material and other wastes placed in the second 'Dry' container, are sorted and marketed. Participation rates in the program are very high (98%) and during the pilot scheme the system recovered 83-95% of all organic materials for composting (Themelis, 2000). The estimated rate of recovery and diversion of total MSW from landfill in the city is 58% of received material with the compost product sold to top soil blenders and landscapers (Themelis, 2000). Similar programmes are being used in other cities such as Toronto.

Anaerobic digestion was not yet playing a significant role in North American organic waste management a few years ago (Vazquez & Bagley, 2002).

2.5.3.3 Organic Waste Experience in Developing countries

Large-scale, centralised composting has tended to be unsuccessful in developing countries for technical, market, and organisational reasons, the most important of which is operating cost. Vermiculture, which produces humus, appears to be more successful as an organic waste composting strategy especially in Latin America since production times are much shorter (days as opposed to months) and the product has a wider market than compost. Successful cases have been reported in Colombia, Peru, and Cuba (UNEP, 2009b). There are however some examples of successful urban organic waste valorisation in developing countries, via small to medium scale composting operations, anaerobic digestion and animal feeding. These are described below.

- **Sri Lanka, Colombo: Medium scale biogas and compost production from market waste**
  Rees (2005) describes a pilot project being run by the municipal authorities in Colombo that produces biogas and compost from the organic waste from local vegetable markets. Up to 480 tonnes of organic waste are handled by the anaerobic digesters yearly. Organic material typically spends 4 months in the digesters forming $1m^3$ biogas/tonne/day which in turn can generate up to 7500 kWh of electricity annually. The gas is piped from the digester and used to power a 220 volt, 5 kilowatt converted engine, a baker's oven and a catering size gas burner at the site.
- **Thailand, Rayong Municipality: Co-generation of MSW**
  Rayong municipality in Thailand has a MSW treatment facility for the stabilisation of waste, electricity generation through anaerobic digestion and production of soil conditioner (Polprasert, 2007). The facility treats 70 tonnes MSW/day and produces 2.2 million cubic metres of biogas, 5100 MWh electricity per annum and 5600 tons/year of soil conditioner. The plant is expected to pay the invested cost of US$ 4.3 million in 10 years from financial gains from electricity sales and soil conditioner.
- **Urban organic waste use as animal feed – Manila, Philippines**
  Rees (2005) observed that commercial feeds for pig rearing in Manila are expensive and pig owners often turn to organic scraps to supplement or replace the commercial feed. A network of collectors of organic waste from restaurants in the city centre distributes the food scraps amongst the farmers at about half the price of commercial feed. A cost comparison carried out shows that profit from pig rearing has more than doubled by feeding the pigs on organic scraps, even after accounting for all other costs such as veterinary costs, transport and fuel (Rees, 2005). Highly localised integrated organic waste recycling and reuse is also utilised on the 24ha Maya animal and crop farm complex in the Philippines, and in Thailand on the 100 ha Kamol Kij Co. Rice Mill and Kirikan Farms (Polprasert, 2007).
- **Organo-synthetic commercial mixed fertiliser production using compost – Dhaka, Bangladesh**
  An attractive avenue for the production and utilisation of compost from urban organic waste is mixed organo-synthetic fertiliser production with established fertiliser manufacturers and traders, resulting in the development of fertiliser products that tap into the strengths of each component. A successful example of this business model is in operation in Dhaka, Bangladesh where the Agro-fertiliser company involved in this business model is confident it can sell up to 10 times the present volume purchased from the urban organic waste composters (Rouse *et al,* 2008).

2.6 Conclusions from literature and implications for ISWM planning in Nairobi

From the literature reviewed, the following pertinent observations can be drawn:

- The bulk of municipal solid waste generated in Africa and the developing world can be expected to consist of organic wastes. Generation rates in Africa typically are ≤ 1 kg/capita/day.
- Developing cities in Africa are generally characterised by low waste collection levels; seemingly owing to rapid population growth and urbanisation rates, which prevalent slower economic growth rates cannot support. This has created an urgent need for holistic, inclusive waste management strategies employing ISWM principles, as well as locally inspired innovations and approaches.
- There is growing evidence of the success of bringing traditionally peripheral actors in waste management in the informal resource recovery and recycling sector, into the formal solid waste management arrangements in developing countries to fill the vacuum left by low public sector waste service delivery.
- The increasing adoption of Mebratu's (1998) cosmic interdependence model as a conceptualisation of the world implies the need for the use of systems thinking and systems-based tools for all aspects of design for sustainable development, including waste management. While engineering methods have evolved from simple problem-oriented to "integrated" approaches, they have not yet adequately made the leap into a systems-based discourse.
- While systems' thinking provides tools to investigate and articulate the structures that often underlie complex situations - situations that are often evident in waste management in African cities with its spectrum of actors and challenges involved; few attempts have been made to employ it in developing an understanding of these situations, as well as to develop solutions at a more fundamental level.
- The application of systems thinking in waste management planning especially for developing African cities, and of its 'systems dynamics' sub-stream in particular; does not seem amenable to mechanistic mathematical modelling, but rather is valuable as a tool to systematically structure the waste problem/situation and to develop conceptual causal loop models and analyses articulating the solid waste system or arrangement in a given area as a whole (known as "soft systems analysis"). This conceptual modelling and analysis can be used to highlight prevalent behavioural patterns, inherent system strengths, weaknesses, drivers and leverage points, and to provide guidance to appropriate interventions for ISWM.
- Organic waste valorisation, long established as a waste management strategy in the developed world, represents a currently under-tapped opportunity in most developing world cities, although encouraging examples have been reported from Latin America and South East Asia.

3 Project Motivation and Methodology

In response to the dire solid waste situation in Nairobi described in Section 2.2.4, plans are underway to establish a sanitary landfill for Nairobi, and the Kenyan government agreed in 2009 to collaborate with the United Nations Environment Program (UNEP) to develop an Integrated Solid Waste Management (ISWM) Strategy for Nairobi City dealing with the entire waste chain. The project was initiated in March 2009, and a National Task Team comprising 21 members from various government departments, academia, and civic society was established to oversee the development of the strategy along with a team from the Environmental & Process Systems Engineering Group at the University of Cape Town, of which the author was part.

As discussed in Chapter 1, the core elements of the resulting Nairobi City ISWM Strategy (CCN & UNEP, 2010) were finalised in April 2010 and included, alongside the formal use of the UNEP ISWM planning methodology (Section 2.3.1), some application of systems analyses of the underlying causal and feedback relationships in Nairobi's waste system. These systems analyses could however only be done partially due to project delivery time constraints. This dissertation extends these analyses and re-examines the adequacy of the interventions finally proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010).

In line with the thesis objectives and key questions outlined in Chapter 1 (Section 1.4), the methodology employed in this work is presented in the sections following.

3.1 Systems Thinking as an Analytical Framework: Motivation

Besides waste generators, the spectrum of actors involved in the provision of solid waste management services in Nairobi ranges from those in the formal economy in the form of private companies and the City Council, to actors in the semi- and informal sectors in the form of community based organisations and informal waste recovery (scavenging) and trading. All these actors are motivated by different factors, face different constraints and occupational challenges, and operate using different mechanisms towards different goals. The Nairobi ISWM Strategy developed had to be implementable under these conditions of semi-formality or otherwise risk failure if it failed to build on these existing systems.

To understand the waste system across the city and the various positions, behaviour and contexts of its actors; the system was viewed as consisting of a multiplicity of subsystems, variables and actors; an analytical framework that was consistent with the presumptions and objectives of systems thinking (see Section 2.4). The underlying premise for systems thinking, and in particular the 'system dynamics' stream of this research field, is that the multiplicity of variables existing in complex systems become causally related in feedback loops that themselves interact (Jackson, 2008). The systemic interrelationships between these feedback loops constitute the structure of the system, and this structure is the prime determinant of system behaviour (Jackson, 2008).

In cognisance of the higher value in changing system paradigms than in modelling precise numerical solutions (see Meadows (1999) in Section 2.4.2) to solid waste challenges in developing cities as in most conventional ISWM plans, especially in Africa; this work emphasizes the 'soft systems' aspects of systems thinking and dynamics (Section 2.4.2) – systematically structuring the waste problem and

situation in Nairobi, and developing conceptual causal loop models to articulate the solid waste system in Nairobi as a whole, highlight its inherent drivers, behavioural archetypes, strengths and weaknesses, and determine appropriate system intervention recommendations towards ISWM. The insights generated from this are used to inform the examination of whether the developed intervention strategies towards Integrated Solid Waste Management in the city as in the Nairobi ISWM Strategy (CCN & UNEP, 2010) were adequate at a fundamental level and contextually relevant.

3.2 Systems Analysis of Nairobi's Waste Management

The UNEP ISWM planning methodology described in Section 2.3.1 was broadly followed in the collection and collation of data, with a few additional steps introduced to aid the soft systems modelling and analysis of Nairobi's waste management. Over the course of this data collection/collation, specific insights were sought and extracted for the purposes of developing a systems picture of the solid waste system in Nairobi that forms the basis of the analyses in this work. The methodology employed towards this end is summarised in Figure 7 and described in more detail below. Full bordered boxes illustrate the steps normally followed in UNEP ISWM planning data collection; dotted borders illustrate the steps that were specifically introduced to the data collection and analysis process to enable the generation of a systems picture of Nairobi's waste management.

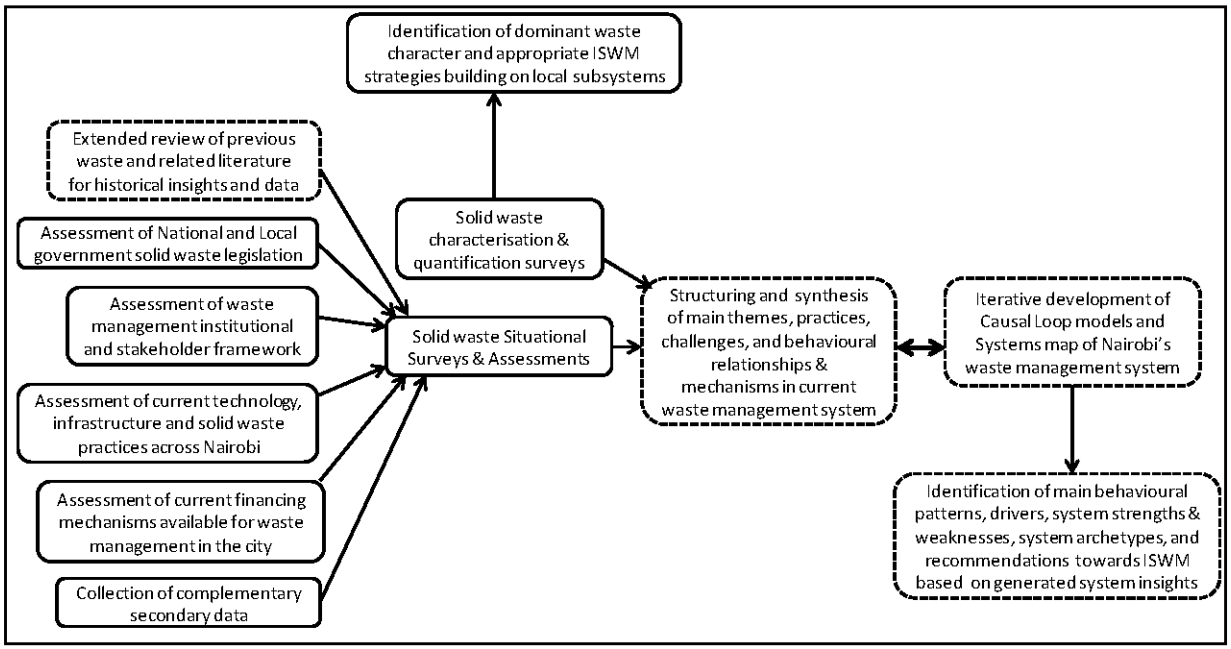

Figure 7: Summary of methodology employed in the development of systems modelling/mapping and analysis of Nairobi's waste management system

3.2.1 Organisation of Data Collection

Initial evidence suggested that the Nairobi ISWM Strategy would have to be implementable under conditions of semi-formality in terms of several of the actors and systems already active in solid waste management in Nairobi, as such it was essential to approach data gathering utilising local knowledge production capacity to tap into local situation familiarities and perspectives. This was achieved with the aid of 30 local university research assistants working with 10 field City Council of

Nairobi staff, a National Task Team established by UNEP-Nairobi to oversee the development of the plan, and the applications of systems thinking and analyses drawing on the collected field data and a multiplicity of previous and current local publications and data.

3.2.2 City-wide Waste Surveys

3.2.2.1 Influence of the nature of waste collection in Nairobi on waste characterisation surveys

Solid waste in the middle to higher income areas of Nairobi is largely regularly collected by large private collection companies via kerbside methods, while waste in the lower income areas is largely collected from neighbourhoods by Community Based Organisations who deposit it at designated communal waste collection points from where the City Council is meant to transport it onward to final disposal at the official Dandora dumpsite (see Section 4.2.2). Owing however to the erratic onward transportation of solid waste material from these points; they are closer to pseudo end-disposal sites in themselves. There is also a large presence of outright illegal waste dumps strewn across the city usually in the vicinity of these designated communal collection points, and in areas where no waste collection service or no designated collection points exist. There is a vibrant informal waste recovery and recycling sector in the city which sources most of its material from these communal collection points and illegal dumps, as well as from the official dumpsite at Dandora (Baud *et al.*, 2004; Karanja, 2005; field observations -2009).

Solid waste characterisations in this work of Nairobi's waste stream were therefore done at both communal waste collection points and illegal dumps (lumped together due to their high similarity), and at immediate source - with waste taken directly from domestic and non-domestic waste generators; with subsequent analyses done to determine the presence of any significant differences between the two sets of characterisation results.

3.2.2.2 Waste Characterisation and Quantification

In order to determine the current character of Nairobi's solid waste, waste characterization surveys were carried out in July and September 2009 at communal waste collection points and illegal dumps (considered and reported together – see 3.2.2.1 above), and at immediate source (waste directly from households and various non-domestic sources). The surveys were conducted by members of the National Task Team (NTT), the author, a team of 30 local university research assistants and 10 City Council field officers. The selected communal collection points and illegal dumps for sampling were evenly spread across the city to reduce bias (see Appendix I for a spatial and photographic illustration), while samples for waste characterisation at immediate source were taken from Starehe, Makadara and Westlands zones. Figure 8 shows the study areas and city zones covered during the waste characterisation surveys.

Figure 8: Map of Nairobi showing solid waste characterisation study areas (Source: CCN & UNEP, 2010)

3.2.2.3 Sampling Protocols and Statistical Confidence

The types of municipal solid waste studied excluded medical waste which falls under the jurisdiction of the Ministry of Public Health and Sanitation, and industrial waste (hazardous and non-hazardous) which the respective industrial generators are responsible under law to dispose of appropriately.

- **Sampling at Communal waste collection points & Illegal dumps**

The number of sampling sites required to achieve a representative characterisation of waste at communal collection points and illegal dumps (sampled and reported together – see Section 3.2.2.1) was determined using the ASTM Standard Test for waste characterisation audits at solid waste transfer stations and disposal sites (ASTM D 5231 – 92) as discussed in Section 2.3.2.2. A total of **163 residential** and **97 non-residential** evenly spread communal collection points and illegal dumps (83 located in business and commercial areas, 14 adjacent to fruit and vegetable markets) were randomly sampled across the city over three weeks.

A minimum of 73 sampling sites was statistically required to achieve a standard error or relative uncertainty of +/-10% at a 90% confidence level. Using the iterative procedure for Equation 1, and the plastic waste composition means and standard deviations determined from the pool above of **163 residential area** communal waste collection points and illegal waste dumps (mean composition - 15.4%, composition standard dev. – 8.6%), and **97 non-residential** area communal collection points and illegal waste dumps (mean composition - 14.3%, composition standard dev. – 7.3%), the minimum statistical sample number required to achieve 90% Confidence and 10% standard error was determined as follows:

(student *t* characteristic, t^*_σ at 90% Confidence = 1.645; standard sampling error or precision of 10%, e = 0.1)

$$n = \left(\frac{t * s}{e * \bar{x}}\right)^2$$

$$n = \left(\frac{1.6634 * 0.086}{0.1 * 0.154}\right)^2 = 87\ residential\ collection\ point\ and\ illegal\ dump\ waste\ samples$$

$$n = \left(\frac{1.667 * 0.073}{0.1 * 0.143}\right)^2 = 73\ non-residential\ collection\ point\ \&\ illegal\ dump\ waste\ samples$$

- **Sampling at immediate source**

The number of waste samples required to achieve a representative characterisation at immediate source was determined using a household waste sampling protocol based on the central limit theorem after Qdais *et al* (1997) and Gomez et al (2007) as discussed in Section 2.3.2.2. **568 residential waste samples** were taken from 109 households, and **336 waste samples from various non-residential waste generators** including retail shops (96 samples); workplaces and offices (27 samples); institutions (primary and secondary schools and universities, religious venues and non-hazardous waste from health care units and hospitals; total of 147 samples reported together due to high similarity in observed waste compositions); and at catering venues and eating places (66 samples) in Starehe, Makadara and Westlands zones. All waste sampling at immediate source was done over a period of one week in line with minimum recommendations for such waste characterisation exercises at source as in Section 2.3.2.5. Sampled household income levels were also estimated according to housing type after Qdais *et al* (1997).

A minimum of 232 samples were statistically required to achieve a relative uncertainty of +/- 5% at a 99% confidence level for residential waste at source. Using Equation 2 and a mean waste generation standard deviation of 0.3 kg/capita/day (exact figure - 0.2957 kg/capita/day) determined from the pool of **568 residential waste samples** described above, the minimum statistical sample number required to achieve 99% Confidence and 5% standard sampling error in waste generation from residential waste surveys at source was determined as follows:

(student *t* characteristic, *z* at 99% Confidence = 2.575; standard sampling error of 5%, *R* = 0.05)

$$n = \left(\frac{z * SD}{R}\right)^2 = \left(\frac{2.575 * 0.2957}{0.05}\right)^2 = 232\ residential\ waste\ samples\ at\ source$$

The extensive heterogeneity in the characteristics and generation rates of non-residential waste generators at source could not allow a similar calculation, but a large total of 336 waste samples were taken from the various non-residential generators sampled as discussed above in order to give a reasonable estimate of their respective waste compositions.

- **Summary of Statistical Confidence**

In all the sampling done therefore for waste characterisation at communal waste collection points and illegal dumps, and at immediate source; the sample numbers taken as described above exceeded the statistically required sample numbers to achieve at least 90% Confidence levels and 10% standard sampling error in residential and non-residential waste characterisation.

3.2.2.4 Sample Handling & Sorting

For all the samples taken at communal collection point and illegal dumps, as well as at immediate source; waste samples were retrieved and handled using the Mixing and Quartering approach as

described in Section 2.3.2.4. Easily manageable final waste sample sizes in the field, of 15 to 50 kg, were retrieved, manually sorted, and weighed in broad material categories namely: Organics (all biodegradable material), Paper, Plastics, Glass, Metal, and Other (all residual material not captured in the prior categories); with material averages determined for the domestic and non-domestic generators sampled.

3.2.3 Complementary Data Sources and Data Collation methods

In addition to the solid waste surveys described above, secondary and field data to aid this work - both qualitative and quantitative, was collected as follows.

3.2.3.1 Secondary Data

A comprehensive secondary data and literature survey was conducted concurrent to the waste characterisation surveys to identify previous work done on Nairobi's solid waste management and gain insights on the historical trends and prior behaviour. Data was sourced from a variety of academic, public and private reports, records from the City Council of Nairobi, as well as from field interviews and visits to formal and semi-formal actors involved in waste collection, transportation, resource recovery and trading in Nairobi by the author and local research assistants.

3.2.3.2 Stakeholder Consultations

Several UNEP and City Council ISWM Training and Stakeholder Consultation Workshops were also held in 2009 with the participation of stakeholders from government, civic society, academia, and from the private and semi-formal waste sectors. Information from these workshops and from field visits and interviews was used by local research assistant teams guided by members of the National Task Team, to draw assessments on the existing institutional and stakeholder framework for waste management in the city (Ndunda *et al.*, 2009; Wangui *et al.*, 2009), national and local government solid waste legislation (Omondi *et al.*, 2009), current technology, infrastructure and solid waste practices across Nairobi (Meeme *et al.*, 2009), and current financing mechanisms available for waste management in the city (CCN DoE, 2009a).

3.2.4 Methods for Systems Analysis

3.2.4.1 Situation Analysis of Current Solid Waste Management in Nairobi

The data collected as described in 3.2 above was used to estimate current waste characteristics in Nairobi, waste generation volumes, and to estimate the material quantities moving through Nairobi's waste sources and sinks. This was combined with a historical documentation and analysis of the behavior of key variables and actors in Nairobi's waste management to help describe the general nature and direction of the entire waste system towards the development of a soft systems map of solid waste management in Nairobi.

3.2.4.2 Development of Causal Loop Models & Systems Analysis of Nairobi's Solid Waste Management System

The historical documentation and analysis of the behavior of key variables and actors in Nairobi's waste management system as in 3.2.4.1 above was used in an iterative process to develop causal loop models and a system map of the city's current solid waste management system with all its current major actors and practice mechanisms. The causal loop maps/models were then used to identify major behavioral patterns, system drivers, and archetypes at play in Nairobi's waste

management system, and to determine prescriptive actions based on the system archetypes at work. The insights generated from this were then used to re-examine the proposed Nairobi ISWM Strategy interventions (CCN & UNEP, 2010) to determine their adequacy in solving the challenges observable in Nairobi's waste management at a more fundamental level.

3.3 Organic waste valorization as a system driver in Nairobi's waste management: Investigation of current practice and economic feasibility

It was determined from the waste characterization surveys in 3.2.2 that the bulk of solid waste generated in Nairobi is organic in nature. It was also observed that the material recycling capacity of the city is a key system driver in its waste management, and that organic waste valorization shows good potential to expand this capacity. It was therefore of interest to determine the current capacity and potential role that the expansion of organic waste valorization activities in the city could play in amplifying material recycling capacity as waste system driver towards ISWM in Nairobi.

3.3.1 Secondary Data Collection

Another comprehensive data and literature survey was conducted as in 3.2.3.1 with a focus on identifying current practices and organisations or entities in Nairobi working on the derivation of value from urban organic wastes in the city. Estimates were drawn from this on current organic waste valorisation in Nairobi through composting and use as animal feed, and associated economic feasibility. Little information was however available on the economic feasibility of anaerobic digestion at scale, this was modelled instead as discussed in Section 3.3.2.

3.3.2 Economic modelling of Anaerobic digestion of Organic waste in Nairobi

The anaerobic digestion of 10 tonnes/day of organic/biodegradable solid waste for electricity generation at a hypothetical medium-scale biogas-to-energy digestion facility in Nairobi was modelled and investigated with a view to establishing the order of magnitude of investment necessary to establish the necessary infrastructure, and the potential economic returns and benefits in the Nairobi context. Potential incomes from selling carbon emission reduction credits through the Clean Development Mechanisms are acknowledged but were excluded from these analyses.

3.3.2.1 Plant sizing and Economic modelling

Digester sizing for the biogas-to-energy plant was conceptually based on the wet digestion (see Section 2.5.2.3), Continuous Stirred Tank Reactor design (agitated fixed dome or tank reactor, with external gas storage) which is already familiar in Kenya (Onduru *et al.,* 2009). The scaling of the digestion chamber was based on retention time after Sasse's (1988) work on the design of simple biogas plants in Africa and Asia. The design and economic modelling undertaken is summarised in Figure 9.

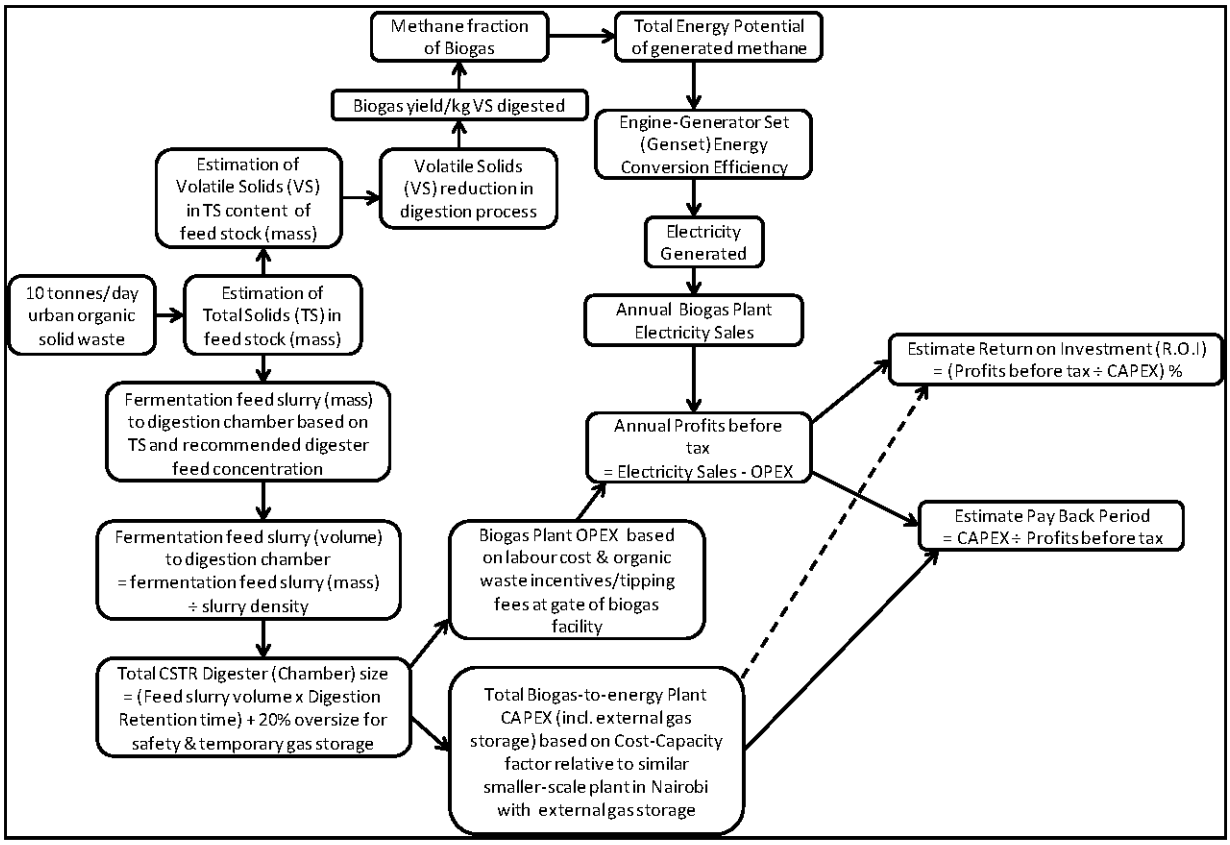

Figure 9: Summary of the techno-economic modelling procedure employed for a hypothetical 10 tonne/day biogas-to-energy plant in Nairobi

Modelling assumptions were made towards the development of a conservative sizing and economic model i.e. model assumptions and inputs tended to the lower range of literature. Key assumptions made in the calculations and modelling were as follows;

Plant Sizing and Capital/Operating cost assumptions

- Costing was done using the cost-capacity (Lang) factor approach (+40%, -20% accuracy), utilising a cost-capacity factor of 1.2 (Amigun & Blottnitz, 2007). Amigun & Blottnitz (2007) have recently shown that biogas installations in Africa do not seem to exhibit the economies of scale usually assumed with process plants.
- Fixed capital costs for the biogas-to-energy plant were calculated using the cost-capacity approach above based on the capital cost of the Keekonyoike Slaughter House biogas plant in the peri-urban Kajiado North District bordering Nairobi, discussed in Section 5.3.3.2. The capital cost for the Keekonyoike biogas plant of KShs. 8 million includes all biogas-to-energy plant components including feeding chambers, digesters, slurry pumps, digestate storage, Generator-Engine Set (Genset), piping and temporary gas storage, etc.
- Labour: 1 full time assigned technician and 2 assistants/casual labourers per biogas plant facility of this size (10 tonnes organic waste/day) each earning about KShs. 50,000/month and KShs. 15,000/month respectively. Wages are approximated based on interactions with Nairobi residents.

- Engine-Generator (Genset) efficiency of 25% (biogas energy conversion to electricity via Genset)

Approximations of the physical and chemical nature of urban organic solid waste in Nairobi

The physical and chemical nature of urban organic wastes in Nairobi was assumed to be similar to that in Dar-es-Salaam, for which data was available from previous scientific biogas work done on urban household and market organic wastes (see Riuji, 2005). This approximation was made in light of both cities' East African context and the cultural and lifestyle similarities across the region, as well as financial caps in data gathering for Nairobi given the broad nature of the Nairobi ISWM project. The physical and chemical characteristics of urban organic wastes in Dar es-Salaam are as follows:

- Digester feed total solids concentration is assumed to be 10% (Vazquez & Bagley (2002) report wet digestion in the range 10% to 15%).
- Digestion/Fermentation feed slurry density equal to that water (1000kg/m^3) due to high feed dilution rate above (10% total solids).
- Total solids (TS) content of 20% (Riuji, 2005) in feed organic waste. Organic/biodegradable waste in Nairobi is comprised mostly of food and green wastes.
- 90% Volatile Solids (VS) in the solid fraction (TS) of urban organic waste (Riuji (2005) found 91% VS for food wastes and 88% VS for market wastes).
- 75% average Volatile Solids (VS) reduction during anaerobic digestion (Riuji (2005) observed 65% to 90% VS reduction in ARTI digester).
- Average biogas yield of urban household and market organic wastes of 0.5 m^3/kg VS (Riuji (2005) found 0.6 - 0.7 5 m^3/kg VS).
- Average methane concentration of 55% in biogas (Riuji (2005) observed 56 to 66%).
- Energy content of methane of 11.04 kWh/m^3 (Duerr *et al.*, 2007).
- Conservative organic material retention time in digester of 40 days, similar to household ARTI Digesters in Dar-es-Salaam (Riuji, 2005).

3.3.2.2 Modelling Outputs

Using the assumptions in 3.3.2.1 and the modelling summary in Figure 9; the total digester size(s) necessary to anaerobically treat 10 tonnes/day biodegradable solid waste, total potential electricity generation from such a plant, and the fixed capital investment required for such a facility were computed. In addition the following outputs were obtained at different selling prices for the electricity generated, and different organic waste buying incentives or tipping fees at gate of the hypothetical biogas facility:

- Capital pay-back periods for the plant;
- Estimate annual incomes before tax;
- Returns on Plant Investment.

4 Systems Analysis of Nairobi's Solid Waste Management

This chapter begins by drawing in Sections 4.1 to 4.3, the situational observations (system data) that were extracted towards the development of a soft-systems model of Nairobi's waste management; of the prevalent social, economic and solid waste specific conditions in Nairobi, as determined over the course of the ISWM Strategy development process. This data is brought together in causal loop maps/models and soft systems analyses of the current solid waste management system in Nairobi in Section 4.4, with discussions on appropriate remedies from a systems perspective following. The chapter closes out with a summary of interventions recommendable from the systems analyses carried out, and a re-examination of the interventions that were proposed earlier in the Nairobi ISWM Strategy (CCN & UNEP, 2010) in Section 4.5, to determine their adequacy and fill any possible gaps highlighted.

4.1 Overview of Nairobi's Social and Economic Climate

Waste management in Nairobi is a sub-system of the wider social and economic circumstances in the city. A brief overview is provided below of the overarching social and economic influences at play.

Nairobi city is the capital of Kenya and consists of 9 administrative zones as shown in Figure 10.

Figure 10: The administrative zones of Nairobi (Source: UNEP & UN-Habitat-Kenya, 2007)

It was initially founded in 1899 as a rail depot on the railway linking coastal Mombasa to neighbouring Uganda, and has grown to become the most populous city in East Africa (City-data, 2009). Its economy is driven by the agricultural sector, financial and service industry along with sizable manufacturing and tourism sectors. These are described further below.

4.1.1 Nairobi's Economy

The cornerstone of Kenya's economy is agriculture, employing about 80% of the population and accounting for up to 50% of the country's exports (City-data, 2009). The areas around Nairobi are particularly prime agricultural lands. Agricultural activity includes horticulture, flower exports,

cultivation of cash crops like coffee, and several food crops including maize, sorghum, cassava, beans, and fruit (City-data, 2009). Nairobi itself is a regional financial and political hub housing the headquarters of several international companies and organizations. Other industry in Nairobi includes textiles, tobbacco, food processing and beverages, and tourism as a result of the Nairobi National Park bordering the city. Kenya's economic growth in 2007 was reported at 7% (Thomasson, 2009), showing signs of resurgence after decreasing markedly from the 1960's to 1999 (Baud *et al.*, 2004).

4.1.2 Demographics

The majority of wealthy Kenyans live in Nairobi, however 50-60% of the city's residents are estimated to live in poverty (UN-HABITAT & UN-OCHA, 2009). The city's poor live largely in slums that cover just 5% of the city area (Sheehan, 2005), the most famous being Kibera which is believed to be the largest and poorest slum in Africa (BBC, 2005). Poverty rates range from 32% in Westlands to 59% in Makadara across Divisions, and from 8% in Nairobi West to 77% in Makongeni (east of Nairobi) (Kenya National Bureau of Statistics, 2003). The west of Nairobi - with the exception of Kibera, is generally the more affluent part of the city.

4.1.3 Population growth and trends

Nairobi's population in 2008 stood at 3.03 million (Brinkoff, 2009) and growth since 2000 has averaged 4% per annum (UNEP & UN-Habitat-Kenya, 2007). Figure 11 below adapted from UNEP & UN-Habitat-Kenya (2007) shows Nairobi's rapid population growth.

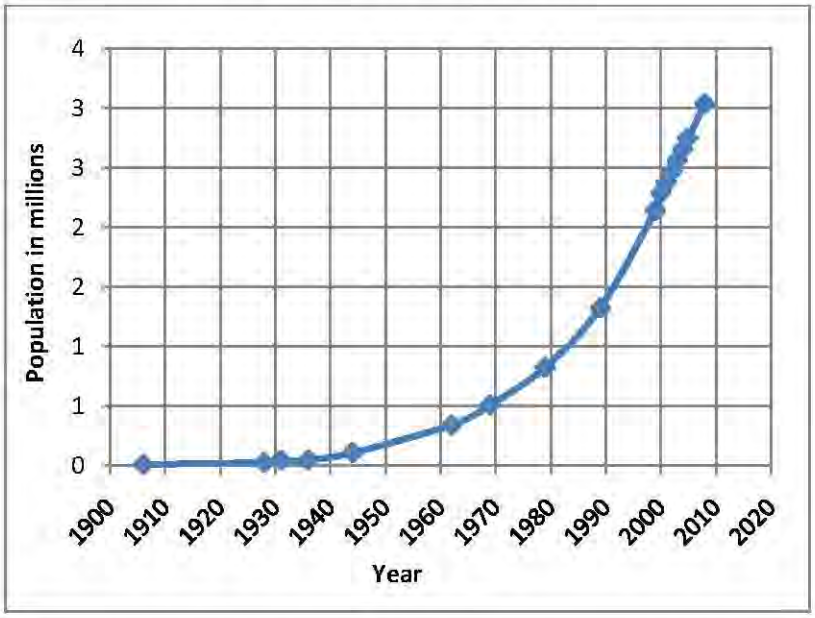

Figure 11: Nairobi's population growth (adapted from UNEP & UN-Habitat-Kenya, 2007)

4.2 Key Actors and Variables in Nairobi's Municipal Solid Waste Management

Drawing on a multiplicity of previous local publications on Nairobi's solid waste management including JICA (1998), Baud et al (2004); Bahri (2005), and Karanja (2005); solid waste management situation analyses drawn during the ISWM Strategy development process by Ndunda *et al* (2009), Wangui *et al* (2009), Omondi *et al* (2009), Meeme *et al.* (2009), and CCN DoE (2009a); and field data and observations made over the course of the ISWM Strategy development, several cross-cutting key actors and variables were identified in Nairobi's solid waste management. This section summarises major findings regarding these actors and variables.

4.2.1 Solid Waste Collection by the City Council of Nairobi

CCN DoE (2009a) reported that prior to the 1980's the City Council of Nairobi (CCN) held the solid waste collection monopoly in Nairobi and was able to collect over 80% of the waste generated. The 1990's however saw an increase in waste to over 1500 tonnes yet total collection trucks had reduced radically due to reduced budgetary allocations and low priority given to solid waste management from the council administration and central government. Consequently there was a decrease in collection service which led to increased public outcry and complaints which necessitated the contracting out of waste collection in Central Business District to private collectors. The national government then scrapped general waste service charges and introduced a Local Authority Transfer Fund through the Local Government reform programme, with however little consideration into solid waste management infrastructure and operational budget. In addition national water sector reforms led to the creation of a Water and Sewerage Company which resulted in the scrapping of dustbin charges that were previously collected with the water bills, a previous source of revenue for solid waste management. This led to a 50% drop in revenue collected by the City Council of Nairobi for solid waste management (SWM). There is currently a lack of direct government grants or central borrowing directly aimed at providing SWM services. Income for SWM operations is now collected by the CCN Department of Environment (CCN DoE) from various sources including the annual budget from CCN Council which draws from city taxes (Oyake, 2010), and some direct user fees from commercial generators and institutions, as well as fines and permits that the CCN DoE is allowed to levy (CCN DoE, 2009a). CCN DoE budgets are reviewed and approved by the council's chief accountant, finance committee, city treasurer and the national minister of local government (CCN DoE, 2009a). The annual allocation of funding to solid waste management specific operations has decreased from 7.3%, to 7%, 4%, 4%, and 3.6% respectively of total council budgets over the period 2005/6 to 2009/10.

Karanja (2005) observed that user dissatisfaction is high and public acceptance and ratings of municipal solid waste service are very low. Karanja (2005) further highlights the following factors as having affected CCN collection performance over the years: financial mismanagement, excessive workforce and low productivity, poor revenue collection, corruption and misappropriation of official resources, and loss of clients to the private sector. In addition Baud et al (2004) also highlight inadequate financial resources available to the CCN due to slowing Kenyan economic growth since the 1960's, as one of the contributing factors.

4.2.2 Other Actors in Solid Waste Collection & Management in Nairobi

The decline in waste collection performance of the CCN led to the emergence of private waste collectors and Community Based Organisations to provide this service. Solid waste in the middle to higher income areas of Nairobi is generally collected via kerbside collection by private collection companies operating under open unregulated competition, complemented by some City Council collection (Karanja, 2005; field observations). In the lower income areas, solid waste is largely collected by Community Based Organisations (CBOs) consisting of community members who go round neighbourhood households on agreed days (field observations). CBOs evolved to fill an increasing vacuum in service delivery by the City Council of Nairobi, and due to initial disinterest by the private collection sector in low income areas (Karanja, 2005). Most CBOs deposit their collected waste at designated communal waste collection points from where the City Council is meant to transport them onward to final disposal at the official Dandora dumpsite. Owing however to the erratic onward transportation of solid waste from these points, they are closer to pseudo end-disposal sites in themselves.

There is also a large presence of outright illegal waste dumps strewn across the city usually in the vicinity of these designated collection points, and in areas where no service or designated collection points exist. A vibrant informal waste recovery and recycling sector in the city sources most of its resource materials from these communal collection points and illegal dumps, as well as from the official Dandora dumpsite (Baud *et al.,* 2004; field observations). The majority of CBOs are also involved in some composting and inorganic waste recovery, trading, and recycling to complement the low collection fees they charge in the low-income areas (Baud *et al.*, 2004).

Karanja (2005) notes that the government (with the City Council having jurisdiction over waste management activity in Nairobi) has failed to supervise and monitor the activities of the myriad actors now involved in solid waste service provision in the city, including those in recovery and recycling. She adds that these activities are not seen as integral to SWM, with emphasis placed instead on collection and disposal. There is also very poor control of disposal activities at the official Dandora dump and at illegal dumps across the city due to inadequate legislation and enforcement of existing laws (Karanja, 2005; Omondi *et al.*, 2009; field observations).

4.2.3 Waste Generators, Practices, Final Disposal and Implications

4.2.3.1 Households

Households in Nairobi are involved in some degree of waste diversion. Vegetable wastes are used for fertilising and mulching kitchen gardens and livestock feeding while food wastes are used to feed chickens, pigs and dogs (Baud et al, 2004). Baud *et al* (2004) found that 70% of interviewed households diverted waste materials at some level for reuse or sale including plastics, clothing, shoes, and wood from furniture. Approximately 15% of sampled households also traded with diverted materials. While CCN by-laws make provision for the source separation of waste for collection, little to no separation is actually done by generators or is actively pursued and encouraged by the CCN (Omondi *et al.*, 2009).

The inadequacy of solid waste collection services also forces some households to resort to wild dumping, open burning and burying (Baud et al, 2004).

4.2.3.2 Institutions and Commerce

Institutions and enterprises (such as schools, hospitals, hotels, restaurants, shops and markets) either contract private companies for solid waste collection or sell/give waste free to farmers and waste pickers (Baud et al, 2004). Esho's survey (1997) found that 47% of 19 institutions interviewed handled waste themselves, 45% of these through burning and 53% by selling to waste pickers. About 67% of 18 commercial enterprises also sold their waste to waste pickers. Baud's (2004) own survey in 1998 also indicated that some of the organic waste from 43 markets and institutions in Nairobi is used as animal feed.

4.2.3.3 Industry

Industrial waste is not formally considered a part of the MSW waste stream and each generator is responsible for its disposal. Industries either dispose of their waste themselves; hire private contractors, or the CCN to do it. Alternatively they may sell it to recyclers or recycle it themselves (Baud et al, 2004). Esho in 1997 found that 50% of industry contracted private waste handlers, while the other 50% handled it themselves - 60% of them through recycling and the rest through open dumping or selling to waste pickers for recovery (Baud et al, 2004).

4.2.3.4 Final Disposal

The city has only one official dumpsite at Dandora, an open and un-engineered landfill, 7.5 km east of the CBD which has reached capacity (JICA, 1998). The site receives all types of solid waste, i.e. domestic, industrial, commercial, institutional, hospital and hazardous waste (JICA, 1998). Segregation of hazardous wastes from MSW largely does not take place and the CCN collects all domestic, commercial, industrial, hospital and market waste together (JICA, 1998). The dump is owned and operated by the CCN with generally low tipping charges (Baud *et al*, 2004); there is however also a significant presence of non CCN mafia-type gang control within the dump's actual premises. Corruption involved in collecting the already low tipping fees at the dump denies the CCN a significant portion of revenue (Baud *et al*, 2004). The dump's peripheral location, lack of garbage transfer facilities in the city, and insecurity due to gang type control lead to a rise in overall disposal costs for collectors. This coupled to poor monitoring of private collection companies has led to widespread illegal dumping across the city (Baud et al, 2004; Karanja, 2005; Omondi *et al.*, 2009; field observations).

No facilities exist at Dandora to prevent secondary pollution at the site and controls to prevent entry of hazardous and toxic waste are ineffective (JICA, 1998). The dumpsite borders a densely populated low income residential area, the Dandora Housing Estate, and is adjacent to the Nairobi River. The risk of spread of diseases, contamination, and water/air pollution is especially high due to the hazardous substances in the waste stream deposited there and the presence of open burning and rodents. Due to secondary pollution, residents of the dumpsite area protested against the continued use of the dumpsite in 2001 (Baud et al, 2004). A 2006 study commissioned by UNEP to determine the environmental and pollution effects of the dumpsite showed that soil samples collected from the site recorded high levels of lead and other heavy metals relative to international standards (Kimani, 2007). The study found medical records obtained from a Catholic Church dispensary at Kariobangi near the dump showed that an average 9,121 people were treated for respiratory tract-related problems in 2003-2006. Cases of skin disorders, abdominal problems and eye infections were also

common among those tested (IRIN, 2009). The conclusions from the study painted a sobering picture of the current state of the dumpsite and its resulting effects on the population around it;

> "This pilot study has linked environmental pollution to public health. Soil samples analyzed from locations adjacent and within the dumpsite show high levels of heavy metals emanating from the site in particular lead, mercury, cadmium, copper and chromium. At the same time, a medical evaluation of the children and adolescents living and schooling near the dumpsite indicates a high incidence of diseases that are associated with high exposure levels to these metal pollutants. For example, about 50% of children examined who live and school near the dumpsite had respiratory ailments and blood lead levels equal to or exceeding internationally accepted toxic levels (10 μg/dl of blood), while 30% had size and staining abnormalities of their red blood cells, confirming high exposure to heavy metal poisoning." (Kimani, 2007)

In March 2001 a decision was made on the recommendation of JICA (1998) to move the dumpsite to a new sanitary landfill site, Ruai, which is 30km east of the CBD.

The CCN does not operate any incinerators. Some hospitals and pharmaceutical plants have their own incineration units for hazardous waste treatment at source, and Kenyatta National Hospital has plans to sell this service to other institutions (Baud et al, 2004; Bahri, 2005). Some private collectors and entities also operate their own incinerators for clientele (Bahri, 2005; Omondi *et al.*, 2009).

There have been some efforts by CBOs at indirect thermal reuse of waste through the production of cooking fuel briquettes from waste paper, saw dust, rice & coffee husks, bagasse and household waste, as a substitute for charcoal (Karanja, 2005); and to a lesser extent through the production of candles from waste oils and fats (Karanja, 2005).

4.3 The Temporal Behaviour of Key Actors and Variables in Nairobi's SWM system

Building on the previous Section 4.2, this section charts in more detail the historical behaviour of the key actors and variables in Nairobi's solid waste management.

4.3.1 Solid Waste Generation & Projection

Solid waste generation rates in Nairobi as observed from waste characterisations done at immediate source from households in Makadara, Starehe, and Westland zones are summarised in Table 1.

Table 1: Solid waste generation rates in Makadara, Starehe & Westlands zones - Nairobi

Zone	Household Income levels	per capita residential waste generation (kg/cap/day)	
		generation rate range observed	Average
Makadara	low to middle	0.21 – 0.65	0.49
Starehe	low to middle	0.24 – 0.82	0.43
Westlands	high income	0.41 – 0.79	0.65

An average residential waste generation rate of 0.53 kg/person-day was determined from all the households sampled in 2009, but it was also observed that households in the low to middle-income zones separate valuable materials for sale or recycling. The upper observed rate of 0.65 kg/person-day from Westlands might therefore be more realistic. Applying the range 0.53 – 0.65 kg/person/day and the city's current population estimate of 3.265 million (ISWM Stakeholders Workshop Report, 2009) yields a residential waste generation rate of 1730 - 2122 tons/day. With a 68% share of residential waste as determined in 2003 (Ngau & Kahiu, 2009), total waste generation in Nairobi is estimated at 2540 - 3120 tons/day, representing a 65% –100% increase in waste generation in the ten years from 1530 tons/day in 1998 (JICA, 1998). With slowing population growth in future as discussed in Section 4.3.6, it can be expected that waste generation growth will decrease likewise, although it remains to be seen if the city's economic growth can support the reduced growth in waste volumes.

4.3.2 History of City Council vs. Private/CBO Waste Collection, and levels of safe waste disposal

Historical waste generation data for Nairobi is shown below in Figure 12 using records from the City Council from 1973-1988 (Karanja, 2005), and results from more recent work by JICA (1998), ITDG (2004) (cited in Bahri, 2005), and the waste surveys in 2009. This is compared against average city council waste collection levels, total waste collection and private collection contributions over the same period, using information adapted from the same sources and from ISWM Stakeholder Workshops held in 2009. Average disposal amounts at the designated Dandora dumpsite are based on an estimation of 22.5% of total generated waste in 1998 (JICA, 1998), and weighbridge records from 2006 - 2009 (CCN DoE, 2009b).

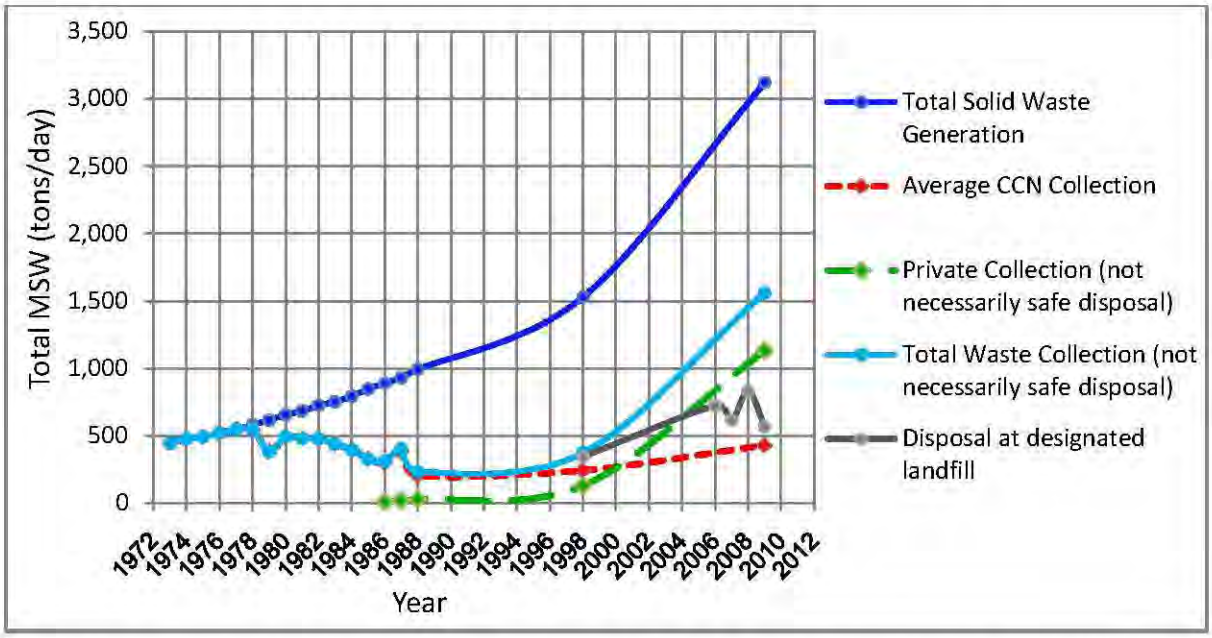

Figure 12: History of City Council vs. Private/CBO Waste Collection, and levels of safe waste disposal (adapted from: JICA, 1998; ITDG (2004) cited in Bahri, 2005; Karanja, 2005; ISWM Stakeholders Workshop Report, 2009; CCN DoE, 2009b; and the waste surveys in 2009 – Section 4.3.1)

From the information available, it is observable that while the total waste collection levels of the City Council of Nairobi (CCN) (including contracts awarded to private companies to execute some of the work) have increased somewhat from 1998 to 2009, their overall contribution to waste collection in the city has dropped from 16% to 14% of total waste generated. Private Collector contributions to total waste collected - in the form of private company and CBO operations, seem to have increased from 8% to 36% of total waste generated over the same period. Given the City Council's historical dismal performance in centrally collecting and managing service fees from the city's predominantly lower income residents (Karanja, 2005; CCN DoE, 2009a; Njenga, 2009b), this trend is likely due to the emergence of more dependable private waste collection (with its mix of more efficient non-central and semi-formal charge collection mechanisms) and more amiable CBO collection in low income areas; whose services the populace find more agreeable and in turn are more willing to pay for. Over time, this will have led to an increase in the collection capacity, market power and political clout of private collector companies relative to the City Council; thereby leading to reduced central government willingness to spend on waste management specific budget grants to the City Council, constraining its performance in this area. This seems to bear out in the City Council governing body's drop in fund allocations to solid waste management specific operations from 7.3%, to 7%, 4%, 4%, and 3.6% of total (government allowed) council budgets over the period 2005/6 to 2009/10 (see Section 4.2.1).

4.3.3 Growth of Private Actors & CBOs in solid waste management activity

Owing to declining waste collection performance by the City Council; private collection companies started to emerge in 1986, with CBOs and Youth Group involvement in Solid Waste Management (SWM) activity including collection, composting and recovery and sale of recyclables evolving later in 1994 with the heightened lack of service delivery especially in low income areas and informal settlements (Karanja, 2005). Both sets of actors in Nairobi's SWM system have since blossomed as

shown by the timeline in Table 2, adapted from records from JICA (1998), Baud *et al* (2004), Karanja (2005), and Ngau & Kahiu (2009), and explain the rapid increase in private waste collection since 1998 shown in Section 4.3.2.

Table 2: Timeline of the increase of Private Actors and CBOs involved in Nairobi's solid waste management (adapted from JICA, 1998; Baud *et al.*, 2004; Karanja, 2005; and Ngau & Kahiu, 2009)

Type of Actor	Year				
	1986	1994	1998	2007	2009
No. of Private Waste Collectors / Companies	2		60	87	200
No. of CBOs & Youth Groups in SWM		Year of entry	15		166

4.3.4 Solid Waste Characteristics in Nairobi

4.3.4.1 Residential Waste

The results of the residential waste characterisations carried out at immediate source, and at communal waste collection points and illegal dumps located in residential areas are summarised in Table 3.

Table 3: Residential solid waste characterization at immediate source, and at communal collection points and illegal dumps

Waste Type	Composition (%)	
	At Immediate Source (directly from Households)	At Communal Waste Collection Points located in Residential areas
Organic/Biodegradable	58.6	46.1
Paper	11.9	8.9
Plastics	15.9	15.4
Glass	1.9	5.6
Metal	2.0	2.3
Other	9.7	21.7

4.3.4.2 Non-Residential Waste

Table 4 below summarises the non-residential waste characterisations determined at immediate source, and at communal waste collection points and illegal dumps located in business/commerce areas;

Table 4:Non-residential solid waste characterisation at immediate source, and at communal waste collection points and illegal dumps

	Waste Characterisation					
	At immediate Source				At Communal Waste Collection Pts in Business/Commerce areas	At Communal Waste Collection Pts adjacent to Markets
	Retail & Shops	Offices & Work places	Institutions	Catering		
Waste Type	Composition (%)	Composition (%)	Composition (%)	Composition (%)	Composition (%)	Composition (%)
Organic	43.6	25.9	48.9	69.2	36.4	51.3
Paper	22.0	42.1	19.8	10.2	18.9	11.1
Plastics	19.8	17.1	10.9	8.7	14.3	14.3
Glass	2.3	0.0	3.7	1.4	5.5	3.1
Metal	2.1	0.8	2.7	1.6	3.4	2.2
Other	10.2	14.0	14.0	8.9	21.5	18.0

4.3.4.3 Overall City-wide Solid Waste Characteristics

The Kenyan National Environmental Management Authority (NEMA) found in 2003 that residential waste contributes 68% of the total waste generated in Nairobi; while non-residential waste contributed a combined total of about 32% of the total waste generated (Ngau & Kahiu, 2009), broken down as follows; Industrial: 14 %; roads: 8 %; hospitals: 2 %; markets: 1 %; and 7 % from other sources. To determine overall waste characteristics in the city, this knowledge was combined with selected 2009 waste characterisations from Sections 4.3.4.1 and 4.3.4.2 used as proxies for NEMA's 2003 categories as follows:

NEMA (2003) Waste category & contribution to total city waste (in brackets)	**2009 Waste characterisation category used as proxy for NEMA (2003) characterisations**
Residential waste (68%)	Residential waste compositions at immediate source
Industrial waste (14%)	Office/Workplace waste compositions at immediate source
Road waste (8%)	Compositions at collection points & illegal dumps in business/commerce areas
Hospital waste (2%)	Non hazardous/non medical waste compositions at immediate source
Market waste (1%)	Compositions at communal collection points & illegal dumps adjacent to markets
Other sources (7%)	Retail/Shop waste compositions at immediate source

The resulting overall city-wide waste characterisations at immediate source and at communal waste collection points and illegal dumps are estimated as shown in Table 5.

Table 5: Summary of city-wide solid waste characteristics at immediate source, and at communal collection points and illegal dumps

	City-wide solid waste compositions (%)	
Waste Type	At immediate source	At Communal Waste Collection Points & Illegal dumps
Organic/Biodegradable	50.9	43.0
Paper	17.5	12.1
Plastic	16.1	15.1
Glass	2.0	5.6
Metals	2.0	2.7
Other	11.4	21.7

4.3.4.4 Temporal trends in the character of Nairobi's municipal solid waste

Nairobi's general waste character has been evolving, and a summary is shown in Table 6 of Nairobi City's solid waste characteristics over time as determined from several previous studies.

Table 6: Nairobi's evolving waste character (adapted from Kibwage, 1996; JICA. 1998; Bahri, 2005 & Section 4.3.4.3)

Waste type	MoLG & FARID 1985 (cited in Kibwage, 1996)	JICA 1998	ITDG 2004 (cited in Bahri, 2005)	CCN /UNEP 2009 (Section 4.3.4.3)
Organic	78	58	61.4	50.9
Paper	10.2	17	11.8	17.5
Plastic	4.1	12	20.6	16.1
Glass	3.8	2	0.7	2.0
Metals	1.9	3	0.6	2.0
Other	2	8	4.9	11.4

While the waste character varies slightly between the 1998, 2004 and 2009 surveys as carried out by different researchers, what is unmistakably observable in the space of 25 years since MoLG & FARID (1985) (cited in Kibwage (1996)) is the sharp decrease in the organic material content of solid waste in the city, alongside an increase in the amount of paper and even more sharply of plastic content. This suggests a gradual shift in the lifestyles of Nairobi's residents towards the consumption of more packaged goods, and the emergence of more paper and stationery in the day to day lives and business/enterprise of the city's residents. There also seems to be a growing residual or 'other' waste stream consisting of material not traditionally present in Nairobi's solid waste, pointing to the emergence of a need for new end-of-life material recycling and/or treatment capacity for these material types.

4.3.5 Nairobi's Solid Waste Sources and Sinks

4.3.5.1 The Informal Waste Resource Recovery, Trading, and Recycling Supply chain in Nairobi

Inorganic waste recycling in Nairobi is comprised of waste dealers who buy from large groups of unregistered individual waste pickers based on the streets, at dump areas, and in neighbourhoods; and sell in bulk to large-scale recyclers (Baud *et al*, 2004). Waste pickers at the designated Dandora dumpsite alone numbered over 2000 in 2005 (Karanja, 2005), and current estimates put this as high as 3500 families (Ngau & Kahiu, 2009). Most waste picking activities are concentrated around dump areas and communal waste collection points due to the concentration and availability of (access to) waste materials, and are rarely found in higher income areas which are mostly serviced by private collectors (Karanja, 2005; field observations). Anecdotal evidence however suggests the informal recovery sector is starting to venture here likewise. Karanja (2005) observed that waste picker's earnings ranged between ≈ US$ 1.3 - 1.5/day, while waste dealer's incomes averaged US$163/month and ranged between ≈US$31 – 500/month, giving an indication of the recovery market's value. Some challenges to waste resource recovery and recycling in Nairobi include the lack of waste separation leading to resource material contamination, and the lack of political, legal and infrastructural support from the government and city council (Karanja, 2005; ISWM Stakeholders Workshop Report, 2009; Omondi *et al.*, 2009). Examples of waste recovery and trade activity in Nairobi are shown in Appendix II.

Important waste materials on the waste recovery market include; paper, plastics, scrap iron - used by local artisans and metal working companies, and whole bottles. A record of waste material preferences and selling prices on the informal waste recovery and trading market is shown in Table 7. Based on Karanja's (2005) investigation into informal waste market pricing, and field visits and interviews in 2009 (Section 3.2.3.1); Table 7 suggests a robust informal waste recovery and trading market for most materials with the exception of broken glass which appears to be undesirable amongst the waste recovery circles (see discussion of declining glass recycling capacity in Section 4.3.5.4).

Table 7: Informal Waste Material Recovery & Trading Market Price Trends in Nairobi 1998 – 2009 (adapted from Karanja, 2005 & data from field visits and interviews in 2009 - Section 3.2.3.1)

Material Type	**Avg. buying price (1998)**		**Avg. buying price (2009)**	
	KShs/kg	US$/kg **	KShs/kg	US$/kg **
Paper (general)	3	0.0375	4 (white paper at 8)	0.0537 (0.1072)
Old newspapers	-	-	15 - 27	0.2014 - 0.3625
Broken glass	3	0.0375	1	0.0134
Unbroken glass			50 cts per bottle	0.0067
Steel	5	0.0625	15*	0.2014
Scrap iron	5	0.0625	15*	0.2014
Plastics (general)	5	0.0625	12, also see below	0.1608
PET			6	0.0805
HDPE			20	0.2685
Trash Bags			20	0.2685
Whole bottles	1-15/kg	0.0125 - 0.1875		
Bones	4	0.05	4	0.05
Aluminium	12	0.15	15*	0.2013
Copper	10	0.125	15*	
Old Tyres			50 - 300 per tyre	0.6713 – 4.0275

*Referred to generally as 'metal' from field visits and interviews with waste recovery groups in 2009
** Note: Average 1998 US$ exchange rate: 80 KShs/US$; 2009 US$ exchange rate: 74.6 KShs/US$.

4.3.5.2 Plastics Recycling and Reuse

As of 2005 the level of re-use and recycling of post-consumer plastic in Nairobi was very low, with approximately only 1% recycled (Bahri, 2005; Ngau & Kahiu, 2009). Using this figure and assuming a plastics composition of about 15% as a bridge between JICA (1998) and the 2009 waste characterisation survey results (Section 4.3.4.3), plastic reuse in 2005 was about 3.6 tons/day based on ITDG's (2004) total waste generation estimation of 2400 tons/day in Nairobi .

Ngau & Kahiu (2009) noted the presence of several private companies and groups actively involved in plastic waste recycling in Nairobi currently including; Devani, RH, Green Loop International, Eurasia plastics and community based recyclers. One of these groups, Green Loop International, has a total waste plastic recycling/re-manufacturing capacity of about 450 tons/month (15tons/day) of HDPE, LDPE and plastic lumber (Bahri, 2005). Other plastics recyclers noted from field visits during the ISWM Strategy development included Premier Plastics (Ruaraka) (15 tons/day) and Plastic Recyclers Sacco. Ltd (Jericho) (≈ 2 tons/day) (Ndunda *et al*, 2009), KenPoly Manufacturers Ltd (≈ 20 tons/day), Brush Manufacturers Ltd (≈ 3 tons/day), Nairobi Plastics (≈ 0.6 tons/day), and up to 20 other plastics industries that use both virgin and post consumer plastics as inputs to their processes

(Ministry of Industrialisation, 2009). During preliminary zone surveys prior to the characterisation surveys in 2009 it was also noted that a number of community based recyclers are currently being supported by Practical Action (formerly ITDG), which has identified 13 functional plastic waste collection points, 37 recycling groups and 1,613 individuals in the city's Eastland's area that can spearhead the recycling program through a legally defined cooperative framework (Ngau & Kahiu, 2009). The registered cooperative is operating on a 5-year business plan.

In July 2006, the KNCPC, supported by UNDP and UNEP also finalized a Comprehensive Plastic Waste Strategy for Nairobi City centred on the reduction, reuse and recycling of plastic wastes in the city (KNCPC, 2006). Progress on the Strategy to date however has not yet been documented.

Given the capacities of the plastic recycling companies discussed above (alone totalling 60 tons/day of plastic recycling), the ITDG estimates in 2005, the presence of several companies that utilise as yet undeclared virgin and post consumer plastic inputs, and of sub-national players (KNCPC) in plastics recycling; it is conceivable that current plastics recycling and reuse capacity in the City is of the order of 100 tons/day.

4.3.5.3 Paper Recycling

Chandaria and Madhupaper are the most established and dominant players in the trade and recycling of waste paper in Nairobi (Karanja, 2005), with remanufacturing capacities of about 24 tons/day and 20 tons of waste paper/day respectively. Both companies, owned by *Chandaria Group of Companies*, primarily work through a single wholesaler - *Kamongo Waste Paper*; and don't deal with individual dealers or waste pickers. Other industrial paper recyclers exist outside Nairobi such as Kenya Paper Mill in Thika, and the recently collapsed Webuye Paper Mill in western Kenya.

All the major paper recyclers are supplied by *Kamongo Waste Paper*, who reportedly buy ≈ 100 tonnes of waste paper per day from smaller pickers and dealers, which they compress and package for resell to the larger companies (Karanja, 2005; Ndunda *et al*, 2009).

4.3.5.4 Glass Recycling

Glass recycling in Nairobi is dominated by *Central Glass Industries* (CGI), a subsidiary of *Kenya Breweries Ltd* (KBL). CGI uses about 720 tonnes of clear glass and 1260 tonnes of green/amber glass per month (≈ 66 tonnes glass /day) (Karanja, 2005). Karanja (2005) however noted that glass recycling of especially broken glass is on the decline as the reprocessing of broken glass was found to be too costly and unprofitable due to high maintenance costs of the imported precision equipment. Power constraints (with shortages resulting in rationing), economic conditions and increasing competition from lighter and more durable aluminum cans, plastics and Tetra-pack containers from the early 2000's were also attributed as likely contributing factors. Progress to date on the status of glass recycling is not clear, although the presence of elevated glass levels at communal waste collection points and illegal dumps relative to at immediate source (see Section 4.3.4.3) likely indicates the lack of informal waste recovery interest in the predominantly broken glass at the collection point stage.

With an estimated 2% waste glass composition in Nairobi's current waste stream (Section 4.3.4.3), equal to about 62 tons/day of glass, it would seem that CGI's capacity was once sufficient to reuse a

substantial amount of the waste glass available but has since declined due to high costs of broken glass recycling. Current recycle levels are unknown.

4.3.5.5 Metal Reuse and Recycling

Karanja (2005) noted the presence of up to 9 rolling mills in Nairobi, some of which were however closed at the time of the researcher's work. One of the largest and still in operation, *Roll Mill Ltd,* however consumes about 30 tons of scrap/day equivalent to about half of the available 62 tonnes/day of total metal in Nairobi's waste. There is also a very vibrant *Jua Kali* small scale metal recycling and reworking industry in the City. Given that not all the waste metal available is necessarily scrap metal suitable for reuse or metal working, and also that the capacity mentioned is only consumed by one entity, it seems reasonable to conclude that Nairobi has sufficient metal recycling capacity for the waste metal it generates, i.e. > 62 tonnes/day metal recycling.

4.3.5.6 Organic/Biodegradable Waste Valorisation

A number of CBOs and private holdings are involved in the composting of organic waste for sale. An investigation done on the biggest entities involved in the activity in Nairobi; including community/self-help groups and private companies, showed a combined compost production capacity of about 1.2 tonnes/day (Onduru *et al*, 2009), equivalent to about 2.4 tonnes/day of raw organic waste feed assuming an average 50% mass reduction during the composting process. This in turn is equivalent to less than 1% of the available organic biodegradable material in Nairobi, the bulk of which is food material.

There is also evidence of the active current use of fresh raw organic wastes especially from markets and restaurants by urban and peri-urban farmers as animal and livestock feed (Karanja, 2005; Onduru *et al*, 2009; Ngau & Kahiu, 2009). Organic waste material amounts reused in this way are however unquantified at the current time. Early work by Mazingira Institute (Mazingira (1987) cited by Karanja, 2005) indicated that 12-14% of animal producers in Nairobi fed their animals on urban organic waste. Karanja (2005) also found that 43% of markets and institutions interviewed in her work reported that organic waste from their premises was used as animal feed, mostly for pigs. With feeding alone accounting for between 60 to 80% of the total livestock production costs in Kenya (Githinji *et al,* 2009 cited by Onduru *et al*, 2009) and from the work cited above, it seems evident that there is an active interest in using fresh urban organic waste as animal and livestock feed, and that this will only gain in importance in future.

Few attempts have as yet been made to valorise organic solid wastes in Nairobi via anaerobic digestion.

4.3.5.7 Total Waste Collection levels and Safe Disposal

Current total waste collection levels in Nairobi are estimated at 50% at best (UNEP/CCN ISWM National Task Team), in general agreement with previous studies that found that over half of Nairobi's residents don't receive any waste collection service (for example Karanja (2005) in a survey of 128 households found 48% did not receive any service). This equates to total collection levels of about 1550 tonnes/day using the upper estimates for waste generation of 3100 tonnes/day (Section 4.3.1). Based on April 2009 CCN records, CCN and official (NEMA) waste collection levels are currently an average of 430 tonnes/day (Njenga, 2009a). Weighbridge records at the official Dandora

dumpsite over the period 2006 to end 2008 indicated an average total of 830 tonnes/day (CCN and Private Trucks combined) were received there over this period (CCN DoE, 2009b), with waste disposal receipt levels for 2009 dropping to an average of 570 tonnes/day (ISWM Stakeholders Workshop Report, 2009).

Illegal dumpsites in the city currently number about 300 (Ngau & Kahiu, 2009), illustrating the scale and distribution of the problem of improper waste disposal.

4.3.5.8 Summary of Waste Sources and Sinks

The total waste reuse and recycling estimates discussed in the preceding sections put combined reuse and recycling efforts in the city at about 250-300 tonnes/day, and taking the upper limit of 300 tonnes/day, are approximately equivalent to 8–10% of total waste generated (using the upper total waste generation estimate of 3100 tonnes/day – Section 4.3.1). This coupled to the average waste disposal of 570 tonnes/day in 2009 at the designated Dandora dumpsite (ISWM Stakeholders Workshop Report, 2009), means that at most (assuming collection of recyclables happens before final disposal) only 870 tonnes/day of the collected 1550 tonnes/day in Nairobi are in fact properly handled via disposal at the Dandora dumpsite or through recovery and recycling.

The difference between total collected waste (1550 tonnes/day), and the safe disposal and recycle figures above (870 tonnes/day), summed to the uncollected 1550 tonnes/day gives a grand total of 2230 tonnes/day; which may be reasonably assumed to be largely disposed of in inappropriate ways such as open burning and illegal/indiscriminate dumping by collectors, generators or due to outright non-collection; all of which practices were noted to be widespread during the 2009 waste characterisation surveys and were also raised by various stakeholders (ISWM Stakeholders Workshop Report, 2009; field observations).

The various waste sources and sinks in Nairobi City in 2009 are summarised in Figure 13 (the upper total waste generation estimate of 3100 tonnes/day – Section 4.3.1, was used to generate the consequent % figures).

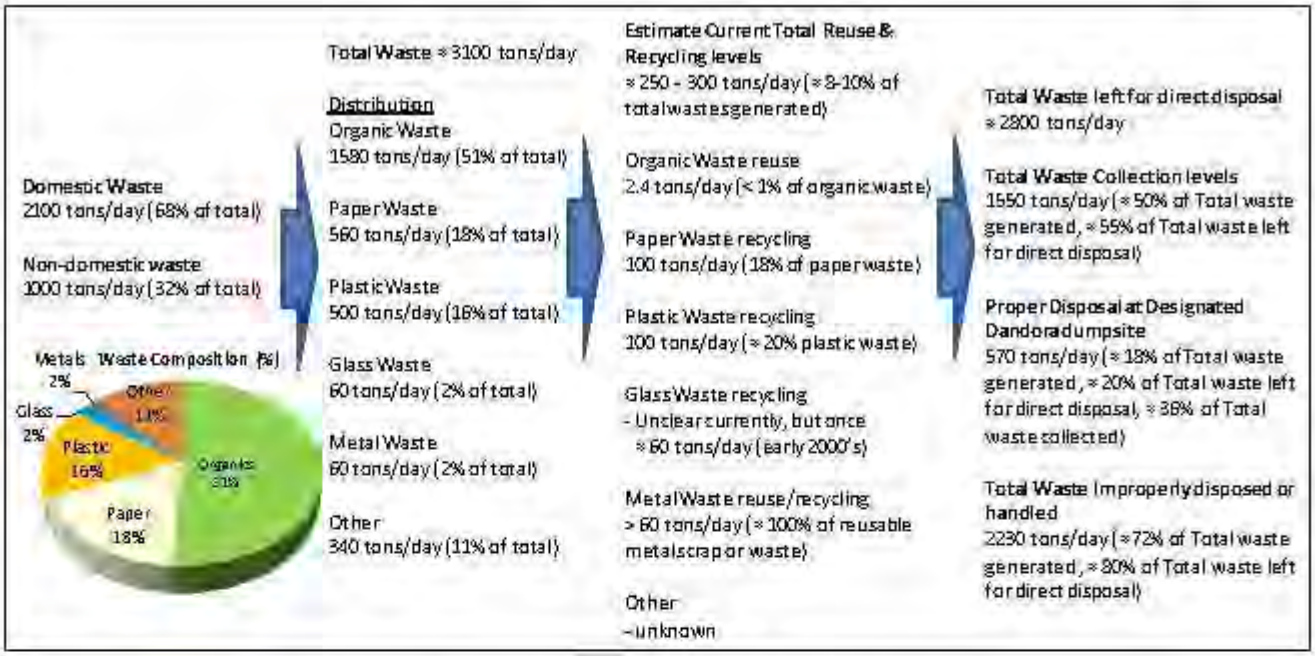

Figure 13: Summary of Nairobi's Waste Sources and Sinks – Estimates 2009

4.3.6 City Population Growth & Projections

As discussed in Section 4.1.3, Nairobi's population has been growing at near exponential rates since 2000. Recent population figures however seem to suggest that growth is slowing down, with annual growth rates for the period 2005 - 2015 projected at 2.8 %, dropping from 4.5% in the period 1995 – 2005 (UNEP & UN-Habitat, 2007). This lends itself strongly to the possibility of population in the city levelling off at some point in the future as postulated in Section 2.3.2.8.

While the physical application of the concept of an area's population 'carrying capacity' is elusive as cities tend to expand geographically and to increasingly import resources from further afield; a population carrying capacity of nine million residents was assumed for modelling logistic population projections for Nairobi, on the basis of trying to match the initial population growth in the logistic model as closely as possible to the recorded growth of Nairobi's population as in Figure 11. The results of the projected vs. recorded population in the past, and population projections from 2009 are shown in Figure 14 (see numerical results in Appendix III).

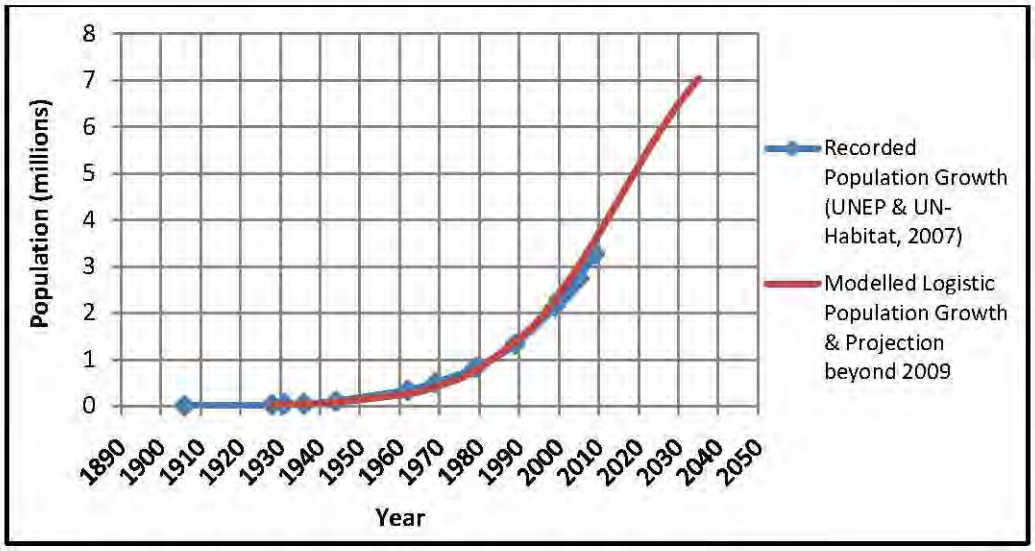

Figure 14: Population growth in Nairobi pre-2009 (UNEP & UN-Habitat, 2007), and future projections post-2009 based on logistic growth model

4.3.7 City Economic growth & Trend analysis

Figure 15 below shows GDP per capita data from the Kenya National Bureau of Statistics (2009), used as a proxy to illustrate the growth of the city's economy and resulting per capita benefits in the past decade.

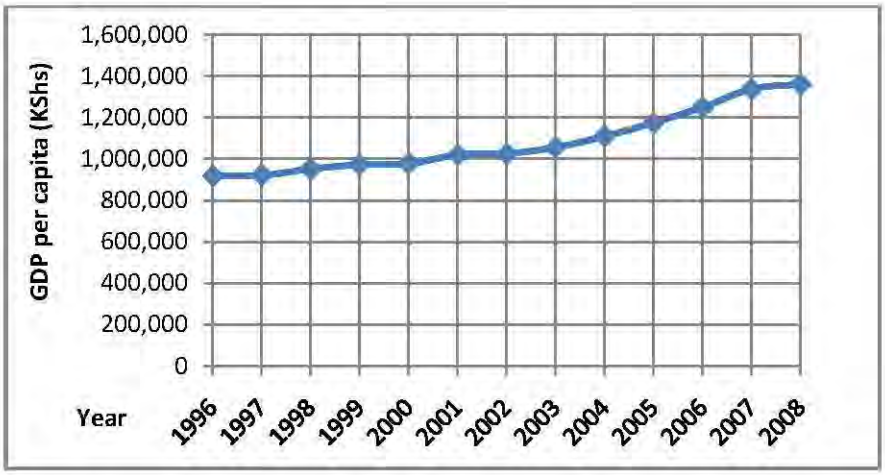

Figure 15: Kenya's GDP per capita growth since 1996 (constant 1982 prices) (derived from Kenya National Bureau of Statistics, 2009)

The data from Figure 15 and Figure 12 lends credence to the hypothesis that population growth as in section 4.3.6 is the greater driver of the rapid increase in solid waste generation in Nairobi, and will continue to be in the foreseeable future. This agrees with observations in the literature (Section 2.3.2.8).

4.3.8 Waste Disposal Costs: Current and Future

Given that tipping fees are negligible at Dandora dumpsite, disposal costs in Nairobi are largely made up of transport costs. Using average CCN disposal costs per ton waste in April 2009 (Njenga, 2009a) for waste from Nairobi's different zones to the designated Dandora dumpsite 7.5 km East of the CBD, approximations can be made as to the future cost of waste disposal straight to the proposed new landfill at Ruai, 30 km East of the CBD, using the factor increase in transportation distance. These are shown in Table 8 below adapted from Njenga (2009a).

Table 8: Disposal costs to current designated Dandora dumpsite (Njenga, 2009a), and in future at the candidate Ruai landfill site based on the factor increase in transportation distance

Zone	Cost/ton to Dandora (KShs)	Estimated Cost/ton to Ruai (KShs)
CBD	1144	4576
Kamukunji	943	3772
Starehe	990	3960
Embakasi	852	3408
Dagoretti	1210	4840
Westlands	1155	4620
Langata	1144	4576
Makadara	849	3396
Kasarani	891	3564
Average	**1020**	**4079**

From these figures average disposal costs to Dandora dumpsite are computed at 1020 Kshs/ton waste disposed, and will increase approximately four fold to about 4079 Kshs/ton waste disposed at Ruai for Nairobi's residents. While a sanitary landfill is necessary, future disposal costs will likely not allow the luxury of current bulk waste to landfill disposal policies, and only heighten the need for significant efforts towards waste diversion.

4.4 Causal Loop Map & Analysis of Nairobi's Waste Management System

The quantitative and qualitative behaviour of the key variables and actors in Nairobi's solid waste management as described in the preceding sections (sections 4.1 to 4.3.8), led to the development of a causal loop representation of the city's current waste system, through an iterative process. The causal loop map resulting from this process is shown in Figure 16, a larger format is also provided in Appendix V (Figure 27). **Bold** arrows and loops show effect emphasis in the source data and documentation. An explanation of how to interpret causal loop diagrams is given in Section 2.4.3.

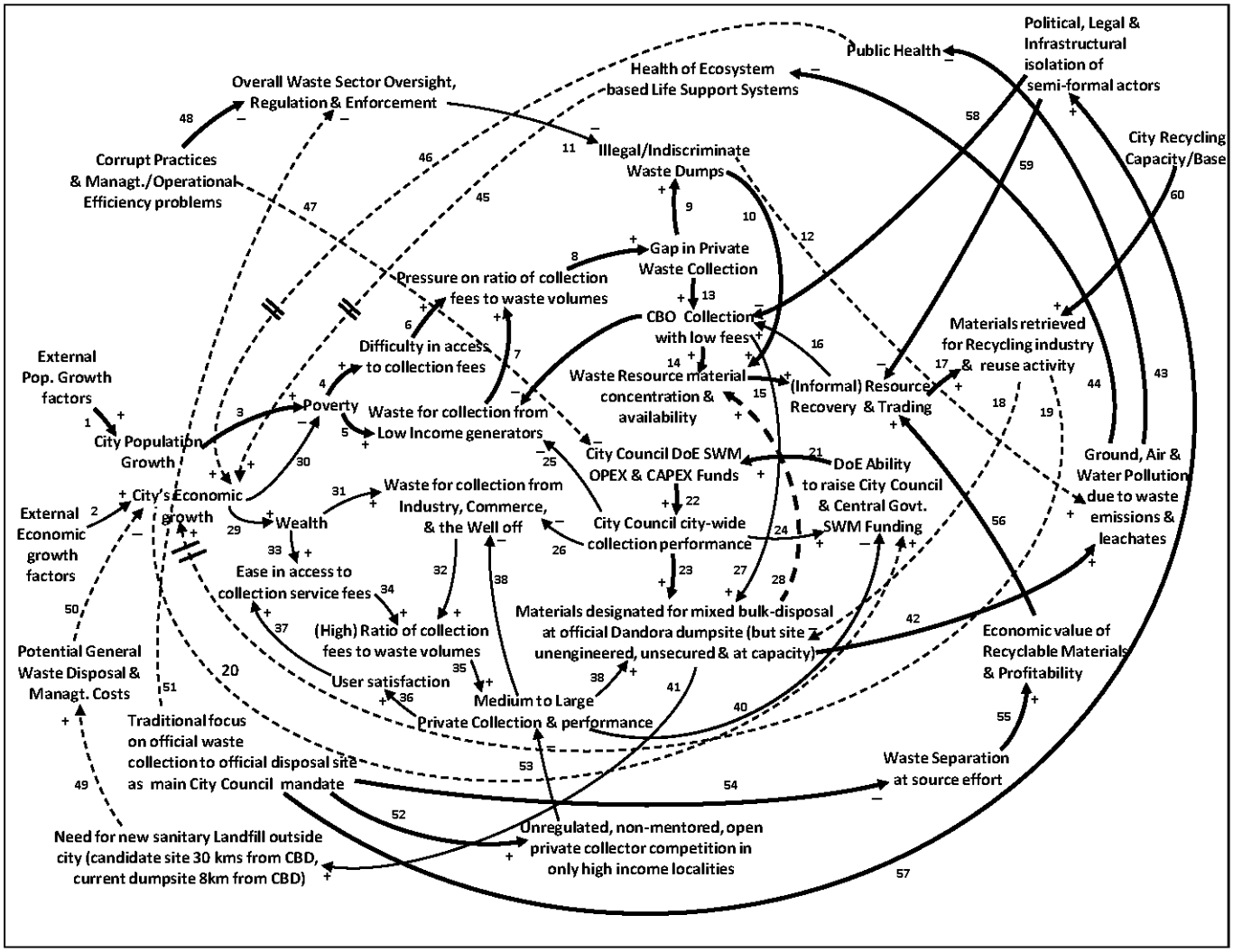

Figure 16: Causal Loop Map of Nairobi's solid waste management system

The causal and feedback relationships summarised in Figure 16 are described in the following Section 4.4.1 with reference to the quantitative and qualitative data from which they were derived or inferred in Sections 4.1 to 4.3. Arrow numbers in the descriptions (e.g. arrow 5) refer to the causal relation arrows in Figure 16; Section numbers (e.g. Sec. 4.6) refer to the relevant discussion areas in the preceding sections highlighting the relationship of interest.

4.4.1 Description of Causal Relationships in Nairobi's Solid Waste Management System

Solid waste generation is generally a result of population growth coupled to economic welfare (arrows 1, 2, 5, 31; Sec. 2.3.2.8) and in Nairobi population growth seems to be the greater driver (Sec. 4.3.6 & 4.3.7). Population growth however with insufficient economic growth rates has resulted in the dominant poverty conditions in the city (arrows 3, 30; Sec. 4.1.1, 4.1.2 & 4.1.3).

The City Council of Nairobi (CCN) depends on various centrally collected funding streams from the city's residents (arrow 20; Sec. 4.2.1) to fund public collection services (arrows 25, 26). Depending on how strong the city's revenue base is resulting from city economic growth, and how effectively the City Council can tap into it via appropriate collection mechanisms; this set of factors dictates how easily the City Council's Department of Environment (DoE) can motivate the council governing structures or central government to fund or increase its solid waste management portfolio budget (arrow 20; Sec. 4.2.1). This in turn determines how much the DoE can spend on waste collection and impacts on its collection performance (arrows 21, 22); the faithful execution of which in turn either eases or hardens its ability to motivate future funding from the same sources (arrow 24; Sec. 4.2.1).

Poor CCN waste collection performance historically due to shortfalls in its mechanisms above (Sec. 4.2.1) led to the development of private collectors and Community Based Organisations (CBOs) in the city's waste collection and movement (Sec. 4.2.2). The dominant poverty conditions in the city's low income areas have resulted in difficulty in private collector access to service fees and low collection-fee-to-waste-volume ratios in these areas due to the lower economic power and evasive nature of these generators (arrows 4, 5, 6, 7, 8; Sec. 4.2.2). This in turn has made low income areas largely unattractive to major private collection (arrow 8), and resulted in high illegal/indiscriminate waste dumping on the one hand (arrow 9; Sec. 4.2.2 & 4.3.5.7), and the emergence of CBOs that, because they consist of community members, are able to draw some, albeit lower, service fees from their operation areas through semi-formal collection mechanisms and complement this with incomes from waste material resource recovery, trading and recycling (arrows 13, 14, 15, 16, 17; Sec. 4.2.2).

The informal resource recovery supply chains to city recyclers and composting groups thrive on the ready availability of waste material collected by individual scavengers and CBOs, and that is present at illegal dumps and the official Dandora dumpsite (arrows 10, 14, 28; Sec. 4.3.5.1). Recycling and reuse activity in turn provides a waste diversion route from the official dumpsite at Dandora (arrow 18), and while the recycle/reuse sector is limited by current capacity (arrow 60) there is scope for its significant contribution to the city's economic welfare (arrow 19; Sec. 4.3.5) – potentially completing a virtuous reinforcing loop of resource-efficient economic growth.

The semi-formal nature of CBO operations and the resource recovery sector have however not received significant appreciation and support from the government and City Council (arrows 58, 59; Sec. 4.2.2 & 4.3.5.1), resulting from a traditional focus on official waste collection avenues to the official Dandora disposal site (arrow 57; Sec. 4.2.2); and thereby hindering the scale up and advancement of these actors and their potential benefits to the city's waste diversion. This 'official waste collection to official disposal' focus has also historically overshadowed the opportunities that could be unlocked by encouraging source separation of waste, which with reduced contamination levels can potentially lead to an increase in the value and levels of material recovery, recycling and

thus waste diversion from landfill (arrows 54, 55, 56). This official collection focus has also inadvertently undermined the long term growth of private waste collection by allowing the open, unregulated and un-mentored operation and unhealthy competition of private collectors in high income only areas, thereby compromising citywide service distribution and their long term business performance and growth (arrows 52, 53) as this ad hoc operation ethos is only likely to continue expand to other areas in future. Finally this traditional view of 'official waste collection to disposal' has also led to the insufficient resourcing of general monitoring, regulation, and oversight over the waste sector in the city (arrow 51), a situation that reinforces the improper waste disposal already prevalent in the city (arrow 11; Sec. 4.2.2).

Illegal/Indiscriminate waste dumping and the continued bulk disposal of mixed wastes at the currently official but non-sanitary Dandora dumpsite (arrows 23, 27, 38), has been noted to cause adverse environmental and health effects (arrows 12, 42; Sec.4.2.3.4), and in so doing indirectly burdens the city's economic reserves via seemingly invisible but real long term public health and environmental costs such as the health costs consequent from poor sanitation; the health costs and water treatment requirements that result from compromised ground and river water quality; the effects of soil contamination and climate change on local food security and prices as well as reduced biodiversity and lost tourism revenue etc (arrows 43, 44, 45, 46; Sec. 4.2.3.4); alongside a myriad of other potential effects (see Hjorth & Bagheri, 2006). The city also faces a potential four-fold increase in disposal distances and economic costs when the Dandora dumpsite is finally closed and land-filling needs to move to the candidate Ruai site (arrows 41, 49, 50; Sec. 4.3.8).

Higher income generators, who have been able to draw from the city's slower economic growth (Sec. 4.1.1 & 4.3.7), represent easier and better facilitated grounds for private waste collection operations with greater ease in collector access to collection fees and higher collection-fee-to-waste-volume ratios (arrows 29, 31, 32, 33, 34; Sec. 4.2.2). The rise and success of private collection companies amongst these higher income waste generators (arrow 35) seems to be growing in a positive reinforcing manner relative to City Council capacity (arrows 36, 37, 40; Sec. 4.3.2), and contributes significantly to waste collection amongst these generators (arrow 39; Sec. 4.2.2). Corrupt practices, and management and operational efficiency problems within the City Council also undermine its current funding resources as well as citywide waste regulation and management (arrows 47, 48).

4.4.2 System Archetypes and Behavioural Patterns at work in Nairobi

At a high level, the solid waste management scene in Nairobi seems to involve a combination of two systems archetypes: '*Success to the successful*' and '*Tragedy of the Commons*' as defined by Braun (2002) (Section 2.4.4). '*Success to the successful*' behaviour is evident in the historical growth of private waste collection relative to that performed by the City Council - waste collection quantities being the traditional indicator of how well actors in Nairobi's waste sector have been performing. This is embedded within a larger '*Tragedy of the Commons*' trend – the commons being the city's economic, human, social and natural capital base, , whose tragic diminishing for all will be the inevitable result if the current operation and disposal practices of both the private collectors and the City Council continue.

4.4.2.1 Success to the Successful

Figure 17, extracted from Figure 16, shows the success to the successful relationship between private collectors and the City Council collection capacity in Nairobi's causal loop map.

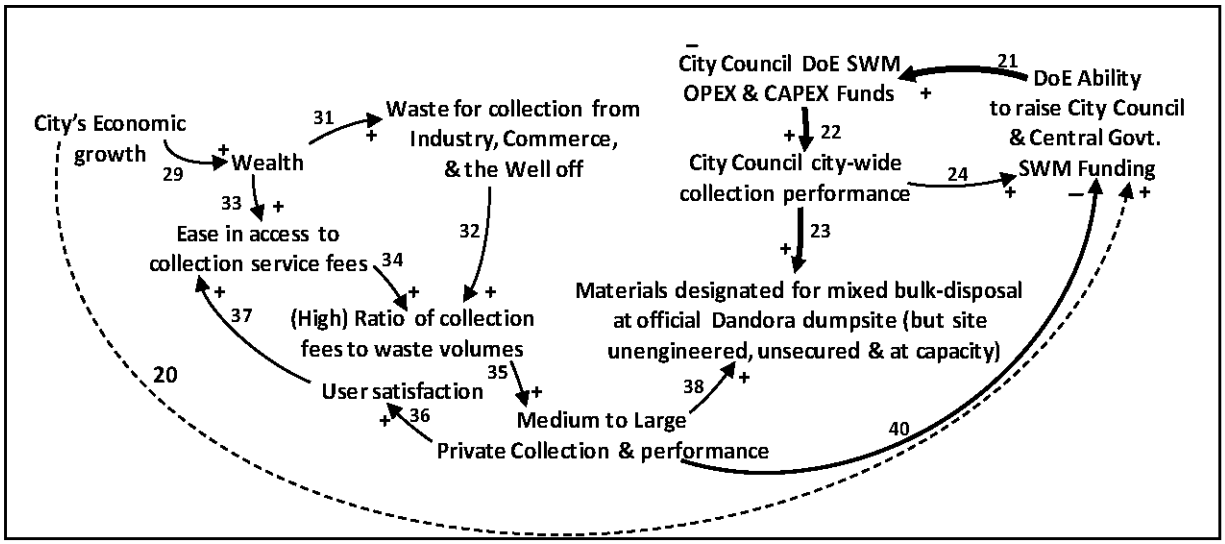

Figure 17: Causal Loop illustration of 'Success to successful' relationship between Private waste collection and City Council Collection

The success-to-the-successful archetype is characterised by two interacting positive feedback loops, whose actors compete for the same resource. Figure 18 shows this structure in the form of loops 21-22-24 (City Council DoE) and 34-37 (for private collectors), with the resources competed for being finances (raised by private collectors entirely from clients, and by the City Council at least partially in the form of city taxes and rates), as well as access to diminishing disposal capacity at Dandora.

This illustration shows how the economic resources in the city will tend to be allocated to the entity doing better with them for the job at hand, with good collection performance rewarded with more funding. In the case of private collectors, consistent collection performance increases user satisfaction and their access to collection service fees directly from paying individual generators, while the City Council's Dept. of Environment relies on the strength of the prevalent council revenue collection mechanisms and its own historical collection record to motivate funding from the council's governing structures and central government.

As described in Section 4.3.2, private waste collection levels (including CBOs) are currently starting to surpass the City Council's collection capacity in the city, waste collection being the traditional indicator of how well actors in Nairobi's waste sector are performing. From Section 4.2.1 it would seem that the defining point in the decline of city council waste collection relative to private collection was the scrapping of dustbin charges that were previously collected with water bills from the city's residents as a result of national water sector reforms leading to the creation of an autonomous Water and Sewerage Company. This led to a 50% drop in revenue collected by the City Council of Nairobi for solid waste management (SWM), and from here on the emergence of more dependable private waste collection (with its mix of more efficient non-central and semi-formal charge collection mechanisms), whose services the populace find increasingly more agreeable and in turn are more willing to pay for, seems to have taken over. Over time, this will have led to an

increase in the collection capacity, market power and political clout of private collector companies relative to the City Council; thereby leading to reduced central government willingness to spend on waste management specific budget grants to the City Council, constraining its performance in this area. Evidence for this decreasing funding allocation to the City Council's solid waste collection operations seems to bear out in the City Council governing structures' drop in fund allocations to solid waste management specific operations from 7.3%, to 7%, 4%, 4%, and 3.6% of total (government reviewed) council budgets over the period 2005/6 to 2009/10 (Section 4.2.1).

Knowledge of the presence this archetype necessitates the investigation of whether this situation is due to the intrinsic merits of each organisation for the job at hand or due simply to initial conditions favouring one over the other. Braun's (2002) prescriptive actions for this system archetype include:

1) Evaluate the current measurement systems to determine if they are set up to favour established practices over other alternatives.
2) Identify goals or objectives that will refocus the definition of success to a broader system.
3) Calibrate internal views of market success against external indicators to identify potential competency traps.

With respect to prescription 1, the current success of private waste collection relative to the older practice of city council waste collection is borne out primarily by statistics of collection volumes. Several actors in the city did however concede during the ISWM plan development process that such statistics might be a false indicator of success, as there is no guarantee i) that collected waste is actually recycled or disposed on the official dumpsite (see Figure 12), and ii) that even if it is, it is now common knowledge that this leads to significant damage to environmental and human health. As such the seeming success of private collectors relative to the city council in collection volumes may be under a narrow definition of mere waste collection as success without necessarily following through to recycling or safe disposal of collected wastes in line with ISWM objectives.

Prescriptive actions (2) & (3) can be interpreted to propose the development a wider definition of success in the Nairobi waste sector beyond waste collection, and the development of mechanisms to overcome competency traps.

In the City Council's current position, barring massive consistent improvements in council revenue collections from city residents, the City Council Dept. of Environment which is charged with solid waste operations seems poorly placed to redeem the collection 'market' or monopoly it once held. It could however instead direct its resources strategically by taking on an increasingly supervisory, strategic oversight and private investment encouraging role under its legal mandate to manage solid waste management in the city, gradually leaving actual waste collection to the private sector and CBOs. By concentrating its resources instead on the strategic management and regulation of the city's waste sector through a mix of legal, infrastructural, and financial incentives; and through standards enforcement and encouraging and directing new private investment in the sector; a new definition of success can be created for the City Council and the waste sector at large. This new definition for the legally mandated City Council could be seen as managing the social, economic, and environmental health of the overall waste chain from waste generation to recovery, recycling, collection and safe residual waste disposal towards ISWM goals, and not merely waste collection to

disposal. For the smaller private entities involved in Nairobi's waste management, success can be defined as how well and efficiently they perform their corporate duties within the sector.

Competency traps on the other hand allude to the prior success of a business approach or strategy by an entity, which because it worked in the past causes that entity to focus its resources and innovative power almost exclusively on that approach. Over time however, competitors learn how to do the same and operating conditions change, meaning that past success cannot necessarily be recreated by past strategy. It would seem that elements of this are present in the City Council's waste management strategy, which over time has attempted to consolidate almost solely its once formidable collection capacity (traditional internal view of success in Nairobi's waste sector) as epitomised in JICA (1998), in spite of changing conditions on the waste management scene in Nairobi, including the emergence of seemingly more efficient private collection and the increasing realisation of a need to pursue wider ranging ISWM goals in the city (external view of success). In this sense then the City Council seems to have been caught in a past competency trap, and current internal efforts should instead start to consider alternative views and strategies to waste management, of which the City Council - owing to its legal mandate, is best placed to position itself as manager of the holistic moulding of the waste sector in Nairobi towards ISWM, and not necessarily hands on collection to disposal.

Within a wider definition of success for the City Council and other entities in Nairobi's waste sector - a definition also looking to avoid past competency traps; both actual waste collection and movement; and the overall management, regulation, and shaping of the waste sector towards ISWM goals in the city can win; resulting from a focus of the various actors in what they are currently doing best and minimising unnecessary duplication of resources. In the Nairobi waste scene this would seem to point to a need to focus the City Council on managing and moulding the waste sector in Nairobi towards ISWM goals, while gradually leaving hands-on waste collection, movement and disposal to private enterprise.

4.4.2.2 Tragedy of the Commons

Figure 18, extracted from Figure 16, shows the bigger 'Tragedy of the Commons' archetype, where the city's economic, human and natural capital base (the commons) is being undermined by the current operations and waste disposal practices of private collectors, CBOs and the City Council.

The Tragedy of the Commons archetype is characterised by a physically limited resource that is made simultaneously available to multiple people or teams, which however declines in performance over time owing to each actor (actors drawing on the commons) regarding the resource as uniquely available for their own goals and purposes. In Nairobi solid waste collection operations are supported directly and indirectly by the city's economic, human, and natural capital, and its resulting revenue base.

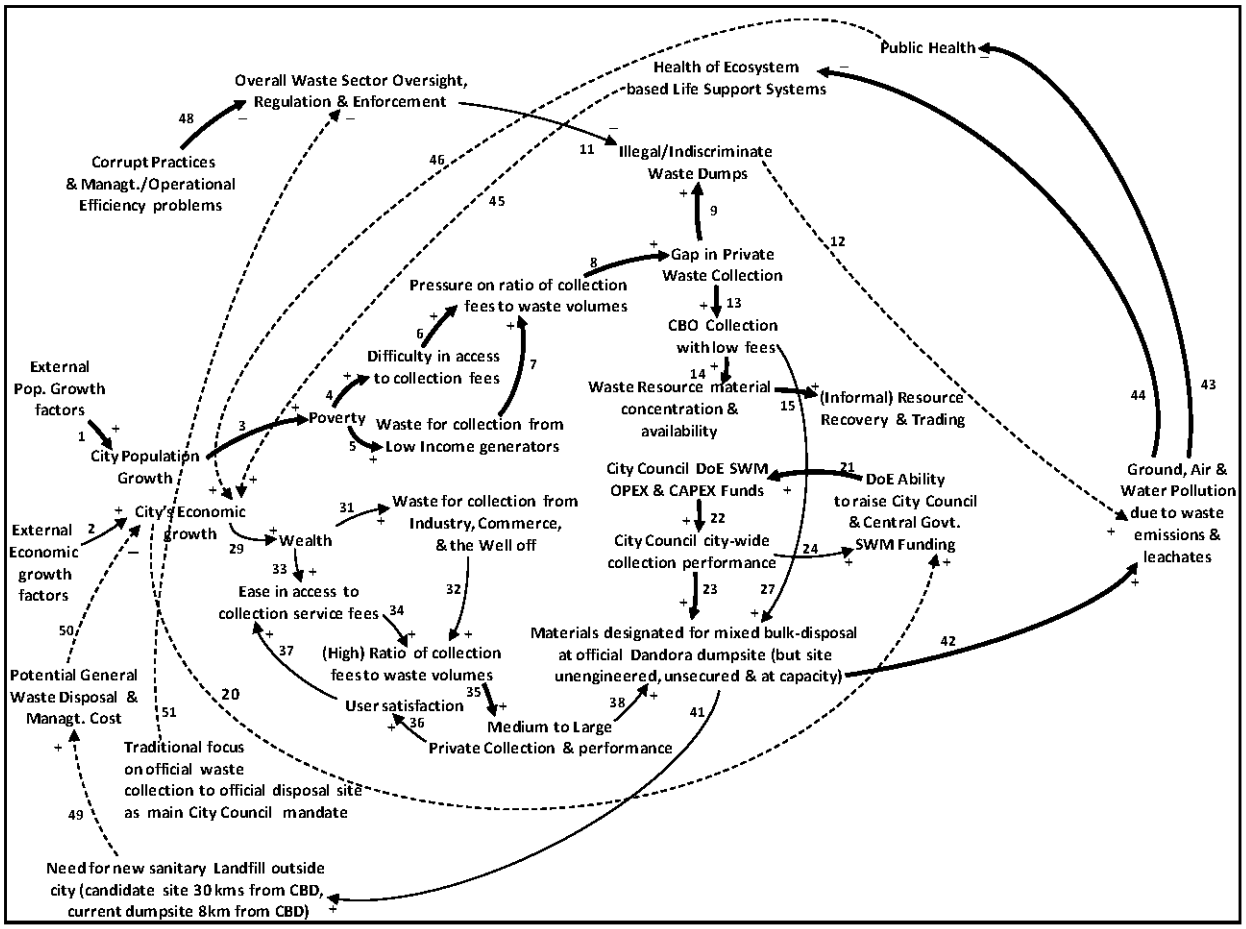

Figure 18: Causal Loop Illustration of 'Tragedy of the Commons' trend with respect to Nairobi's economic, human and natural capital base

In the case of private collectors (arrows 29, 31, 32, 33, 34, 35, 36, 37 – all positive causal relationships) and CBOs (arrows 3, 4, 5, 6, 7, 8, 13 – all positive causal relationships), collection service fees are collected directly from the generators while in the case of the City Council, funding for collection services is sourced indirectly from centralised council tax streams from the city's residents (arrows 20, 21, 22, 24 – all positive causal relationships).

All the collectors however, with the exception of CBOs that undertake some material recovery and trading for recycling (arrows 14, 15), dispose of their collected mixed waste at the official Dandora dumpsite without formal material resource recovery en-route. Waste materials at the open and non-sanitary dumpsite pose severe environmental and public health effects on the surrounding communities and the city's populace at large (arrows 44, 43 – both negative or counter causal relationships), effects with downstream economic costs such as the health costs from poor sanitation consequences; compromised water quality and its subsequent health cost and water treatment requirements; soil contamination and climate change effects on food security and pricing; reduced biodiversity and lost tourism revenues etc. These countering cost effects introduce a counter relationship between increasing private/council collection levels and disposal rates at the current but non-sanitary dumpsite, and the city's economic well-being and implicitly potential revenue base available for these collection operations in the first place.

The cumulative effect then of combining the positive and negative casual relationships described above is the presence of an odd number of negative or counter causal relations (= net counter relationship) in the overall relationship between increasing private collector, City Council, and to some extent CBO waste collection operations; and the city's shared or 'common' economic, human and natural capital base - which fuels their respective operations (see explanation on interpreting causal loop combinations in Section 2.4.3). This depletion of the common 'economic resource/revenue base' in the city is amplified by rampant illegal and indiscriminate waste dumping in the city (arrows 9, 12), which is not helped by a traditional 'official waste collection to official disposal' focus, and corruption and management/operational efficiency problems within the City Council, which combine to undermine the overall oversight, regulation and enforcement of the citywide waste sector by the council (arrows 11, 48, 51). In addition if the current bulk disposal of mixed wastes continues at the rate it is at the official Dandora dumpsite, not only will it accelerate the need for a new landfill further out of the city (with the Ruai candidate site 30km east of the CBD in comparison to the current site's 8km) (arrow 41), it will also radically increase the cost of proper waste disposal for the entire city (arrow 49), further undermining the common economic resource base upon which collection services depend (arrow 50). Figure 19, a simplified illustration of Figure 18, shows in more explicit terms the tragedy of the commons described above of Nairobi's economic, human and natural capital as a result of collectors' current operation and disposal practices. Circled causal arrows and signs highlight the points at which counter relationships leading to the tragedy of the commons emerge.

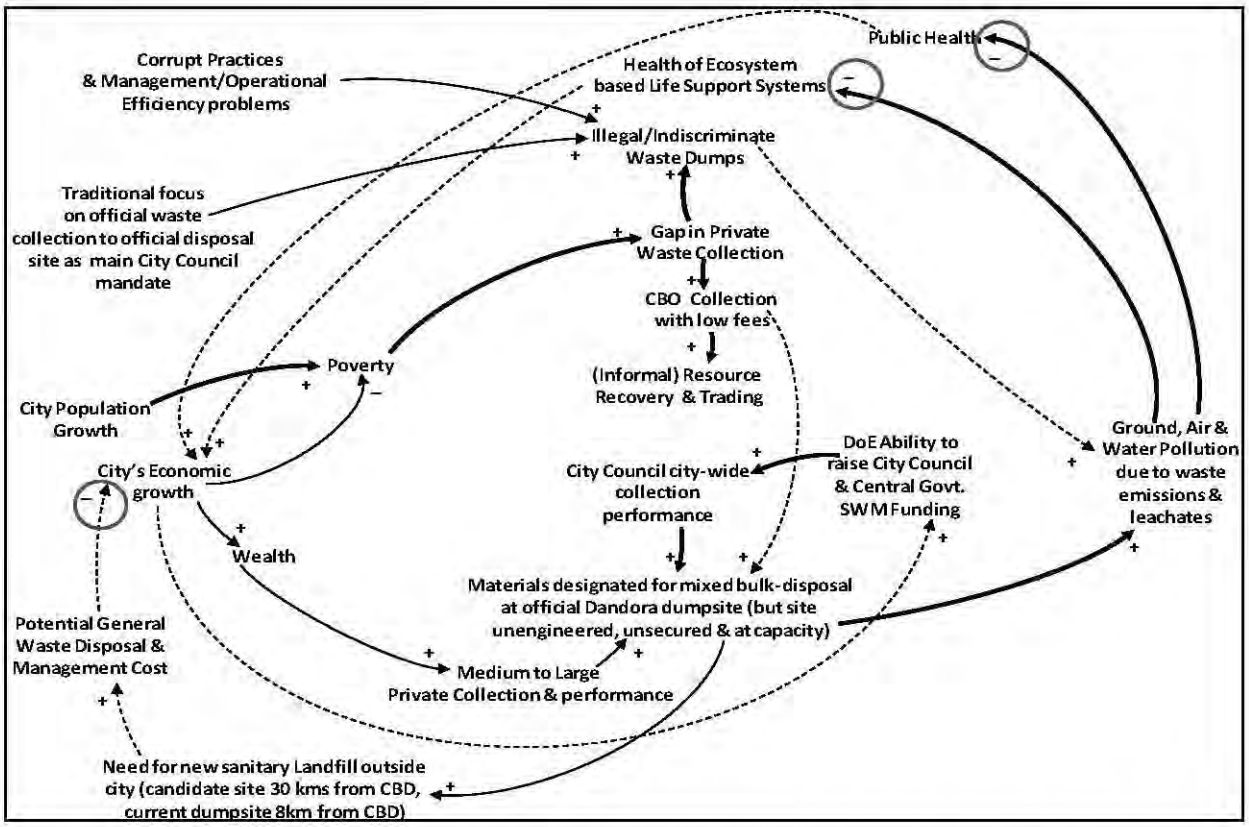

Figure 19: Simplified illustration of 'Tragedy of the Commons' with respect to Nairobi's economic, social and natural capital

Braun's (2002) prescriptive actions for the presence of this system archetype include:

1) Establish methods for making the cumulative effects of using the common resource more real and immediate to the individual players.
2) Re-evaluate the nature of the commons to determine if there are ways to replace or renew (or substitute) the resource before it becomes depleted.
3) Create a final arbiter who manages the use of the common resource from a whole-system level.

Action (1) proposes the use of mechanisms to make the cumulative effects of waste management practices on the city's economic, human and natural capital base more immediate and real to actors in waste management. This calls for regular investigations and public reporting of the state of the city's environment and public health, and its correlation to waste management practices. The institution and efficient enforcement likewise of deterrent tipping fees for excessive waste disposal at landfill; deterrent fines for illegal/indiscriminate dumping; and the stopping of open burning of wastes at generators, dumps, and landfill; would also work to make the effects on the commons more real to individual players.

Action (2) requires a determination of ways in which the city's economic, human and natural capital commons can be replaced or replenished. The commons can be replenished through radical waste diversions from landfill by encouraging the expansion of the city's recycling capacity, especially of organic waste which forms the bulk of waste in Nairobi - preferably close to source to minimise environmental and economic footprints; encouragement and expansion of the associated activity in Nairobi's waste system that supports material recovery and recycling such as CBO collection and recovery, the informal material recovery and trading sector; and the encouragement of source separation of wastes by generators. It is also necessary that actors such as private collectors and City Council that are not already involved in material recovery and trading or recycling should also be required to engage in this, either in collaboration with the informal material recovery and trading sector or directly with the city's recyclers.

Action (3) proposes the creation of a final arbiter who manages the use of the common resource from a whole-system level. Having the legal mandate to manage waste in the city, the City Council is best placed to fulfil this function and may alternatively choose to hand this function over to a larger governance body in the Ministry of Nairobi Metropolitan Development (MoNMD) as the city of Nairobi expands. In particular the City Council needs to manage the final disposal of wastes in the city through actions including:

- Regaining complete control of waste disposal at the current Dandora dumpsite.
- Eventual eradication of waste disposal at the non-sanitary Dandora dumpsite through the financing and construction of a new sanitary landfill.
- Limiting waste volumes disposed at landfill to residual waste.
- Developing deterrent and well calibrated tipping fees at landfill to discourage excessive waste disposal, and resulting pollution potential.
- Minimisation of illegal and indiscriminate waste dumping across the city through greater regulation and more efficient enforcement of Nairobi's waste sector.

- Internal alignment of City Council structures to minimise opportunities for corruption, and to maximise management and operational efficiency in fulfilling these functions.

4.4.2.3 Summary of recommendations towards ISWM arising out of analysis of system archetypes

Based on the analysis of system archetypes described in Sections 4.4.2.1 and 4.4.2.2, the following systems intervention recommendations towards ISWM goals (hereafter referred to by recommendation numbering) are summarised from the discussions.

Intervention Recommendations from Section 4.4.2.1

A1) Widen the definition of success in Nairobi's waste sector from mere waste volumes handled and collection to disposal; to contributions made towards realising the social, economic, and environmental health of the overall waste chain from waste generation to material recovery, recycling, collection and safe residual waste disposal in building to ISWM goals.

A2) Current information does not allow a rigorous determination of how much actors in waste management contribute to material recovery/diversion, recycling, and safe disposal beyond the collection of wastes. Regular research is needed to understand their holistic ISWM contribution.

A3) Concentrate actors and resources in Nairobi's waste sector in areas of expertise to maximise efficiency. In Nairobi the evidence seems to point to a need to focus the City Council on managing and moulding the waste sector in Nairobi towards ISWM goals, while gradually leaving hands-on waste collection, movement and disposal to private enterprise.

Intervention Recommendations from Section 4.4.2.2

B1) Regular investigations and public reporting of the state of the city's environment and public health, and their correlation to prevalent waste management practices.

B2) The institution and efficient enforcement of deterrent tipping fees for excessive waste disposal at landfill.

B3) Deterrent fines for illegal/indiscriminate dumping in the city (and their efficient enforcement).

B4) Stop open burning of wastes at generators, dumps, and landfill.

B5) Radical waste diversions from landfill by encouraging the expansion of the city's recycling capacity, especially of organic waste which forms the bulk of waste in Nairobi - preferably close to source to minimise environmental and economic footprints.

B6) Encouragement and expansion of activity in Nairobi's waste system that supports material recovery and recycling such as CBO collection and recovery and the informal material recovery and trading sector.

B7) Encouragement of source separation of wastes by generators to support material recovery and recycling.

B8) Get private collectors and City Council to engage in material recovery and trading or recycling, either in collaboration with the informal material recovery and trading sector or directly with the city's recyclers.

B9) Regain complete control of waste disposal at the current Dandora dumpsite.

B10) Eventual eradication of waste disposal at the non-sanitary Dandora dumpsite through the financing and construction of a new sanitary landfill.

B11) Limit waste volumes disposed at landfill to residual waste.

B12) Develop deterrent and well calibrated tipping fees at landfill to discourage excessive waste disposal, and resulting pollution potential.

B13) Minimise illegal and indiscriminate waste dumping across the city through greater regulation and more efficient enforcement of Nairobi's waste sector.

B14) Align City Council's internal structures to minimise opportunities for corruption, and to maximise management and operational efficiency in fulfilling these functions.

4.4.3 System Drivers in Nairobi's solid waste management

4.4.3.1 The current drivers and their nature

Depending on the number of causal arrows leaving or arriving at any variable in a causal loop map, it is possible to decipher the system's 'drivers' (variables with more causal arrows leaving than arriving) and 'outcomes' (variables with more causal arrows arriving than leaving) (Section 2.4.3). While conceptual causal loop mapping does not allow a rigorous determination of the dynamic relative strength of each driver besides a qualitative emphasis, it highlights their presence nonetheless and thereby brings attention to areas for influencing the waste system. The Nairobi causal loop map described (Figure 16) suggests the presence of ten major drivers in Nairobi's solid waste system currently, namely;

1) External population growth factors - population growth factors extrinsic to the city's solid waste system e.g. family planning, education, prevalent culture etc
2) External economic growth factors - Economic growth factors extrinsic to the city's solid waste system e.g. national economic trends, education etc
3) Wealth and how it is distributed - within the city's confines
4) Traditional focus by the City Council on official waste collection to the official disposal site
5) Corruption and Management/Operational efficiency factors within the City Council
6) The gap in private waste collection among low income waste generators
7) The City Council's collection capacity and performance city wide
8) Private collection and performance amongst the middle to higher income waste generators
9) The political, legal, and infrastructural isolation of semi-formal actors in the city's solid waste arrangements
10) The city's waste material recycling and reuse capacity or base

Based on the causal relationships deriving from these drivers in

Figure 16, they may be categorised as follows:

- **Negative drivers** – system drivers that need to be eradicated, reversed, or at the very least minimised to achieve ISWM objectives.
- **Positive drivers** – system drivers that need to be encouraged in achieving ISWM goals.
- **"50:50" drivers** – system drivers that can be swayed by actors and governance structures in the city's solid waste management either away from or towards building ISWM objectives. At the moment however the behavioural tendency for these drivers is away from ISWM goals.
- **Near-Fixed drivers** – system drivers that cannot be directly changed much by the actors and governance structures in the city's solid waste management. A little influence may be exerted on

them through liaising with other non-waste specific governance structures and actors in the city or central government, but these drivers are largely out of the control of the solid waste sector.

The current nature of the drivers present in Nairobi's SWM system is summarised in Table 9.

Table 9: Categorisation of drivers in Nairobi's SWM system (numbers in brackets refer to numbering of system drivers above)

Negative Drivers (driving away from ISWM goals)	**Positive Drivers** (driving towards ISWM goals)	**"50:50"** (can be manipulated to either direction)	**Near-Fixed drivers** (cannot be changed much by the city's waste actors & governance)
- Traditional focus by the City Council on official waste collection to official disposal (4) - Corruption and Management/ Operational efficiency factors within the City Council (5) - Political, legal, and infrastructural isolation of semi-formal actors (9)	- Wealth (3), esp. when well distributed - City's waste material recycling and reuse capacity or base (10)	- Gap in private waste collection among low income waste generators (6) - City Council's collection capacity and performance city wide (7) - Private collection and performance in higher income generators (8)	- External population growth factors (1) - External economic growth factors (2)

While the negative, positive, and near-fixed system drivers are reasonably self-explanatory, it is worth discussing the "50:50" drivers present. From

Figure 16, the gap in private waste collection among low income generators (system driver 6) is currently leading to one of two outcomes: illegal and indiscriminate dumping, and the development of CBOs with low collection fees to take up the collection of wastes and who are also involved in waste recovery and trading for recycling revenues to complement their incomes. By making conditions conducive for CBO operation at the political, legal, and infrastructural support levels therefore; CBOs can be encouraged and empowered to take on waste service delivery amongst these generators. On the other hand, the negative outcome of this driver, illegal and indiscriminate dumping, can be minimised through better regulation and enforcement.

Additionally, current City Council and Private collector operations in the city (system drivers 7 & 8), while going some way towards alleviating the city's collection service backlog, dispose most of their waste at the open Dandora dumpsite, which not being an engineered landfill is having severe environmental and public health effects on the surrounding and wider Nairobi community (Section 4.2.3.4). These effects have several immediate and long term downstream economic costs for the city. This situation can however be swayed towards ISWM goals by encouraging this set of collectors to engage in waste diversion to landfill via material recovery and trading with the city's recyclers as do CBOs in lower income areas, preferably enhanced by the source separation of solid wastes at the generator level.

4.4.3.2 Other positive elements in the current waste system to build on to ISWM goals

While not a fundamental driver, the presence of an important but underappreciated informal waste resource recovery and trading sector in the city is also vivid in Figure 16. This sector creates economic opportunities, works in close collaboration with CBOs collecting waste from low income generators, and is also essentially the city's recycling materials supply chain. Aside from contributing to better eco-system health and public health conditions (arrows 45 & 46 in Figure 16), the resource recovery and trading sector's work with the city's recyclers is currently also the only positive contributor to the city's economic growth (arrow 19 in Figure 16) from within the waste management sector.

To enhance the contribution of this sector, it would therefore benefit from the recognition, official support, and encouragement of the City Council and government. It is also rational to develop policy and mechanisms encouraging greater recycling in the city such as specific material sector strategies and incentives to increase total recycling capacity, pushing for source-separation of wastes to decrease material contamination and improve re-usefulness and profitability in material recovery and recycling, and opening up a new waste material sink in the solid waste system possibly in the form of the semi-decentralised biodigestion of the city's predominantly organic waste (discussed further in Section 1) to amplify recycling capacity as a system driver towards ISWM. Such a new waste material sink could serve as a new income source for waste recovery and trading in the city, add value to source separation, and could in turn reinforce current recycling and reuse activity in the city through reduced material contamination. A new waste material sink in the form of the semi-decentralised biodigestion of urban organic wastes, even if it were unable to purchase recovered organic materials from collectors and the recovery sector; would at the very least mean a reduction in waste disposal transport costs for waste collectors, reduced health and environmental hazards from open organic waste degradation at illegal dumps and at Dandora, and would significantly extend landfill life.

4.4.3.3 Summary of recommendations towards ISWM arising out of analysis of system drivers

Based on the analysis of system drivers described in Section 4.4.2, the following systems intervention recommendations towards ISWM goals (hereafter referred to by recommendation numbering) are summarised from the discussions.

<u>Intervention Recommendations from Section 4.4.3.1</u>

C1) Reverse driver (4) by expanding the City Council's focus and vision towards achieving holistic ISWM goals in Nairobi across the whole waste chain from generation to safe disposal and not only focus on collection.

C2) Reverse driver (5)'s leakage of City Council resources by developing mechanisms to tackle corruption and management/operational efficiency problems within the City Council.

C3) Reverse driver (9)'s ignorance of local initiative by providing political, legal, and infrastructural recognition and support to semi-formal actors in the form of CBOs and actors in the informal waste recovery, trading and recycling sector.

C4) Grow wealth and prosperity among city residents to increase collection service willingness and ability to pay by developing and encouraging waste sector-intrinsic and -extrinsic mechanisms to aid the growth of wealth in the city.

C5) Minimise the negative effects of "50:50" driver (6) through greater regulation and monitoring of the city's waste sector to minimise illegal and indiscriminate dumping.

C6) Minimise the negative environmental contributions of "50:50" drivers (7) & (8) by developing mechanisms to encourage and get the City Council and private collectors to recover resource materials from collected wastes and to trade recovered material on the city's recovery and trade market as well as with recyclers, as do CBOs.

C7) Enhance the positive ISWM contribution of driver (10) by working to increase the city's waste material recycling and reuse capacity or base.

C8) Try to influence drivers (1) & (2) by developing policy and active dialogue channels between the City Council and other non-waste specific government governance structures and actors to collaborate on matters such as reducing and planning for population growth in the city, and encouraging economic growth from channels extrinsic to solid waste management.

Intervention Recommendations from Section 4.4.3.2

D1) Provide Political, legal, and infrastructural recognition and support of semi-formal actors in the form of CBOs and the informal waste recovery and trading, recycling sector.

D2) Develop policy to encourage greater recycling volumes in the city.

D3) Promote source-separation of wastes at generator level.

D4) Open up a new waste material sink in the solid waste system in the form of the semi-decentralised biodigestion of the city's predominantly organic waste to serve as a new income source for waste recovery and trading in the city or to at least reduce waste disposal transport costs for waste collectors, reduce health and environmental hazards from organic waste degradation at illegal dumps or at Dandora, and to extend landfill life.

4.4.4 Potential leverage points in Nairobi's solid waste system

4.4.4.1 Leverage points as a guide to ISWM interventions in Nairobi

Besides working out the nature of system drivers and how to use them to influence systems towards certain goals as in 4.4.3, leverage points - points at which small shifts can lead to big changes in the system towards achieving desired goals as proposed by Meadows (1999) in Section 2.4.2, provide a parallel analysis of where and how to intervene in a system, in this case towards ISWM in Nairobi. For ease of reference, Meadows (1999) proposed system leverage points are restated below in order of decreasing effectiveness:

1. The power to transcend paradigms
2. The mindset or paradigm out of which the system arose – its goals, structure, rules, delays, parameters
3. The goals of the system
4. The power to add, change, evolve, or self-organize system structure
5. The rules of the system (e.g. incentives, punishments, constraints)
6. Structure of information flows (who has and doesn't access to what sorts of information)
7. The gain (amplifying effect) around positive loops
8. The strength of negative feedback loops relative to what they're influencing
9. The length of delays relative to rate of system change

10. The structure of material stocks and flows (e.g. transport networks, population age structures)
11. The size of buffers and stabilizing stocks, relative to their flows
12. Constants, parameters, numbers (e.g. subsidies, taxes, standards)

Leverage point types (1), (2) & (3) speak to being able to go above and beyond established traditions so as to change system or management paradigms in pursuit of new or modified goals. In the case of Nairobi, while the traditional waste management focus has been waste collection volumes to disposal there is now a strong expression of a need to go beyond this to achieve more holistic ISWM goals across the entire waste chain from generation to disposal. Given the described nature of Nairobi's solid waste system, achieving this will require a patient 'moulding' of the waste sector appropriately from waste generation to disposal as opposed to top-down panel beating as the ideal command and control type waste management scenario is absent. This will require City Council as leader in the waste sector to expand its vision to see its role in Nairobi's waste sector as managing the realisation of ISWM in the city, and not necessarily hands on waste collection, movement and disposal only. It will need to adopt approaches such as: strengthening, incentivising, and mentoring private waste collection to increase collection volumes and encourage responsible waste movement and handling after collection in line with ISWM; encouraging the source-separation of wastes at generator level to support material recovery and recycling in the city; formally recognising and supporting semi-formal actors in community waste collection and in informal waste recovery and trading as partners in waste management; and strengthening the overall regulation and enforcement of standards in Nairobi's waste sector. A small acceptance and vision of ISWM goals at management thinking level in the City Council in this respect could bring about a large mobilisation of human endeavour and financial resources, which in turn would manifest in physical waste sector changes towards the same. Vision leads resourcing which in turn leads capacity.

Leverage point type (4) is concerned with achieving desired objectives by making structural changes to the system. From the description of Nairobi's waste system in 4.4.1, discernable structural changes that are necessary to achieve ISWM include: the expansion of total recycling capacity in the city for easily reusable materials - chief of which in Nairobi is organic waste; getting the City Council and private collectors to recover resource materials from collected wastes and trade recovered materials either in collaboration with the city's informal recovery and trade sector, or directly with recyclers as do CBOs; proactive encouragement and enforcement of source-separation of wastes at generator level to support material recovery and recycling in the city; and the establishment of safe final disposal of residual wastes at a sanitary landfill to reduce environmental degradation and public health effects.

Leverage point type (5) deals with the use of rules to govern system behaviour. In the case of Nairobi this would entail the use of incentives for activity contributing to ISWM, and punishments or constraints on activity working away from ISWM. In Nairobi incentives for pro-ISWM activity would be desirable for actors involved in communal waste collection, in waste recovery and trading, in private collection, in recycling, and for generators involved in active reuse or recycling initiatives at source. As shown in Section 4.3.4.4, the temporal character of municipal solid waste in Nairobi shows an increasing residual or 'other' waste fraction which points to the emergence of materials not traditionally presents in the city's waste stream. As a result present recycling capacity is increasingly ill-equipped to tackle new material types, and a need exists for the originators of such

materials to contribute to their end treatment or safe disposal in line with the ethos of extended producer responsibility, an objective realisable through the application of constraints on such material generation through the payment of end-of-life levies on such materials at point of manufacture, import, or sale. Punishments/constraints in Nairobi's waste sector may also be utilised to: deter actors from indiscriminate and illegal dumping through greater waste sector regulation and standards enforcement; to minimise excessive collector competition in similar localities at the expense of long term business viability and city-wide service distribution; and to minimise excessive waste dumping at final landfill through well calibrated landfill tipping fees. Waste system rules should however not excessively curb financial incentive counter to free market economics as this correlates closely to efficiency.

Leverage point type (6) deals with who can and cannot access different types of information. In Nairobi's waste system, critical information would include: regular appraisals of the state of the city environment and public health and its links with waste management practices; information on actors involved in, and levels of, waste collection, movement, and diversion from landfill; and local research and development into more efficient and sustainable waste management practices. The nature of this information dictates that it would need to be regularly updated to be useful, as well as publicly accessible to increase responsibility and accountability, and to improve collaboration amongst actors in waste management in attaining ISWM goals over the long term.

Leverage point types (7) & (8) are concerned with amplifying or diminishing the strength of feedback loops to help the system attain desired outcomes. From Figure 16 the most important feedback effects seem to be those affecting the city's economic growth in arrows 45 & 46 resulting from the state of ecosystem and public health; and arrow 50, which sees an increasing need for a new landfill resulting from the continued bulk disposal of waste at the current dumpsite fuelling a radical increase in the city's total waste management costs if the bulk disposal of all waste at landfill continues. Attention therefore needs to be directed strongly at ways in which waste can be diverted from landfill, and to ensure that only residual wastes are necessarily land filled to reduce the negative effects of these feedback loops.

Leverage point type (9) is concerned with ensuring that unnecessary delays in system flows, feedback information, and response times are avoided to ensure timely corrective actions where required, where feedback delays cannot be avoided the rate of system change becomes the target. This points to a need for a strong waste information and research system in Nairobi's waste sector, contributed to collectively but managed on a central platform and made publicly available so that relevant actors can respond and collaborate in a timely and informed manner, as well as be accountable to the wider waste sector and public as to their actions.

Leverage point types (10), (11) & (12) speak to the construction and optimisation of the technical and physical nature of the system structure; its stocks and flows; its buffering capacity against negative upsets; and the constants, parameters and numbers that determine their relative sizes. In Nairobi's waste system this calls for enhancing the structures, stocks and flows, and associated numbers or parameters set to work towards ISWM; and the diminishing of those working against ISWM. Examples would include the size and nature of the designated landfill to minimise environmental and public health effects; the size, nature and efficiency of waste collection, city

recycling, waste diversion, or otherwise treatment capacity as a buffer against increasing waste volumes etc. These last three leverage points would seem to be best prescribed in detail through a technical master plan.

4.4.4.2 Summary of recommendations towards ISWM arising out of analysis of system leverages

Based on the analysis of system leverage points described in Section 4.4.4.1, the following systems intervention recommendations towards ISWM goals (hereafter referred to by recommendation numbering) are summarised from the discussions.

E1) Expand City Council focus and vision to achieve ISWM goals across Nairobi by moulding the entire waste chain/sector and not merely going for increased official waste collection.

E2) Strengthen, incentivise, and mentor private waste collection to increase collection volumes and encourage responsible waste movement and handling after collection in line with ISWM.

E3) Encourage the source-separation of wastes at generator level to support material recovery and recycling.

E4) Formally recognise and support semi-formal actors in community waste collection and in informal waste recovery and trading as partners in waste management.

E5) Strengthen the overall regulation and enforcement of standards in Nairobi's waste sector.

E6) Expand total recycling capacity in the city for easily reusable materials - chief of which in Nairobi is organic waste.

E7) Get the City Council and private collectors to recover resource materials from collected wastes and trade recovered materials either in collaboration with the city's informal recovery and trade sector, or directly with recyclers as do CBOs.

E8) Proactively encourage and enforce source-separation of wastes at generator level to support material recovery and recycling in the city.

E9) Establish safe final disposal of residual wastes at a sanitary landfill to reduce environmental degradation and public health effects.

E10) Develop incentives for pro-ISWM activity, for actors involved in communal waste collection, in waste recovery and trading, in private collection, in recycling, and for generators involved in active reuse or recycling initiatives at source.

E11) Payment of end-of-life levies for materials for which little or no recycling and/or end of life treatment infrastructure exists in the city at point of manufacture, import, or sale.

E12) Greater waste sector regulation and standards enforcement to deter actors from indiscriminate and illegal dumping.

E13) Develop mechanisms to minimise excessive collector competition in similar localities at the expense of long term business viability and city-wide service distribution.

E14) Minimise excessive waste dumping at final landfill through well calibrated landfill tipping fees.

E15) Be careful not to excessively curb financial incentive in the waste sector counter to free market economics as this correlates closely to efficiency.

E16) Regular data collection and appraisal of the state of the city environment and public health and its links with waste management practices; information on actors involved in, and levels of, waste collection, movement, and diversion from landfill; and local research and development into more efficient and sustainable waste management practices. Make this

information publicly accessible to increase responsibility and accountability, and to improve collaboration amongst actors in waste management in attaining ISWM.

E17) Attention needs to be directed strongly at ways in which waste can be diverted from landfill, and to ensure that only residual wastes are necessarily land filled to reduce the general negative effects of land filled waste.

E18) Develop a strong waste information and research system in Nairobi's waste sector, contributed to collectively but managed on a central platform and made publicly available so that relevant actors can respond to areas of need and collaborate in a timely and informed manner.

E19) The City Council Dept. of Environment should subcontract an engineering consultancy to develop a technical master plan looking at construction and optimisation of the technical and physical nature of the waste system structure; its stocks and flows; its buffering capacity against negative upsets; and the constants, parameters and numbers that determine their relative sizes. Example areas for attention would include the size and nature of a designated landfill to minimise environmental and public health effects; the size, nature, and efficiency of waste collection, recycling, waste diversion, or otherwise waste treatment capacity as a buffer against increasing waste volumes etc.

4.5 Re-examination of Nairobi ISWM Strategy in light of current Systems Analysis

4.5.1 Summary of Official Nairobi ISWM Strategy

A summary is given below of the ISWM intervention strategies that were proposed in the official Nairobi ISWM Strategy document finalised in April 2010: *Integrated Solid Waste Management Strategy for the City of Nairobi, Kenya Situation Analysis & Proposed Interventions: Technical Support Document* (CCN & UNEP, 2010).

It should be remembered that at the finalisation of this document the complete systems analysis described in this work had only been undertaken partially, and while it played some role in the development of ISWM interventions proposed in the Nairobi ISWM Strategy document, it was largely tentative at that stage and some additional insights have since been gained as will become evident in 1.1.1. The intervention actions proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010) were as follows (hereafter referred to by action number):

1) ***Strategic Alignment of the City Council Dept. of Environment's Mission*** - to ensure that the philosophy of ISWM is sufficiently strongly present in the council's solid waste mission, funding, and operational policy.
2) ***Legal Recognition and Support of the multiple partners in the City's Solid Waste Management*** - to raise the profile of, and enable the amplified participation and contribution of semi-formal CBOs and currently informal actors in waste recovery and trading; to Nairobi's solid waste collection and management through legal, political, and infrastructural support and protection.
3) ***Development of a Waste Information System and Local Research Capacity*** - to make provision for the regular update of waste information, and to stimulate local research and development in SWM in Nairobi to facilitate future planning, and inform policy and investment decisions in the public and private sectors. Includes proposal for the development of a waste exchange protocol or platform amongst actors in the city's waste sector to encourage material recovery & trading.

4) ***Streamlined volume-based waste collection fees*** – to provide standard collection fee recommendations to residents to improve transparency and accountability in waste fees across the city, and use the volume basis of these fees as a behavioural feed-back mechanism to waste generators to reduce excessive generation & disposal of waste at source.
5) ***Source separation of recyclable and pure organic waste with incentives*** – to reduce waste material contamination and improve its end usefulness and economic value, thereby reinforcing resource recovery, trading, and recycling activity in the city. Incentives proposed for waste separation at source included reduced streamlined collection fees for separated recyclable and organic waste. Separated residual wastes were to retain full collection fees in (4) to minimise residual waste generation, and to encourage the use and eventual disposal instead of readily recyclable and reusable waste materials.
6) ***End-of-Life Treatment Levies for problematic wastes*** - to extend producer responsibility for problematic waste materials that currently have insufficient or no recycling or end treatment infrastructure in the city. Levies would go into a central pool fund enabling the purchase and/or development of appropriate recycling capacity or end of life treatment infrastructure for problem materials.
7) ***Awareness Campaigns and Education*** - towards public education on proper waste handling and the value of waste separation at source.
8) ***Improving and Increasing waste collection and management*** – through multi-actor concentration on best areas of operation in the solid waste management chain, so as to increase both waste collection levels (with private sector focus and investment encouragement in this) and improve waste sector management and regulation (with City Council focus in this area).
9) ***Zoning of waste collection operations*** - to minimize transport and disposal costs to waste collectors and generators, to reduce unhealthy competition of private collectors/CBOs in similar localities, to improve organization and efficiency of waste collection, to create performance accountability in specific areas, and to enable greater service delivery equity as a result of collector distribution.
10) ***Formalised waste collection contracts between waste collectors and serviced generators*** - to improve performance accountability in collection operation areas and provide legal support to both waste service providers and users. Also includes contractual obligation for collectors to responsibly handle collected separated wastes by selling them on the waste recovery & trading market in the city, or directly to recycling companies, or otherwise ensure their transportation to designated landfill.
11) ***Development of Material Recovery & Transfer Stations*** - to reduce waste volumes for disposal at landfill through the extended recovery of recyclables and quality organic waste not already captured through source separation in (5), and to reduce residual waste disposal transportation costs to landfill through material bulking.
12) ***Improved Regulation, Enforcement and Oversight of Private Collector & CBO Waste Collection in the City*** – through the City Council gradually moving out of waste collection activity to full time regulation and monitoring of all aspects of solid waste management in Nairobi. Also through the legal empowerment of Resident Associations in Nairobi to monitor the local performance of waste collectors allocated to specific operation areas, and the formation of an honest, efficient, internal monitoring unit of City Council officials as a ground monitoring force

for the City Council. Lastly through the streamlining the complementary and specific roles of the various governmental organisations related to solid waste management in Nairobi.

13) ***Recovery of value from Organic solid wastes*** – valorisation of Nairobi's predominant organic waste primarily through semi-decentralised anaerobic digestion complemented by smaller-scale composting and use of suitable fresh organic wastes as animal feed.
14) ***Strengthening of Specific Recycling Strategies*** - to develop specific recyclable material strategies in the city to increase recyclable material availability and supply, improve equity in the recyclables supply chains, and to support and increase the city's recycling sector.
15) ***Development of New Sanitary Landfill*** – to take over waste receipt from the currently open non-sanitary designated dumpsite at Dandora. The engineered landfill facility would be primarily for the end disposal of residual waste with greater emphasis placed on waste diversion for recyclable and organic/biodegradable materials via value derivation as in (13) & (14).
16) ***Regaining control of Dandora Dumpsite as a transitional disposal site, and its decommissioning and rehabilitation on completion of a new sanitary landfill*** – partial rehabilitation of the current designated Dandora dumpsite and regain of control from gang presence to enable its use as a transitional disposal site until the new sanitary landfill in (15) is ready.

4.5.2 Comparison of intervention recommendations from completed Systems Analysis, and the Nairobi ISWM Strategy (CCN & UNEP, 2010)

A comparison of the waste system intervention recommendations based on the now completed systems analysis as summarised in Sections 4.4.3.3, 4.4.4.2, and 4.4.2.3, and the intervention actions proposed earlier in the Nairobi ISWM Strategy (CCN & UNEP, 2010) as summarised in Section 4.5.1, shows the following alignment:

Table 10: Comparison of intervention recommendations from completed systems analysis and Nairobi ISWM Strategy proposals

Nairobi ISWM Strategy Intervention actions (numbers & descriptors refer to proposed intervention strategy actions summarised in Section 4.5.1)	Intervention recommendations from completed systems analysis already incorporated in Nairobi ISWM Strategy actions (numbers refer to intervention recommendations from systems analyses in Sections 4.4.3.3, 4.4.4.2, and 4.4.2.3)
1) [Alignment of CCN DoE Mission]	C1), E1), A1)*
2) [Recognition of multiple partners in the City's SWM]	C3), D1), E4), E10), B6)
3) [Devt. of Waste Information System and local Research Capacity]	E16)*, E18), A2)
4) [Streamlined volume-based waste collection fees]	E17), needs to be cognisant of E15)
5) [Source separation of wastes]	D3), E3), E8), E10), E17), B7)
6) [End-of-Life Treatment Levies for problem wastes]	E11), E17)
7) [Awareness Campaigns and Education]	E17), B4)
8) [Improving & Increasing waste collection & managt.]	C1), C5), E1), E2), E5), E10), A3), B13)
9) [Zoning of waste collection operations]	E13)
10) [Formal waste collection contracts btn waste collectors and serviced generators]	C6)*,E7)*, E8), B8)*
11) [Devt. of Material Recovery & Transfer Stations]	C6)*, E7)*, E17)
12) [Improved Regulation, Enforcement and Oversight of Private & CBO Waste Collection in the City]	C5), E5), E12), B3), B13)
13) [Recovery of value from organic solid wastes]	C7), D2), D4), E6), E10), E17), B5)
14) [Strengthening of Specific Recycling Strategies]	C7), D2), E6), E10), E17), B5)
15) [Development of New Sanitary Landfill]	E9), E17), B10), B11)
16) [Dandora Dumpsite as a transitional disposal site]	B9)

	System intervention recommendations not already incorporated in Nairobi ISWM Strategy Actions: **B2); B12); B14); C2); C4); C8); E14); E15); E19); C6)*,E7)*& B8)*** not emphasized adequately in Nairobi ISWM Strategy action **10); E16)*& B1)** not adequately covered in Nairobi ISWM Strategy action **(3); A1)*** not adequately covered in Nairobi ISWM Strategy action **1).**

* Systems based recommendations that are only partially addressed in the Nairobi ISWM Strategy actions

As shown by the comparisons in Table 10 the following ISWM intervention recommendations based on the completed systems analysis find either none or inadequate equivalence in the intervention actions proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010);

- **A1)*** - Widen the definition of success for all actors in Nairobi's waste sector from mere waste volumes handled and collection to disposal; to contributions made towards realising the social, economic, and environmental health of the overall waste chain from waste generation to material recovery, recycling, collection and safe residual waste disposal in building to ISWM goals.
- **B14) & C2) -** Reverse leakage of City Council resources by developing internal mechanisms to tackle corruption and management/operational efficiency problems within the City Council so as to increase the Council's capacity to fulfil its lead role in Nairobi's waste management.
- **B2), B12)**, & **E14) -** Minimise excessive waste dumping and resulting pollution/public health potential at final landfill through well calibrated landfill tipping fees.
- **B8)***, **C6)***, & **E7)*** - Develop mechanisms to encourage and get the City Council and private collectors to recover resource materials from collected wastes and to trade recovered material on the city's recovery and trade market as well as with recyclers, as do CBOs.
- **C4)** & **C8)** - Grow wealth and prosperity among city residents to increase collection service means by developing and encouraging intrinsic mechanisms (inherent within current waste system) that aid the growth of wealth in the city. Attempts may also be made to influence population and economic growth factors external to Nairobi's solid waste system and governance, by developing policy and active dialogue channels between the City Council and other non waste-specific government governance structures and actors to collaborate on matters such as reducing and planning for population growth in the city, and encouraging economic growth from channels extrinsic to solid waste management.
- **E15) -** Do not excessively curb financial incentive in the waste sector counter to free market economics as this correlates closely to operational efficiency.
- **E16)* & B1) –** Conduct regular data collection/investigations and appraisals of the state of the city environment and public health and its links with waste management.
- **E19) –** The City Council Dept. of Environment should subcontract an engineering consultancy to develop a technical master plan looking at construction and optimisation of the technical and physical nature of the waste system structure; its stocks and flows; its buffering capacity against negative upsets; and the constants, parameters and numbers that determine their relative sizes. Example areas for attention would include the size and nature of a designated landfill to minimise environmental and public health effects; the size, nature, and efficiency of waste collection, city recycling, waste diversion, or otherwise treatment capacity as a buffer against increasing waste volumes etc.

4.6 Conclusions

4.6.1 Conclusions from Systems Analysis of Nairobi's waste management

The application of a systems thinking based analysis of Nairobi's waste management, identified the presence of ten system drivers through which to influence the achievement of ISWM objectives in Nairobi. Two of these were determined to be largely out of the control of the solid waste governance structures in Nairobi, while another two were found to be currently actively driving towards ISWM goals. Three of the identified drivers were observed to be driving away from ISWM goals and require a complete reversal or eradication from the city's waste management structures to enable the city achieve its ISWM objectives; while another three, currently tending to anti-ISWM influences, were found to be flexible to manipulation so as to contribute positively to ISWM in Nairobi in future. These are outlined in Section 4.4.3.

The identification and use of system leverage points in Nairobi's waste sector allowed the development of several additional ISWM intervention proposals through which large waste sector changes may be achieved with relatively small inputs (Section 4.4.4). The solid waste management scene in Nairobi also seems to involve a combination of two systems archetypes as defined by Braun (2002): a '*Success to the successful*' trend of private waste collection relative to the City Council, embedded within a larger '*Tragedy of the Commons*' trend – the commons being the city's economic, human and natural capital growth and implicitly its potential revenue base for collection service providers, whose tragic diminishing for all will be the inevitable result if the current operation and disposal practices of both the private collectors and the City Council continue. These archetypes are elaborated in Section 4.4.2.

The systems analyses described identified equivalent actions to all of the proposed intervention actions in the Nairobi ISWM Strategy (CCN & UNEP, 2010), and highlighted a need for eight extra systemic interventions in Section 4.5.2.

As discussed in this Chapter and summarised above, the use of systems thinking approaches in solid waste management planning via systems dynamics' problem structuring and causal loop modelling and mapping, can add value to the UNEP ISWM plan development methodology (Section 2.3.1) by:

- Allowing solid waste practitioners, planners and analysts to visually summarise the major results and observations from situational assessments, literature surveys, field surveys, and other sources pertaining to solid waste in a given area during the course of the ISWM planning process via the use of causal loop modelling and mapping. This systems map summary also has the added benefit of being able to capture observations and trends drawn from different analytical and academic disciplines.
- Allowing the exploration and determination of the fundamental causes of the waste challenges or problems being currently faced in an area, and the development of interventions that are both context specific and that target the fundamental behavioural causes, and not merely the common visible symptoms such as growing waste volumes, low collection levels, and poor financing.

- Highlighting sometimes counter-intuitive system drivers, their nature, and areas for special attention in building on existing structures to achieve ISWM goals.
- Identifying and using system leverage points to develop complementary ISWM interventions to bring about system-wide changes simply.
- Making possible the determination of the high level or big picture patterns at work beneath the surface of current waste management practice and mechanisms, and providing insights into their downstream consequences from a life cycle perspective. These insights can inform the nature of the interventions developed in an ISWM Plan and can aid in the management of solid waste more holistically.

4.6.2 Recommendations for ISWM in Nairobi

Given the additional insights generated from the completed systems analysis of Nairobi's waste management as in Section 1.1.1; over and above the intervention actions proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2009) there is need for the City Council Department of Environment to examine and develop policy consistent with the following areas:

Systemic recommendations on broad strategic measures

1) Widen the definition of success for all actors in Nairobi's waste sector from mere waste volumes handled and collection to disposal; to contributions made towards realising the social, economic, and environmental health of the overall waste chain from waste generation to material recovery, recycling, collection and safe residual waste disposal in building to ISWM goals. This shift in waste management goals needs to be disseminated widely both within Nairobi's waste sector and to the public.
2) Grow wealth and prosperity among city residents to increase collection service willingness and ability to pay, by developing and encouraging intrinsic mechanisms (inherent within current waste system or sector), and extrinsic mechanisms (extrinsic to waste sector) to aid the growth of wealth in the city. Examples to this effect would include the active support and incentivising of material recovery and recycling activity in the city. Attempts may also be made to influence population and economic growth factors external to Nairobi's solid waste system and governance, by developing policy and active dialogue channels between the City Council and other non waste-specific governance structures and actors to collaborate on issues such as adequately planning for population growth in the city, and encouraging economic growth from channels extrinsic to solid waste management. Partners to this effect could include the Kenya National Bureau of Statistics for statistical collaboration; the Ministry of Public Health and Sanitation and the Ministry of Education as regards population planning and education; and the Ministry of Industrialisation in planning for strategic economic growth channels complementary to the City Council's city development vision but extrinsic to the current solid waste management system as described in this work.

Institutional recommendations on policy and institutional measures at national and local level

3) Reverse leakage of City Council resources by developing internal mechanisms to tackle corruption and management/operational efficiency problems within the City Council so as to

increase the Council's capacity to fulfil its lead role in Nairobi's waste management towards achieving ISWM. JICA (1998) and Karanja (2005) deal with this area rigorously and provide recommendations.

4) Do not excessively curb financial incentive in the waste sector counter to free market principles, freedom in the market place provides incentive for operational efficiency and reduced costs as operators compete for clients. This is especially important in the refinement and implementation of stream-lined waste collection fees in the city as proposed in the Nairobi ISWM Strategy intervention action **(4).**
5) Conduct regular data collection/investigations and appraisals of the state of the city environment and public health and its links with waste management, and report results publicly, as part of the Waste Information System proposed in Nairobi ISWM Strategy intervention action **(3)**.

Operational recommendations covering specific technical and organisation interventions

6) Develop mechanisms to encourage and get the City Council and private collectors to recover resource materials from collected wastes and to trade recovered material on the city's recovery and trade market as well as with recyclers, as do CBOs.
7) Minimise excessive waste dumping and resulting pollution/public health potential at final landfill through well calibrated landfill tipping fees. The current tipping charges at about KShs. 280 per truck (≈US$ 3.5 – US$4/truck) appear too low to act as a deterrent for excessive waste disposal at collector level. It is recommended that this be one of the action items taken up by JICA - Nairobi. (JICA is one of two development partners alongside UNEP with the City Council of Nairobi to improve solid waste management in the city, and commenced a parallel technical waste master plan at the end of 2009 to update previous similar work initiated in 1998, and to complement the Nairobi ISWM Strategy).
8) As part of the JICA waste master plan study, to develop a techno-economic master plan looking at the construction and optimisation of the technical and physical nature of the waste system structure; its stocks and flows; its buffering capacity against negative upsets; and the constants, parameters and numbers that determine their relative sizes. Example areas for attention would include the size and nature of a designated landfill to minimise environmental and public health effects; the size, nature, and efficiency of waste collection, waste recycling (especially organic waste valorisation), waste diversion, or otherwise waste treatment capacity in the city as a buffer against increasing waste volumes etc.

Intervention recommendations 1), 3), 4), 5), 6), and 8) may be considered critical to the long term success of ISWM efforts in Nairobi, while recommendations 2) and 7) can be considered secondary, important only after the implementation of the former.

5 Deriving Value from Urban Organic Waste in Nairobi

The city's waste material recycling and reuse capacity was highlighted in Chapter 4 as one of the critical system drivers in Nairobi's waste management system (Section 4.4.3.1; Driver 10), one of only two drivers currently working towards ISWM goals in the city. It is also one of the key recommendation areas for ISWM in Nairobi (Section 4.6.2; recommendation 8). Organic/biodegradable waste in particular also represents the single largest waste fraction in the City of Nairobi, at 51% of total waste generated (see Section 4.3.4.3). Specific intervention measures therefore to intercept this fraction and generate value from it, treating it as a resource and not waste, would go a long way towards the reduction of its disposal at landfill, and towards amplifying the driving effect of the city's recycling capacity towards ISWM goals. This would not only avoid disposal costs and provide landfill space savings, but also limit the potential for disease-causing pathogens and vectors such as rodents from its uncontrolled degradation, and encourage a behavioural culture of seeking hidden value in what is too easily called 'waste'.

This chapter presents an overview of current organic waste valorisation practice in Nairobi, assesses its economic feasibility, and discusses ways in which organic waste valorisation can be expanded to increase the city's material recycling and reuse capacity as a system driver towards ISWM.

5.1 Material Balance of Organic Waste Degradation in Nairobi

As described in Section 4.3.4.2, non-residential waste at communal collection points and illegal dumps includes waste from a highly heterogeneous mix of generators, and the contribution of each generator to the total waste composition at these points is generally unknown. With no way to relate the composition at immediate source from individual generators to the aggregated composition at communal collection points and illegal dumps, a statistical comparison between these two levels for non-residential waste generators would not be meaningful. Residential areas (estimated to be generating 68% of total waste in Nairobi (Ngau & Kahiu, 2009)) however provided an opportunity for such a comparison between compositions at immediate source and compositions at communal collection points and illegal dumps due to the homogeneity of their waste generators at both levels - essentially all contributing generators at immediate source and at collection points and illegal dumps were households with relatively similar characteristics.

Table 11, a reproduction of Table 3 discussed earlier, shows the average residential waste composition at immediate source and at communal collection points and illegal dumps. It is of particular interest that the compositions show a sharp reduction in the organic content between waste generated at source, and what is eventually available after an average but currently unknown time, t, at randomly sampled communal collection points and illegal dumps in Nairobi.

Table 11: Residential solid waste characterization at immediate source, and at communal collection points and illegal dumps (Section 4.3.4.1)

Waste Type	Composition (%)	
	At Immediate Source (directly from Households)	At Communal Waste Collection Points located in Residential areas
Organic/Biodegradable	58.6	46.1
Paper	11.9	8.9
Plastics	15.9	15.4
Glass	1.9	5.6
Metal	2.0	2.3
Other	9.7	21.7

An Analysis of Variance (Anova) was carried out to determine whether there were statistically significant differences in the composition of the residential waste stream between source and collection points, on the basis of the available residential sampling data. The results, summarised in Table 12 (see numerical results in Appendix IV), show that there were indeed statistically significant differences in the proportions of organics, paper, glass and the 'other' or residual waste fractions between immediate source, and waste at communal collection points and illegal dumps for residential generators.

Table 12: Anova to compare residential waste compositions at immediate source and at communal waste collection points

Statistically significant differences evident?					
Paper	Glass	Plastic	Organics	Metals	Other
Yes	**Yes**	**No**	**Yes**	**No**	**Yes**

This statistically supports the above observation, that the content of organic waste in the residential waste stream as generated at source decreases sharply at collection points and illegal dumps, likely due to open natural degradation (rotting) at these points as limited organic waste valorisation exists in the city (see Section 4.3.5.6).

By assuming that the 'other' or residual waste fraction generated at source remains unrecovered and undegraded between generation at source and the time eventually spent at communal collection or illegal dump (i.e. is a tie component between generation at source and degradation at collection points or dumps), we can use the aggregated residual waste composition at collection points and illegal dumps to approximate how much of a hypothetical 100 tonnes of residential waste generated and received at collection point or dump survives after an average time, t, as in Table 13:

Table 13: Residential waste material balance between immediate source, and communal collection points and illegal dumps in Nairobi using the residual fraction as a tie component (to 2 s.f.)

Residential Waste Composition (%) (from Table 11)

Waste type	At Immediate Source	At Collection Pts & Illegal Dumps
Organics	58.6%	46.1%
Paper	11.9%	8.9%
Plastic	15.9%	15.4%
Glass	1.9%	5.6%
Metals	2.0%	2.3%
Other	9.7%	21.7%

Waste Quantities (tonnes)

Material Quantities	At Immediate Source (tonnes)	Materials at Collection Pts & Illegal Dumps (tonnes)	Materials disappearing between Source & Collection Pts or illegal dumps due to recovery & degradation (tonnes)
Organics	59	21 (=46.1% x 45)	38
Paper	12	4.0 (=8.9% x 45)	8.0
Plastic	16	6.9 (=15.4% x 45)	9.1
Glass	1.9	2.5 (=5.6% x 45)	- 0.6*
Metals	2.0	1.0 (=2.3% x 45)	1.0
Other/Residual	9.7	→ 9.7 (untouched from generation)	0.0
TOTAL	**100**	**45** (45 = Residual 9.7 tonnes ÷ 21.7% compositional fraction at this point)	

* Statistical variability will show up more strongly for the small waste fractions, especially glass and metal, and therefore less precision for the estimated tonnages for these two fractions; this might be the reason for the seeming accumulation of glass at communal collection points and illegal dumps. An alternate material balance is shown in Appendix VI using glass as the tie component on account of its inertness, declining recycling use in the city, and its undesirability in informal waste recovery (see Section 4.3.5.1 & 4.3.5.4); and confirms the sharp degradation of organic waste shown here.

The conclusion then from these observations is that for every 100 tonnes of residential waste generated at source with 59% (59 tonnes) organic waste, that goes through communal collection points or ends up at an illegal dump in Nairobi, only 21 tonnes of the original organic waste will be available after an unknown time, t, at a randomly sampled communal collection point or illegal dump. This is equivalent to a loss of up to 64% of all the biodegradable organic waste generated domestically that goes through communal collection points and illegal dumps in Nairobi.

In a city where 68% of total waste generation is from residential sources (Section 4.3.4.3), 55% of the residents are estimated to live in poverty (Section 4.1.2) and are therefore likely using communal collection points and illegal dumps, and 59% of residential waste at source is organic; this represents an open leakage and rotting of at least 14% of all the generated waste in the city. Given that an upper estimate of 2230 tonnes/day of waste in Nairobi (72% of total waste generated) neither makes it to proper disposal channels nor is recovered for reuse and recycling (see Section 4.3.5.8), it is also possible that the biodegradable fraction in up to 72% of the city's total waste, inclusive of that generated in the formally serviced residential sector and commercial sector, suffers a fate similar to that described above. As such it is conceivable that as high as 23% of the city's total waste is lost

through such open dump leakage and rotting [= 72% of total waste x 50.9% (organic fraction in city waste at source – Sec. 4.3.4.3) x 64% (biodegradable waste loss at collection points and illegal dumps)]; with untold public health, environmental and sanitation costs, and lost material resource use opportunities.

5.2 Opportunities for organic resource recovery and reuse in Nairobi

There are prime agricultural lands and large farms on the outskirts of Nairobi with the average farm size in and around Nairobi about 1.2 acres (Karanja, 2005). There is however a scarcity of local fertiliser. The Ministry of Tourism, Trade & Industry (1999) reported that there are only 2 small fertiliser manufacturers in Kenya; KEL Chemicals (Thika) which manufactures single superphosphate (10,000 tons per annum) and MEA Ltd (Nakuru) which imports manufactured fertilizers and blends them into various grades (40,000 tons per annum). The majority of fertiliser in Kenya is imported. Kenya is additionally not endowed with raw materials for the fertilizer industry except filler materials such as limestone and soapstone. As such, proposals have been mooted to build a fertilizer factory, encourage the use of organic fertilizers such as nitrogen fixing organisms and organic residues (Ministry of Tourism, Trade & Industry, 1999), and to invite external investors in the fertiliser sector (Barsito, 2008).

As highlighted in Section 4.1.1, current agricultural activity in Nairobi includes horticultural and flower exports, as well the cultivation of cash crops like coffee, which are mainly exported to the EU which has an increasing demand for products from organic farming. Additionally, the increasing price of oil will only continue to push the price of synthetic fertilisers up. Excessive artificial fertiliser usage over the long term is also not in Kenya's interests as improper use could eventually lead to the eutrophication of water bodies, and compromised ground water quality in an already water stressed country. There is therefore opportunity for the use of compost from urban organic waste for dedicated organic farming and for blending with artificial fertilisers for soil nutrient improvement and conditioning.

Data from Kenya's National Bureau of Statistics (2003) also indicates that only 53% of households in Nairobi had lighting by electricity in 1999, with up to 45% utilizing paraffin lamps. It also showed that 76% of cooking in the city was done using paraffin, with charcoal, firewood and other sources meeting the remainder of the energy demand. This presents opportunities for energy generation from biogas from organic waste bio-digestion.

5.3 Organic Waste to Resource: Options for Nairobi

Municipal or urban organic waste can be handled in one of three main ways; to produce fertiliser or soil improver from composting or co-composting with human excreta; as a source of energy through production of a fuel gas through anaerobic digestion or pyrolysis, or directly in thermal processes (which may involve pre-treatment such as briquetting); or as a source of food for animals for relatively fresh wastes (Rees, 2005). Current organic waste valorisation practices in Nairobi are summarised below.

5.3.1 Use of fresh organic waste as livestock feed

As highlighted in Section 4.3.5.6, there is an interest in the use of organic waste as animal feed in Nairobi City (Karanja, 2005; Onduru *et al*, 2009; Ngau & Kahiu, 2009), with evidence of such activity

already prevalent in Nairobi. Organic waste material amounts reused in this way are however unquantified at the current time. Early work by Mazingira Institute (Mazingira (1987) cited by Karanja, 2005) indicated that 12-14% of animal producers in Nairobi fed their animals on urban organic waste. Karanja (2005) also found that 43% of markets and institutions interviewed in her work reported that organic waste from their premises was used as animal feed, mostly for pigs. With feeding alone accounting for between 60 to 80% of the total livestock production costs in Kenya (Githinji *et al,* 2009 cited by Onduru *et al*, 2009), interest in using fresh urban organic waste as animal and livestock feed is likely to be significant.

An income generating opportunity therefore exists for the rapid transfer and movement of high purity fresh organic wastes such as from local restaurants and markets, to farmers, livestock keepers and feed millers in the city and its surrounds as livestock feed. Options also exist in such a chain for private sector involvement in the pre-treatment and fortification of the fresh organic wastes for animal feed purposes. The benefits of such activities have been highlighted in developing cities such as Manila in the Phillipines – where CBOs collect and sell market/restaurant waste to pig farmers at about half the price of commercial feeds, saving on commercial feed costs and resulting in a doubling of profits after accounting for all rearing costs (Rees, 2005).

5.3.2 Composting Operations and Performance in Nairobi

While Kenya's economy is dominated by the agricultural sector and Nairobi has significant peri-urban and urban agricultural activity (Section 4.1.1), bulk compost production directly from urban organic waste for sale as bio-fertiliser in Kenya is currently economically unattractive relative to synthetic fertiliser pricing. This is in spite of compost's useful soil conditioning advantages over synthetic fertiliser.

5.3.2.1 The Economics of Composting in Nairobi

Onduru *et al.* (2009) summarise their findings comparing costs of compost produced by local groups vs. several commercial synthetic fertilisers (23-23-0, 17-17-17, 20-20-20, DAP, TSP, CAN and UREA) on the Nairobi market for the provision of a finite amount of soil nutrients to agricultural land. These are shown in Table 14 below. These findings strongly suggest that from an economic perspective, while compost production by CBOs could compete with synthetic fertilisers on a Nitrogen (N) basis, compost-based fertilisers in Nairobi are really uncompetitive as a Phosphate source. It would then appear that the bulk diversion and derivation of value from biodegradable organic waste in Nairobi might be better achieved through an alternate route such as anaerobic digestion first. This could then be followed by smaller scale composting of the relatively lighter (volume wise) dried sludge left from anaerobic digestion, and of other non-digestion suitable organic wastes e.g. hard biodegradables such as wood chips, hard greens etc.

Table 14: Comparative Analysis of fertiliser value of compost and inorganic fertilisers based on market prices and nutrient contents, July 2009 (Source: Ondaru et al, 2009)

Nutrient source	Supplying 60 kgN ha-1		Supplying 60 kg P_2O_5 ha-1 (= 26 kg P ha^{-1})	
	Quantity of materials required (kg)	Cost (KES)/ha	Quantity of materials required (kg)	Cost (KES)/ha
Compost-CBOs	9,292	16,709	20,503	411,664
Cattle manure	21,490	38,676	47,113	187,143
Mazao gold compost	5,455	109,091	3,086	121,212
Mazao Bora® Compost	5,455	272,727	2,424	121,212
23-23-0	261	19,652	261	19,652
17 17 17	351	22,941	351	22,941
20 20 0	300	10,000	300	10,000
DAP (18-46-0)	333	19,333	130	7,565
TSP (0 46 0)			130	6,130
Minjingu Rock Phosphate (0-30-0)			200	10,000
CAN (26 0 0)	231	9,923		
Urea (46 0 0)	130	7,826		

5.3.2.2 Strengthening the role of compost production in Nairobi's organic waste valorisation

In order to strengthen the economic potential of composting in Nairobi and Kenya at large, it will be necessary for the Dept. of Environment City Council of Nairobi, the National Environmental Management Authority, NGOs, and organisations such as Kenya Organic Agriculture Network (KOAN) and other relevant stakeholders to lobby the Ministry Of Agriculture to develop policy recognising, and supporting active compost use among farmers, to harness compost's non-nutrient soil enhancing properties such as improved texture, water retention capacity, pest inhibition, and provision of soil carbon which improves beneficial soil microorganism activity and root development, and leads to reduced nutrient leaching. The use of compost alongside artificial fertiliser by farmers can result in better overall crop yields and agricultural land management. The implications of such policy development in an already water stressed country like Kenya would include reduced potential for the eutrophication of current water bodies, and greater protection of ground water quality from excessive nutrient leaching resulting from artificial fertiliser use alone. Other results that could be expected from such policy development would include better pest management, reduced pesticide expenses incurred by farmers longer term. There is also the possibility for such a policy to encourage local organic farming to tap into higher EU and global market prices for organic agricultural produce.

Another potentially attractive avenue for the production and utilisation of compost could be collaborative mixed organo-synthetic fertiliser production with current Kenyan fertiliser manufacturers and traders, resulting in the development of optimal organo-synthetic fertiliser products that would tap into the strengths of each component, and which would be superior in performance to either fertiliser component applied alone. In this way composting groups such as CBOs can gain reasonable markets for their compost product, and tap into the already established distribution and marketing chains of synthetic fertiliser manufacturers and sellers in the country, leaving them to concentrate on compost production and quality assurance. Such an arrangement

with established fertiliser manufacturers and traders would not only mean reduced distribution and marketing expenses for composting groups but would also help to build the credibility of compost as an agricultural product, as it positions it among 'modern' chemical fertilisers which are already bought and positively perceived by many farmers (Rouse *et al,* 2008). A successful example of this business model is in operation in Dhaka, Bangladesh where the Agro-fertiliser company involved in this business model is confident it can sell up to 10 times the present volume purchased from the composters (Rouse *et al,* 2008).

Finally, the use of vermi-compost production methods is also a possibility for compost production as they give greater nutrient value than aerobic composting (Baud *et al*, 2004) and would return better nutrient value for the established selling prices in Table 14 above. The composting worms used in the process can also be sold as poultry feed or fish bait after use.

5.3.3 Anaerobic Digestion of Nairobi's Organic Waste: Current Activity and Economic Feasibility

The direct composting of organic waste in the City of Nairobi is economically unattractive at the moment due to its high pricing for nutrient value relative to synthetic fertiliser (see Section 5.3.2). Owing to this, the anaerobic digestion of biodegradable organic waste for energy might lend itself to the greater generation of value and benefits from organic waste than straight composting in the Nairobi context, while also allowing for the radical reduction of total waste amounts requiring disposal. The minimal digestate volumes left after anaerobic digestion are also more stable in nature, and could be made available for uptake by smaller scale composting, application on agricultural lands (if appropriate mechanisms are put in place), or for significantly reduced disposal via sewer system or at landfill.

5.3.3.1 How best to utilise biogas from anaerobic digestion in Nairobi's urban setting?

Biogas digestion uses the microbial degradation of organic material in the absence of oxygen, which both stabilises the waste and generates biogas containing methane, a valuable fuel. Nairobi's urban context lends itself to the use of biogas to generate electricity, but not at scale for cooking.

While the direct utilisation of biogas for cooking is more energy efficient owing to minimal energy conversion losses, such a scenario is likely to be difficult to implement in Nairobi's urban setting. In order to be utilised directly for cooking, biogas cannot be piped over excessive distances and a maximum piping distance in the region of 300 m radius from the source of the biogas is often recommended. Given that any zone-based or semi-decentralised digester facilities near waste generation sources are likely to be adjacent to material recovery facilities initially, it is unlikely that residential areas or potential direct biogas-to-cooking clients would be within close proximity to these facilities. Other challenges that would need to be addressed in such a direct use scenario include the metering and billing of biogas supplied to clients; the critical need for leak prevention along supply lines, extending the risks and safety costs beyond the biogas facility itself; and the need for extended behavioural change among residents, who would need to culturally accept the use of the biogas for cooking as well as buy appropriate stoves to utilise it. In light of these challenges, it would be rational to instead utilise any generated biogas from organic waste at the zonal or semi-decentralised scale for the generation of electricity, possibly via biogas-driven generator-engine sets (Genset). Electricity is a good/service that the city's populace is already familiar with, is willing to pay for (with minimal behavioural changes required), and for which distribution infrastructure is already

largely available in Nairobi. The electricity generated can then be supplied to either local users at agreed rates with the approval of the national Electricity Regulatory Commission (ERC) and Kenya Power and Lighting Company (KPLC), or fed into the national grid at negotiated rates with the ERC. This approach also makes economic sense in light of Kenya's currently stretched electricity generating capacity (Section 5.2).

Direct biogas use for cooking can however still be encouraged at waste source or generator level, such as for large institutions, large caterers like hotels and big restaurants, or at markets which naturally tend to have the presence of small to medium-scale caterers on-site, cooking meals for traders and neighbouring workers.

Two approaches to the anaerobic digestion of biodegradable waste for energy and its encouragement in Nairobi are therefore envisaged:

1) Encouragement of organic waste derived biogas for cooking and compost at large institutions and commercial premises, especially those with organic/biodegradable-rich wastes. This could be achieved through the development of sub-national policy encouraging onsite digestion or composting through various economic and moral instruments.

2) Development of close-to-generation-source anaerobic digestion facilities for organic/biodegradable municipal solid waste in Nairobi's zones, with pilots initially adjacent to planned material recovery and transfer stations (planned for in Nairobi ISWM Strategy – CCN & UNEP, 2010), but later expanding further into other locations closer to waste sources to minimise organic waste transportation distances, and to favour waste movement by CBOs on foot. The biogas generated would be used to generate electricity for sale locally or to the national grid, with selling prices to be negotiated with local clients or with the Electricity Regulatory Commission (ERC). The Nairobi sewage and waste water treatment works at Ruai would also provide a good opportunity in future for the co-digestion of organic municipal solid waste with treated sewage for the generation of methane for energy generation.

5.3.3.2 Biogas-to-energy installations in Kenya

Although Nairobi itself has scant examples of biogas-to-energy installations at scale, Kenya has seen some promising adaptation and application of organic waste digestion for biogas to energy at the small to medium scale outside of the capital. Some of the biggest examples are noted from surveys by Onduru *et al* (2009) summarised in Table 15.

Table 15: Examples of biogas to energy installations in Kenya (Source: Onduru *et al*, 2009)

Examples of Biogas to energy installations	Summary of features
Sisal Estate *- Kilifi, coastal Kenya:*	- Industrial scale 700 m^3 biogas digester. Biogas produced is used to run two Genset generators producing electricity with a potential to supply to the national grid. Entrepreneur however does not supply the grid due to perceived low payments from Kengen (≈ 7 US cents /kWh), which do not cover production costs. Generated biogas is used to run sisal estate machinery.
Individual farmer in Kiambu Municipality	- Fixed dome reactor constructed in 2008 at a cost of KES 500,000. The reactor is fed with manure-water mixture from zero-grazing animals. The biogas is piped to the farmer's house and five additional households within a radius of 300 meters. Although the biogas is currently not metered or paid for, the farmer estimates he could earn KShs.3000 per month (US$ 40 at exchange rate of 74.6 KShs/US$) if the beneficiary households were to pay on agreed terms. The plant sludge is used for growing vegetables, maize, and Napier grass.
Individual farmer in Matuu, Yatta District	- Fixed dome biogas plant in Matuu using a mix of farm vegetable residues, slaughter house residues and manure. The plant runs a 12 KVA generator using 20% diesel and 80% biogas. The generator can provide energy 12-14 hours a day and the farmer has the potential to commercialise the biogas generated. The farmer saves 20 litres fuel/day as a result.
Biogas plants in public institutions	- Biogas plants of 124 m^3 and 91 m^3 digesters have been constructed at Egerton University (Njoro) and Moi University respectively. The biogas generated is used within the institutions as a cost saving strategy. At Egerton University the biogas is metered to monitor its use and the digester capital cost took a mere 12.7 months to pay back from energy savings accrued.
Biocentres in informal settlements in Nairobi	- Biogas generating latrine and bathroom blocks managed by community groups, established in crowded informal settlements in Nairobi to ease sanitation needs. Excreta from the toilets are led into one central underground fixed dome digester, with standard sizes of the order of 196m^3. Biogas generated is piped into an upper room for use in heating bathroom water, cooking, lighting, piping to neighbours etc.

Karekezi (2002) notes the presence of up to 500 digesters at the <100 m^3 scale in Kenya, and observes from experiences in several African countries that larger combined septic tank/biogas units run by institutions such as hospitals and schools have proved to be more viable than small-scale household biodigestors.

Onduru *et al.* (2009) further report an interesting case study showing the active utilisation of biogas from organic waste for electricity generation from a medium-scale biogas-to-energy plant on the outskirts of Nairobi, and are quoted below;

> "Keekonyoike Slaughter House is in Kiserian Town in the peri-urban Kajiado North District bordering Nairobi. The slaughter House installed twin digesters of 124 m^3 each (modified fixed domes) in 2006. The modified plant has a feeding chamber, digester and expansion chamber. There are also two slurry pumps to mix the slurry/waste (scam) from the slaughter house before being fed into the digester. The slurry pumps are run by a generator using about 80% biogas and 20% diesel. The two digesters are able to cope up with about 9-15m^3 waste generated from slaughter house daily. The digesters have a metal lid at the top. The gas generated from the digesters is piped into a room where there is a balloon for storing the gas (storing 60-70 m^3 biogas). The gas is also used to run a Genset engine/generator (20KVA) with a three-phase output. The plant (feeding chambers, digesters, slurry pumps, digestate storage, Genset, pipings etc.) was constructed at a cost of KES 8 million with the digester alone and the associated units taking about KES 3 million. The plant can generate (50 m^3 x 2) 100m^3 of biogas per day. Pipes have been laid to supply six hotels with biogas within a 300 meters radius with support from GTZ-PSDA. The total consumption of these hotels are estimated at 76 m^3 biogas daily. The biogas meters purchased by GTZ-PDA have been fitted in each hotel to measure consumption and to levy appropriate charges. The initiative has prompted about 20 other people and entrepreneurs requesting to be connected to the biogas plant. The slaughter House has excess organic materials (slaughter waste e.g. from rumen of animals, blood etc.) for feeding the biogas plant."

5.3.3.3 Biogas to energy in the developing world

Contrary to the contention that the anaerobic digestion of urban organic waste at larger scale is beyond the financial reach of developing world cities, there is increasing evidence for its successful use in this context. Successful case studies in the developing world have been discussed in Section 2.5.3.3.

5.3.3.4 The economics of anaerobic digestion of organic waste for biogas-to-energy in Nairobi

Drawing from the discussions above, the anaerobic digestion of 10 tonnes/day of organic biodegradable solid waste for electricity generation at a hypothetical medium-scale biogas-to-energy digestion facility in Nairobi was modelled and investigated with a view to establishing the order of magnitude of investment necessary to establish the necessary infrastructure, and the potential economic returns and benefits in the Nairobi context. The modelling procedure used is outlined in Section 3.3.2.

From the modelling, a generic medium-scale biogas digester facility in Nairobi treating 10 tonnes/day of urban organic solid waste in a CSTR-type digester would need a reactor volume totalling approximately 960 m^3. The biogas-to-energy plant would generate about 675 m^3/day of biogas, have an electricity generation potential of approximately 1020 kWh/day, and have a fixed capital cost of the order of KShs. 41 million (≈US$ 550,000). Calculations and detailed modelling results are shown in Appendix VII.

The subsequent sale of the generated electricity locally or to the national grid at different selling prices, and the potential use of buying incentives or tipping fees at gate for pure separated organic wastes from waste collectors or from actors in waste recovery and trading yields several economic feasibility scenarios. These economic scenarios are shown graphically in Figure 20, Figure 21 and Figure 22 in terms of:

- Approximate fixed capital investment pay-back periods for the biogas-to-energy plant relative to electricity selling prices, and pure organic waste buying incentives indicated with a [+] sign, or tipping fees indicated with a [-] sign (Figure 20);
- Estimate net annual incomes before tax relative to electricity selling prices, and pure organic waste buying incentives (Figure 21);
- Estimated returns on investment (using net annual incomes before tax) relative to electricity selling prices and pure organic waste buying incentives (Figure 22).

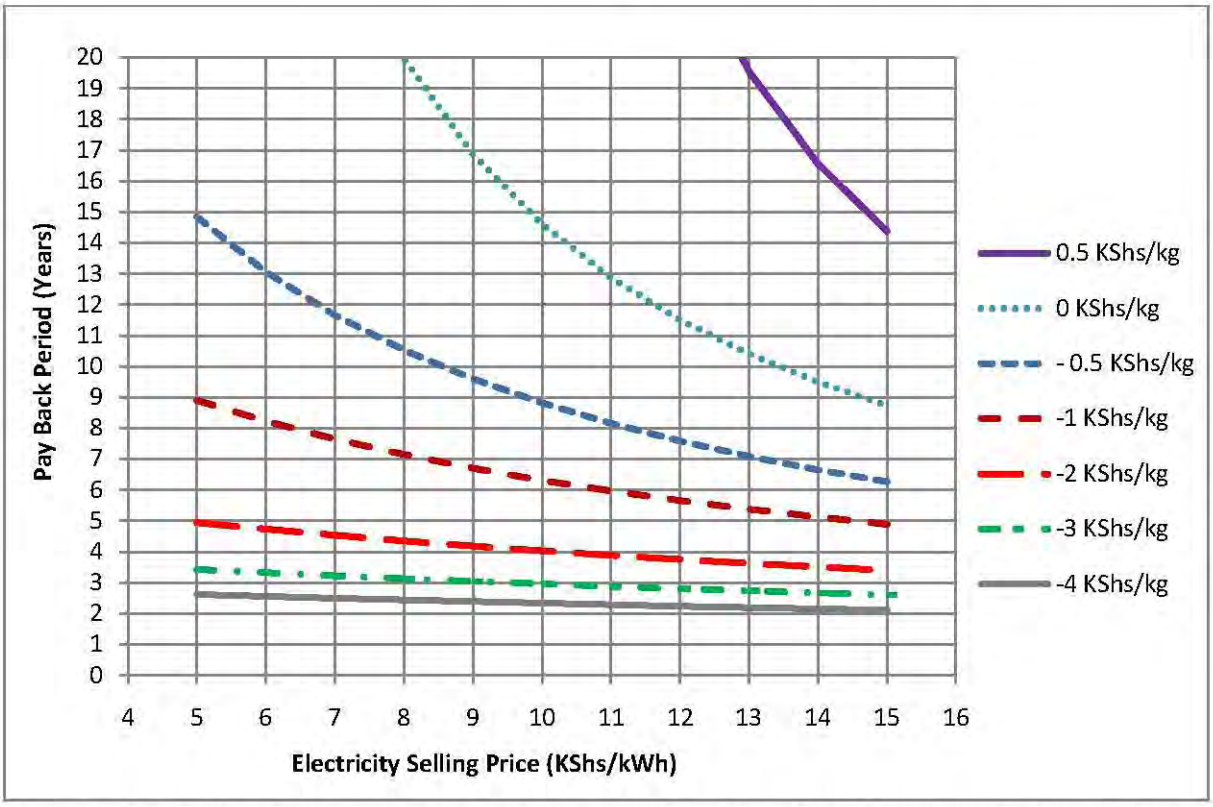

Figure 20: Estimate Biogas plant pay back periods relative to electricity selling price and pure (source-separated) organic waste buying incentives (indicated as [+]) or tipping fees (indicated as [-])

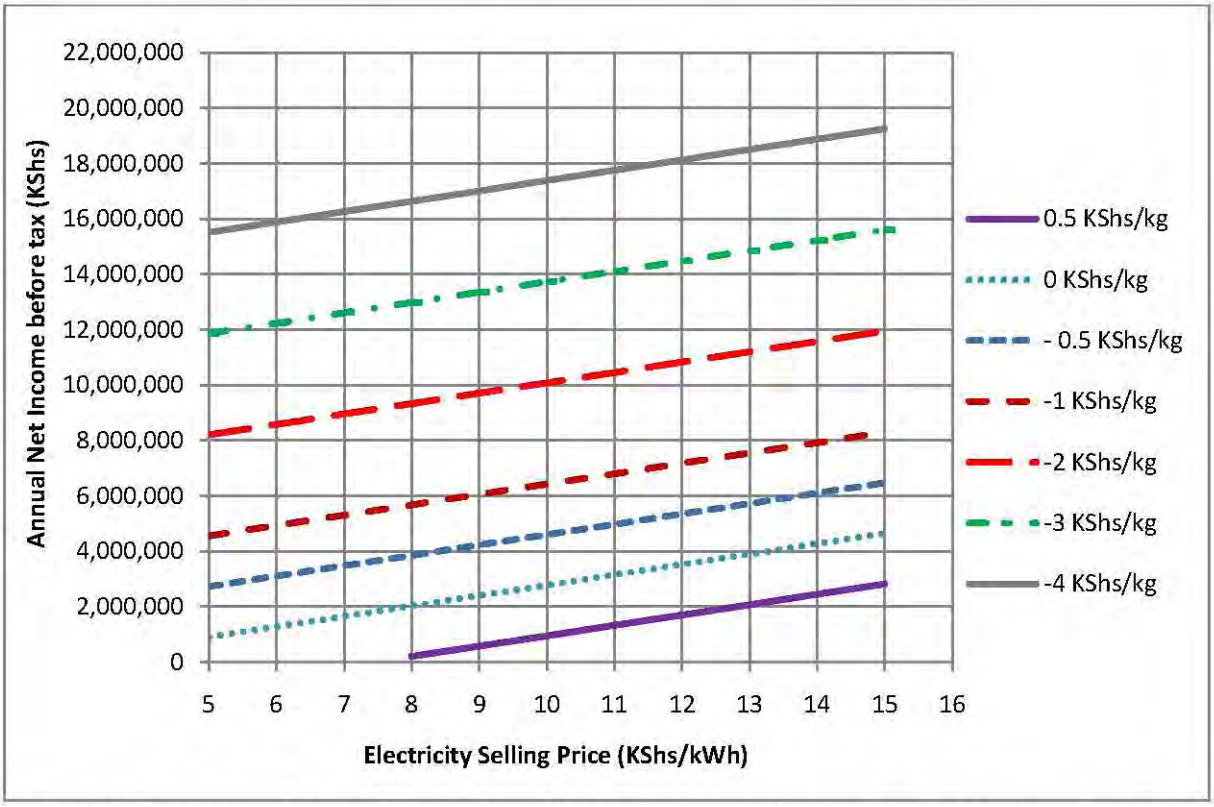

Figure 21: Estimate biogas plant net annual incomes before tax relative to electricity selling price and pure (source-separated) organic waste buying incentives (indicated as [+]) or tipping fees (indicated as [-])

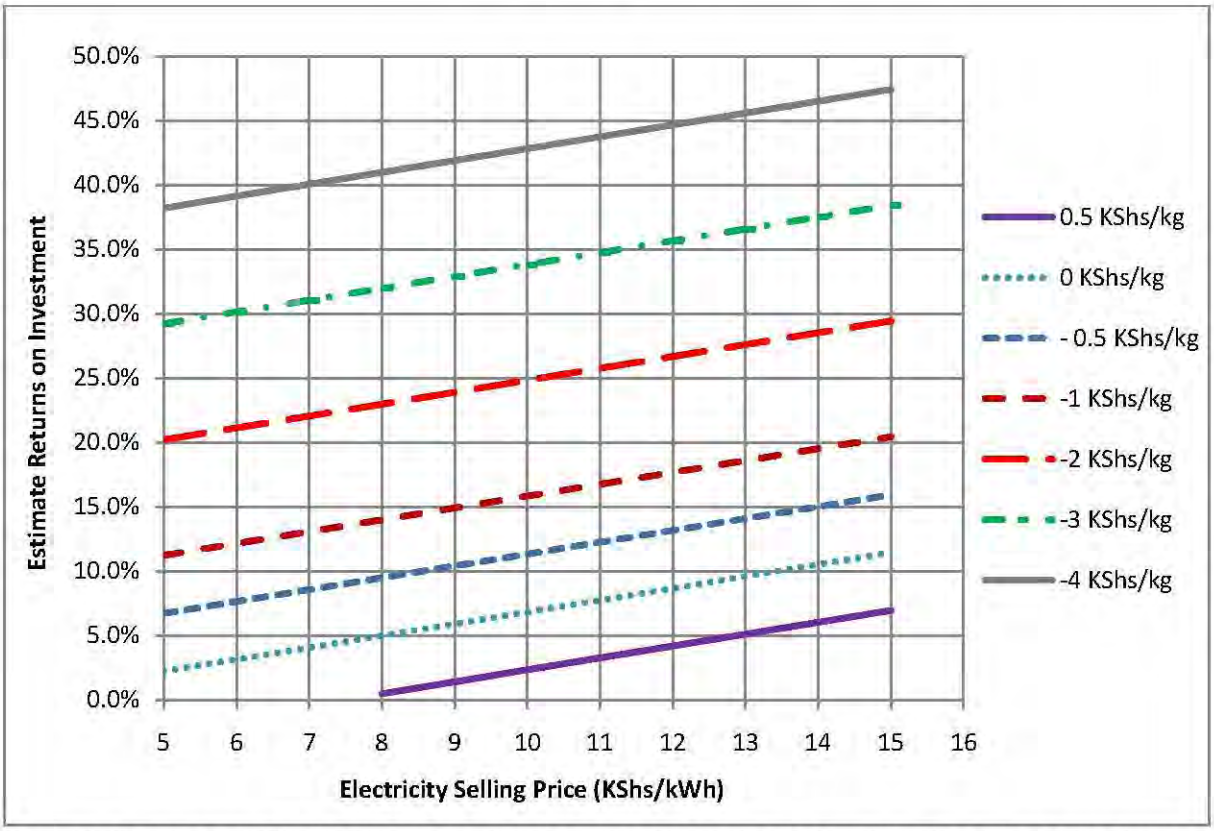

Figure 22: Estimate annual biogas plant pre-tax returns on investment relative to electricity selling price and pure (source-separated) organic waste buying incentives (indicated as [+]) or tipping fees (indicated as [-])

The current grid feed-in tariff for electricity from biogas by the Kenyan Electricity Regulatory Commission (ERC) is 8 US Cents/kWh, equivalent to about 6 KShs/kWh (@ average exchange rate of KShs.74.5/US$). From the economic modelling results shown, it does not seem feasible to buy pure/separated organic wastes from waste collectors or scavengers, unless the negotiated electricity selling prices with ERC or with local private clients substantially exceed the 15 KShs/kWh mark. At this point an incentive of KShs. 0.5/kg pure organic waste from collectors starts to yield a distant pay-back period of about 15 years. For the free deposit of pure/separated organic wastes by waste collectors or scavengers at biogas plant facilities (no buying incentive; shown as 0 KShs/kg organic waste in Figure 20), plausible pay-back periods of under 10 years start to emerge from selling the generated electricity at 13-14 KShs/kWh.

The requirement of a tipping fee of KShs. 1/kg (i.e. the collector pays to leave organic waste at the digester facility; shown as -1 KShs/kg organic waste in Figure 20), yields a reasonable pay-back period of about 8 years for the sale of electricity at the current feed-in-tariffs for electricity from biogas. This seems a fair operating condition for the establishment of such digester facilities given that private collectors on average currently spend more than KShs. 1/kg to transport waste to the designated Dandora dumpsite (see Table 8), and will spend much more (about KShs. 4/kg) in the future for waste disposal at the candidate Ruai landfill site, or any other similarly distant site out of the city (see Table 8) when the Dandora site is finally decommissioned. The attractiveness of establishing biogas digester sites for municipal organic waste in Nairobi is also likely to increase given current lobbying by private Kenyan biogas investors for the ERC to raise the biogas feed-in-

tariffs in the next tariff review (2011), something that is likely to happen given Kenya's electricity shortage and renewable energy goals (GTZ/ERC, 2009).

In summary, the calculated plant investment pay-back periods under the current feed-in-tariffs for electricity from biogas of 8 US cents/kWh, show that the investment in and establishment of organic waste anaerobic digestion biogas-to-energy facilities for Nairobi, charging a small tipping fee of KShs. 1/kg, makes long term financial and strategic planning sense for the City. Currently however, given the pay back periods, the set up and operation of any such anaerobic digestion plants in Nairobi seems best suited to organisations serving the public interest and looking at longer term planning and public benefits such as the City Council, the Kenya Energy Generation Company (KenGen), Ministry of Nairobi Metropolitan Development (MoNMD), or other government departments. If the feed-in-tariffs however increase, there would be a vibrant private sector interest in biogas for energy from municipal organic waste in Nairobi (GTZ/ERC, 2010) that would find such investments highly attractive. A suitable feed-in-tariff target to this end would be 13-14 KShs/kWh generated electricity (17-19 US Cents/kWh) with a tipping fee of KShs. 1/kg of received organic waste, to achieve attractive payback periods of under 5 years. This generally agrees with GTZ feed-in-tariff recommendations for the Kenyan agro-industrial biogas sector of 18.05 US Cents/kWh from combined heat and power CSTR-type biogas facilities (Fischer *et al.*, 2010).

While the results above are only estimates, it can be seen that the establishment of anaerobic digestion biogas-to-energy facilities for the treatment of organic waste in Nairobi is within the financial reach of the City, if the possibility is embraced pro-actively and in a visionary manner by all stakeholders, and especially supported by KenGen, the ERC as well other appropriate government departments.

5.3.4 Potential domino effects of organic waste valorisation in Nairobi

The following potential chain effects are envisaged from the active treatment of, and derivation of value from organic waste in Nairobi primarily through biogas plants generating electricity, and through the strengthening Nairobi's compost production potential and the use of fresh organic waste as animal feed:

- Behavioural change by city residents viewing waste as a resource and not simply a nuisance.
- The attachment of value to organic waste in Nairobi can have reinforcing effects on inorganic waste recycling, with an increased incentive for the encouragement of source waste separation by collectors to clients so that the waste collectors can deposit organic wastes at biogas, compost or animal feed treatment facilities cheaply. In the process this would mean less recyclable material contamination in the waste stream, and would lead to greater reuse/recycling potential of both the organic and inorganic waste streams in Nairobi, and greater waste diversion from landfill.
- The anaerobic digestion of organic waste for energy at the municipal level, alongside the current Lake Turkana Wind Energy farm project can serve as a trigger and driver for the national growth of Kenya's renewable energy industry – an area that Kenya and indeed other developing countries should increasingly seek to develop alongside their existing concerns, so as to secure their energy and economical futures in an increasingly volatile oil price and climate change global environment.

5.4 Conclusions

It is estimated that there is an open leakage and rotting of at least 14%, and possibly as high as 23%, of all the generated waste in the city due to open dump organic waste degradation, with untold public health, environmental, and sanitation costs (Section 5.1). There is a prevalent interest in the use of such organic wastes as animal feed in Nairobi City, and this use represents a promising but seemingly under tapped organic waste valorisation potential that is likely to gain in importance in future (Section 5.3.1). Bulk compost production from organic waste in Nairobi is economically unattractive under prevalent market conditions (Section 5.3.2), and does not currently represent a rational option for the bulk valorisation of organic wastes in Nairobi.

The anaerobic digestion of organic waste for energy shows potential to achieve radical organic waste valorisation levels in Nairobi, and from the economic modelling and analyses shown of potential medium scale biogas-to-energy plant investments in Nairobi in Section 5.3.3, the following conclusions may be drawn:

1) The buying of pure or separated organic wastes from waste collectors or scavengers at potential biogas-to-energy digestion facilities in Nairobi does not seem feasible at the current biogas energy feed-in tariffs. The requirement of a small tipping fee of KShs. 1/kg (i.e. the collector pays to leave organic waste at the digester facility) would be necessary, and yields a fair pay-back period of about 8 years for plant capital investments from the sale of electricity at the current feed-in tariffs. This would seem to be a reasonable operating condition for the establishment of such biogas-to-energy digestion facilities given that waste collectors in Nairobi currently spend on average more than KShs. 1/kg to transport waste to the designated Dandora dumpsite, and will spend about KShs. 4/kg for future waste disposal at the candidate Ruai new landfill site (see Section 4.3.8).
2) Given the pay back periods at the current biogas energy feed-in tariffs as in (1), the set up and operation of biogas-to-energy digestion facilities in Nairobi seems best suited to organisations serving the public interest with mandates on longer term economic planning and public benefits, such as CCN, KenGen, ERC, MoNMD, and regional development banks.
3) A suitable feed-in-tariff target of about 13-14 KShs/kWh electricity (17-19 US Cents/kWh) and an organic waste tipping fee of KShs. 1/kg organic waste received at such facilities is recommended to achieve attractive payback periods of under five years for especially private investors. This generally agrees with GTZ feed-in-tariff recommendations for the Kenyan agro-industrial biogas sector, of 18.05 US Cents/kWh electricity from combined heat and power CSTR-type biogas facilities (Fischer *et al.*, 2010).

The anaerobic digestion of organic waste for biogas-to-energy at-scale in Nairobi's current solid waste management environment therefore shows a promising potential to contribute radically to the reduction of waste volumes currently causing significant pollution and health risks, and to increase waste conversion to resource and recycling capacity in Nairobi as a waste system driver towards ISWM. From the conclusions above it appears that a key driver for the growth of this waste valorisation subsystem is the provision of a renewable energy feed-in tariff above a threshold of about 13-14 KShs/kWh electricity.

6 Conclusion

This final Chapter of the dissertation revisits the objectives and key questions that motivated this work, and outlines explicitly the conclusions that have been drawn with respect to each of these. Key lessons from this work for ISWM planning efforts in other developing African cities are discussed briefly thereafter, and the dissertation closes out with recommendations for further work in the application of systems based analyses for waste management planning.

6.1 Achievement of objectives

This thesis set itself three objectives:

1) To investigate the fundamental underlying causal relationships and patterns that have led to the current solid waste management situation in Nairobi, using 'soft systems' modelling and approaches, and to utilise the knowledge generated to gain strategic insights on how to achieve ISWM goals in the city by targeting the fundamental causes, and not merely the symptoms.
2) To re-examine the recommendation of the Nairobi ISWM Strategy (CCN & UNEP, 2010) in light of the recommendations from the systems analysis application.
3) Given the high prevalence of organic waste and the high promise of its valorisation as a system driver in Nairobi's waste management; to investigate current organic waste valorisation practice, and the subsequent techno-economic feasibility of expanding its contribution to the city's material recycling capacity towards achieving ISWM.

Objectives (1) & (2) are investigated and the results presented sequentially in Chapter 4 via a collation of data on Nairobi's waste system, the identification of causal/feedback relationships and development of conceptual models from this, and a systems analysis of Nairobi's waste system and re-examination of the ISWM intervention actions proposed earlier in Nairobi's ISWM Strategy (CCN & UNEP, 2010). Objective (3) is explored and presented in Chapter 5 through an investigation of current organic waste valorisation practice in Nairobi via use as livestock feed, use for compost production, and modelling the potential for medium scale biogas-to-energy plant investments in Nairobi to expand organic waste valorisation and implicitly material recycling capacity as a system driver for Nairobi's waste management towards ISWM.

6.2 Conclusions to Key Questions

In line with the objectives set, three key questions were formulated to provide a platform to meet the thesis objectives. The following conclusions were reached with respect to each key question.

6.2.1 Key Question 1

Can systems thinking as an analytical framework adequately capture the current waste situation and aid the generation of valuable insights into its causes, patterns and intervention recommendations?

The use of systems thinking approaches in solid waste management planning via systems dynamics' problem structuring and causal loop modelling and mapping as illustrated in this work in Chapter 4, provides a flexible analytical framework to capture current waste situations and to generate

behavioural insights and recommendations towards ISWM, and can add value to the conventional application of the UNEP ISWM Plan development methodology by:

- Allowing solid waste practitioners, planners and analysts to visually summarise major results and observations drawn from situational assessments, literature surveys, field surveys, and other sources pertaining to solid waste in a given area during the course of the ISWM planning process via the use of causal loop modelling and mapping. This systems map summary also has the added benefit of being able to capture observations and trends drawn from different analytical and academic disciplines. The UNEP ISWM plan development methodology currently offers no formal structure to synthesize, in the same space, the observations made from the collected waste management data; and the formulation of intervention actions in the resulting ISWM plan, even within multiple stakeholder workshops, may sometimes overlook subtle but important trends without an adequately unifying synthesis.
- Allowing the investigation of the fundamental causes of the waste challenges or problems being currently faced in an area, and the development of interventions that are both context specific and that target the fundamental behavioural causes, and not merely the common visible symptoms such as waste volumes, low collection levels, and poor financing.
- Highlighting sometimes counter-intuitive system drivers, their nature, and areas for special attention in building on existing structures to achieve ISWM goals.
- Identifying and using system leverage points to develop complementary ISWM interventions to aid in the attainment of system-wide changes relatively simply.
- Making possible the determination of the high level patterns at work beneath the surface of current waste management practices and mechanisms, and providing insights into their downstream consequences from a life cycle perspective. These insights can inform the nature of the interventions developed in an ISWM Plan and can aid in the management of solid waste more holistically.

For the case of Nairobi, the application of a systems based analysis of Nairobi's waste management, identified the presence of ten system drivers through which to influence the achievement of ISWM objectives in Nairobi. Two of these were determined to be largely out of the control of the solid waste governance structures in Nairobi, while another two were found to be currently actively driving towards ISWM goals. Three of the identified drivers were observed to be driving away from ISWM goals and require a complete reversal or eradication from the city's waste management structures to enable the city achieve its ISWM objectives; while another three, currently tending to anti-ISWM influences, were found to be flexible to manipulation so as to contribute positively to ISWM in Nairobi in future. These are outlined in Section 4.4.3.

The identification and use of system leverage points in Nairobi's waste sector also allowed the development of several additional ISWM intervention proposals through which large waste sector changes may be achieved with relatively small inputs (Section 4.4.4). The solid waste management scene in Nairobi also seems to involve a combination of two systems archetypes as defined by Braun (2002): a '*Success to the successful*' trend of private waste collection relative to the City Council, embedded within a larger '*Tragedy of the Commons*' trend – the commons being the city's economic, human and natural capital and implicitly its potential revenue base for collection service providers, whose tragic diminishing for all will be the inevitable result if the current operation and

disposal practices of both the private collectors and the City Council continue. These archetypes are elaborated in Section 4.4.2.

6.2.2 Key Question 2

Following the systems insights generated, do the interventions proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010) adequately target the fundamental causes?

The interventions proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010) were found to have targeted many of the fundamental causes leading to the current solid waste situation in Nairobi, due in part to the partial use of systems analysis in their development by the author. However, given the additional insights generated from the completed systems analysis of Nairobi's waste management in Section 4.5.2, over and above the intervention actions proposed in the Nairobi ISWM Strategy (CCN & UNEP, 2010) there is a need for the City Council Department of Environment to examine and develop policy consistent with eight extra systemic interventions. Six of these may be considered critical to the long term success of ISWM efforts in Nairobi. These are outlined in Section 4.6.2.

6.2.3 Key Question 3

What are the current organic waste valorisation practices in Nairobi and how effective are they?

It is estimated that there is open leakage and rotting of between 14% - 23% of total generated waste in the city due to open dump organic waste degradation (Section 5.1). There is a currently an interest in the use of such organic wastes as animal feed (Section 5.3.1) and for compost production in Nairobi City (Section 5.3.2). Compost production from organic waste in Nairobi is however economically unattractive under the prevalent market conditions (Section 5.3.2).

What alternatives are available if current practice is inadequate?

The anaerobic digestion of organic waste for energy shows potential to achieve radical organic waste valorisation and material recycle levels in Nairobi towards ISWM goals.

What is the techno-economic feasibility of expanding the most promising organic waste valorisation practices to increase the city's material recycling capacity and achieve ISWM goals?

From the economic modelling and analyses shown of potential medium scale biogas-to-energy plant investments in Nairobi in Section 5.3.3, the following conclusions are summarised:

- Under current energy feed-in tariffs, the requirement of a tipping fee of KShs. 1/kg waste treated (i.e. collectors pay to leave organic waste at the digester facility) would be necessary at such facilities, and yields a fair pay-back period of about 8 years for plant capital investments.
- Given the current pay back periods, the set up and operation of such biogas-to-energy digestion facilities in Nairobi would seem best suited to organisations with mandates on longer term economic planning and public benefits.
- A suitable feed-in-tariff target of about 13-14 KShs/kWh electricity (17-19 US Cents/kWh) and an organic waste tipping fee of KShs. 1/kg organic waste received at such facilities would be needed to achieve attractive payback periods of under five years for especially private investors.

6.3 Lessons for ISWM Planning in other developing African Cities

As shown in this work, the application of systems thinking based mapping and analysis techniques as illustrated in this work can add great synthesizing power and stakeholder ownership value (see 6.2.1 above) to the current UNEP ISWM plan development methodology (Section 2.3). The application of these techniques would seem most appropriate during the development of situational assessments on the prevailing waste management system, with the systems mapping continuing through the Gap analysis and identification of issues of concern through Stakeholder Consultation Workshops as prescribed in the UNEP ISWM Plan methodology. The causal loop modelling and mapping of prevailing causal relationships and feedback mechanisms in a system or organisation is possible only through input from various parties across different disciplines. As such, the application of the systems thinking techniques proposed in this work would be best achieved through dedicated sessions within the UNEP ISWM plan development steps above, in which participants would be allowed to: mentally process and conceptualise current problems and challenges, draw links between the challenges, and reach consensus on the causal and feedback relationships and behavioural patterns. The process of developing the causal loop models and system maps would also contribute to a much greater understanding and ownership by stakeholders of the resulting interventions proposed as part of an ISWM planning process that incorporates these methods.

Given that Nairobi is largely regarded to be a prime example of the unique challenges and situational experiences in developing cities on the African continent, it is likely that the observations drawn from the systems analysis of its waste management will hold to some degree in many other growing African cities. Further work however is needed in the application of systems based analyses of solid waste management in Africa and in the larger developing world, to better understand the unique fundamental causalities, experiences, and trends faced in especially the cities and urban centres in this part of the world. The Brazilian experience of 'Participatory Solid Waste Management' also shows significant potential to effectively harness the significant informal sector component of solid waste management in many developing cities, and provides an interesting research model and case study example for application in other developing cities.

Findings on organic waste valorisation practice in Nairobi strongly suggest that in order to successfully tap into the under-developed opportunities in organic waste valorisation in developing African cities as drivers towards ISWM- while a possibility - requires strong, visionary, and enterprising government support structures to provide a conducive investment environment for potential investors into such opportunities. This is exemplified by the proactive, long term government support of this sector in Germany. Organic waste valorisation in developing African cities with such a structure – the beginnings of which are emerging in Nairobi, Kenya, especially through the anaerobic digestion of organic waste for biogas at scale; shows promising potential to contribute radically to the reduction of total waste volumes currently going to landfill; and to increase the conversion of waste to resource and the reach of recycling capacity in these cities as a waste system driver towards ISWM goals.

6.4 Recommendations for further work

This work has laid the starting points for the wider scale application of systems thinking in waste management design and analysis, in particular for cities in the developing world which are characterised by high levels of growth, poverty and informality. Recommendations have already been made for revisions and additions to the ISWM strategy developed for Nairobi (section 4.6.2). In this final section of the dissertation, recommendations are made i) for revisions to the UNEP ISWM planning methodology in general, and ii) for further research on the use of systems approaches in ISWM.

On the strength of this work, the application of soft systems approaches in the UNEP ISWM planning methodology as proposed in section 6.3 should be tested in field trials paralleled with academic research in future ISWM planning projects by UNEP for other developing cities after Nairobi. This would help planners to better understand the value and synergies between system driver, leverage and archetype analyses; to discern and improve stakeholder engagement with these techniques; and to refine their possible application within the UNEP ISWM planning framework.

The ISWM planning exercise in Nairobi highlighted some knowledge gaps in the city's waste management. Key areas for further work include a need to better understand quantitatively and normatively the extent, supply and market chain, and contribution or potential, of the use of organic solid wastes as animal feed in Nairobi (see Section 5.3.1); and to quantitatively understand the physical and chemical nature of Nairobi's solid waste fractions, beyond waste compositions and volumes, so as to ease future pilot trials and applications of new solid waste treatment technologies (e.g. as in biogas-to-energy modelling in Section 3.3.2).

The Brazilian experience of 'Participatory Solid Waste Management' and its seeming success in increasing solid waste recovery and recycling levels in that country (see Section 2.2.3.2), also raises interesting research questions as to the reasons behind its success and its potential for replicability in ISWM planning and implementation in other developing cities. Possible synergies between the purely participatory approach and the use of systems thinking in ISWM planning as in this work should be explored.

More generally, there is also a need in waste management to explore in more depth the meaning of Mebratu's (1998) cosmic interdependence model as a conceptualisation of the world for the design of sustainable human systems and the implications of this for waste management analysis and design. This would serve the intellectual body the benefit of parallel analyses by other workers to serve either as confirmation, or to refine the lines of thoughts put forward in this thesis. It is also necessary to investigate the completeness of Mebratu's (1998) model in conceptualising the world, especially as regards the existence of a possible separate metaphysical dimension to how human agents view, interact and shape the physical world, i.e. the non-physical elements that inform their worldview. This is because the generation of knowledge and development cannot exist without a presuming set of assumptions or an underlying philosophy. The scientific method illustrates this with its three core steps: the observation of an event, the formulation of a hypothesis or explanation to that event, and the experimental or experiential testing of the hypothesis; after which it is accepted as valid or not. The formulation however of a hypothesis is not straightforward and employs reasonable imagination and assumption, making it in essence a step equivalent to a leap of

'reasonable faith'. As such it is necessary to investigate the validity and spectrum of applicability of the underlying presumptions behind any systemic conceptualisation of the world, a validity which need not necessarily be limited to the physical and tangible only as in the hard sciences, but that is also open to the experiential and spiritual from the social sciences. An objective and more accurate depiction of the world and all its systemic influences – physical and non-physical, can in turn be expected to lead to a greater understanding of not only the meaning of, but also the pathways to true sustainable development across all spheres of human activity and living.

Appendix I: Spatial distribution and physical nature of the communal waste collection points and illegal dumps sampled in Nairobi

An example of the typical spatial distribution and number of communal waste collection points sampled in each zone in Nairobi during the waste characterisations in 2009 is shown in Figure 23 and Figure 24.

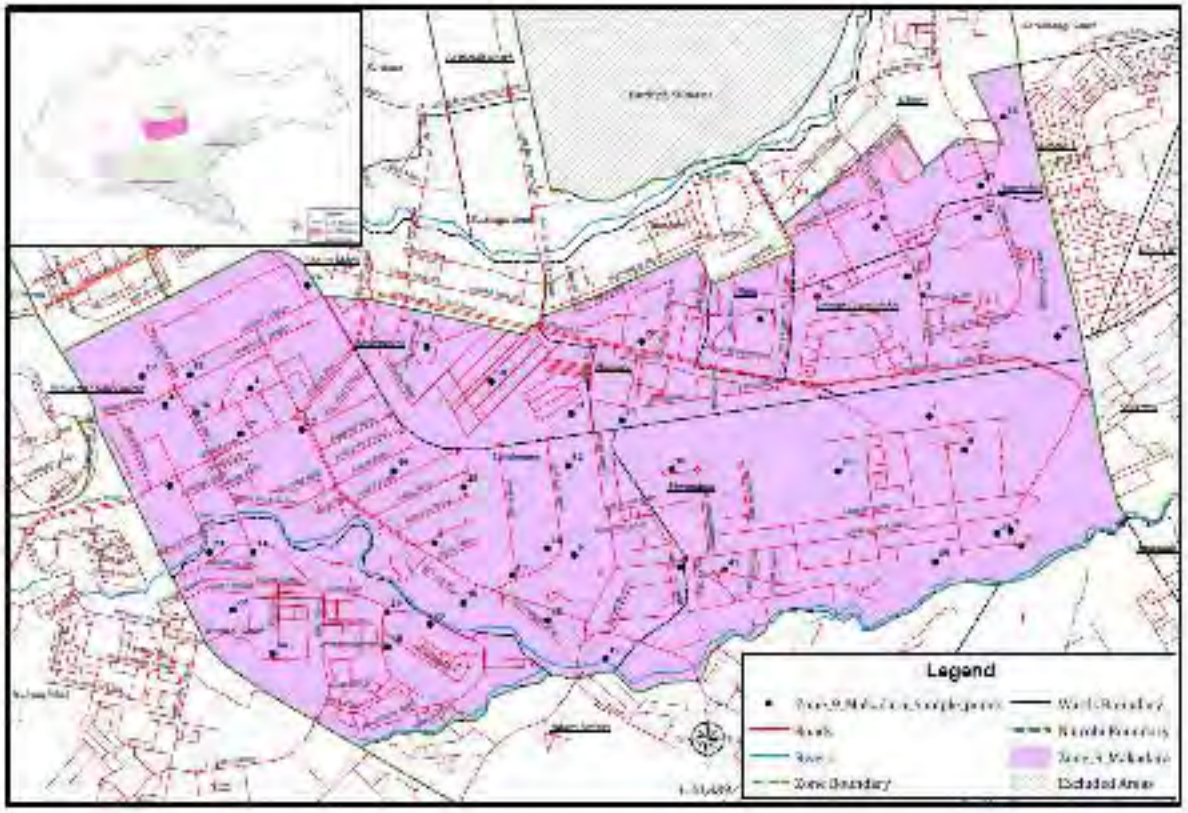

Figure 23: An example of the typical spatial distribution and number of communal waste collection points and illegal dumps sampled for waste characterisations at collection point level in each zone. Mutadara zone shown here.

Appendix I: Spatial distribution and physical nature of the communal waste collection points and illegal dumps sampled in Nairobi

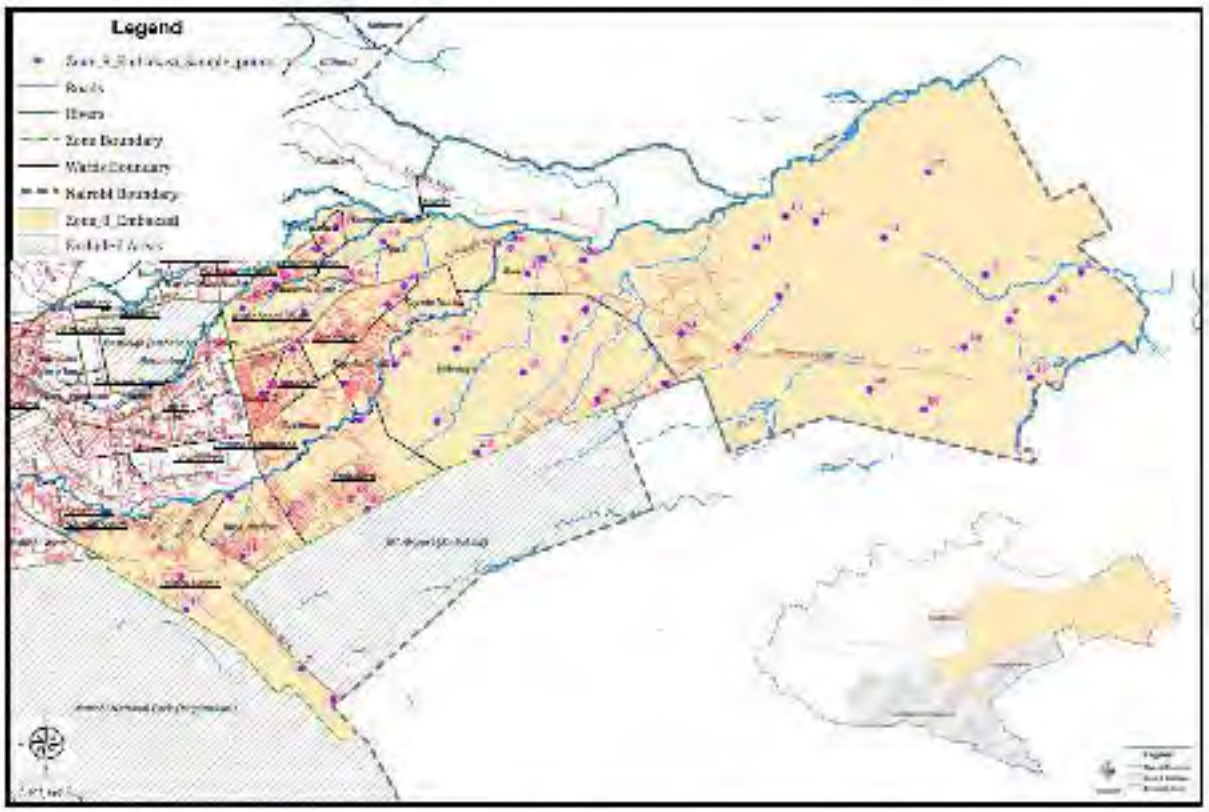

Figure 24: An example of the typical spatial distribution and number of communal waste collection points and illegal dumps sampled for waste characterisation at collection point level in each zone. Embakasi zone shown here

The pictures below taken from various zones in Nairobi depict what communal waste collection points typically looked like during the 2009 waste characterisation surveys.

Appendix I: Spatial distribution and physical nature of the communal waste collection points and illegal dumps sampled in Nairobi

Figure 25: Examples of Communal Waste Collection points in Nairobi

Appendix II: Examples of Waste Recovery and Trading Activity in Nairobi

The pictures below illustrate some of the waste recovery and trading activity carried out in Nairobi City. Shown below are various waste traders and dealers at their premises.

Figure 26: Examples of Waste Recovery & Trading activity in Nairobi

Appendix III: Logistic projection of Nairobi's population growth

Nairobi recorded Population growth (UNEP & UN-Habitat - Kenya 2007)

Table 16: Recorded population growth in Nairobi

Year	Nairobi Population	Population in millions	% Increase	Average annual increase
1906	11 512	0.0115		
1928	29 864	0.0299	159.4	7.2
1931	47 919	0.0479	60.5	20.2
1936	49 600	0.0496	3.5	0.7
1944	108 900	0.1089	119.6	14.9
1962	343 500	0.3435	215.4	12.0
1969	509 286	0.5093	48.3	6.9
1979	827 775	0.8278	62.5	6.3
1989	1 324 570	1.3246	60.0	6.0
1999	2 143 254	2.1433	61.8	6.2
2000	2 290 049	2.2900	6.8	6.8
2001	2 379 741	2.3797	3.9	3.9
2002	2 470 850	2.4709	3.8	3.8
2003	2 563 297	2.5633	3.7	3.7
2004	2 656 997	2.6570	3.7	3.7
2005	2 751 860	2.7519	3.6	3.6
2009	3 265 000	3.2650	18.6	4.7

Nairobi Population projections under logistic conditions

Modelling Assumptions (see modelling methodology in Section 2.3.2.8)

City population carrying capacity assumed (millions of residents), K = 9 million
Initial annual population growth rate assumed (%) = 6.5%, based on early population history

R_o = 0.065

N_o = 0.0299

r = 0.065216403

Projection Results overleaf >>>

Projected Population			
Year	Time, t (years)	Population after time, t N(t)	% Annual Population Growth
1906			
1928	0	0.0299	
1931	3	0.0363	
1936	8	0.0502	
1944	16	0.0843	
1962	34	0.2670	
1969	41	0.4144	
1979	51	0.7631	
1992	64	1.6004	
1998	**70**	**2.1811**	
1999	71	2.2907	5%
2000	72	2.4038	5%
2001	73	2.5205	5%
2002	74	2.6405	5%
2003	75	2.7638	5%
2004	**76**	**2.8902**	5%
2005	77	3.0196	4%
2008	80	3.4239	13%
2009	**81**	**3.5633**	4%
2010	82	3.7046	4%
2011	83	3.8475	4%
2012	84	3.9918	4%
2013	85	4.1372	4%
2014	86	4.2833	4%
2015	87	4.4299	3%
2016	88	4.5766	3%
2017	89	4.7231	3%
2018	90	4.8692	3%
2019	91	5.0145	3%
2020	92	5.1588	3%
2021	93	5.3016	3%
2022	94	5.4428	3%
2023	95	5.5821	3%
2024	96	5.7193	2%
2025	97	5.8540	2%
2026	98	5.9861	2%
2027	99	6.1154	2%
2028	100	6.2417	2%
2029	101	6.3649	2%
2030	102	6.4847	2%
2031	103	6.6012	2%
2032	104	6.7142	2%
2033	105	6.8236	2%
2034	106	6.9294	2%
2035	107	7.0315	1%

Table 17: Logistic projections of Nairobi population growth

Appendix IV: ANOVA (one-way) of residential waste compositions at source, and at communal waste collection points & illegal dumps

- Analysis of Variance between residential Paper compositions at immediate source, and at communal waste collection points and illegal dumps. Evidence of Statistical difference: Yes, $F_{value} > F_{critical}$

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Source (%)	568	6754.654481	11.89199733	199.499743
Collection Pt (%)	163	1450.561771	8.899151969	30.18853024

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1134.454592	1	1134.454592	7.008212438	0.008288926	6.66977195
Within Groups	118006.8962	729	161.8750291			
Total	119141.3508	730				

- Analysis of Variance between Glass composition at immediate source, and at communal waste collection points and illegal dumps. Evidence of Statistical difference: Yes, $F_{value} > F_{critical}$

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Source (%)	568	1105.711757	1.946675629	48.5592508
Collection Pt (%)	163	912.5769206	5.598631415	28.85903652

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1689.155318	1	1689.155318	38.23225038	1.04557E-09	6.66977195
Within Groups	32208.25912	729	44.1814254			
Total	33897.41444	730				

- Analysis of Variance between residential Plastics compositions at immediate source, and at communal waste collection points and illegal dumps. Evidence of Statistical difference: No, $F_{value} < F_{critical}$

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Source (%)	568	9034.772779	15.9062901	211.6969521
Collection Pt (%)	163	2511.30949	15.40680669	73.26004497

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	31.59808085	1	31.59808085	0.17463949	0.676144098	6.66977195
Within Groups	131900.2991	729	180.933195			
Total	131931.8972	730				

- Analysis of Variance between residential Organic/Biodegradables compositions at immediate source, and at communal waste collection points and illegal dumps. Evidence of Statistical difference: Yes, $F_{value} > F_{critical}$

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Source (%)	568	33268.20931	58.57079104	562.780232
Collection Pt (%)	163	7508.475924	46.06426947	343.9556063

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	19810.3266	1	19810.3266	38.53005705	9.04472E-10	6.66977195
Within Groups	374817.1998	729	514.1525374			
Total	394627.5264	730				

- Analysis of Variance between residential Metal compositions at immediate source, and at communal waste collection points and illegal dumps. Evidence of Statistical difference: No, $F_{value} < F_{critical}$

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Source (%)	568	1149.47032	2.023715353	42.66307886
Collection Pt (%)	163	375.2538013	2.30217056	10.22776843

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	9.820401685	1	9.820401685	0.276980324	0.598847358	6.66977195
Within Groups	25846.8642	729	35.4552321			
Total	25856.6846	730				

- Analysis of Variance between residential Residuals or 'Other' waste compositions at immediate source, and at communal waste collection points and illegal dumps. Evidence of Statistical difference: Yes, $F_{value} > F_{critical}$

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Source (%)	568	5487.181354	9.660530552	196.1939604
Collection Pt (%)	163	3541.822092	21.72896989	196.6742863

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	18446.78928	1	18446.78928	93.97210163	5.53908E-21	6.66977195
Within Groups	143103.2099	729	196.3006995			
Total	161549.9992	730				

Appendix V: Causal Loop Map of Nairobi's solid waste management system – Larger format

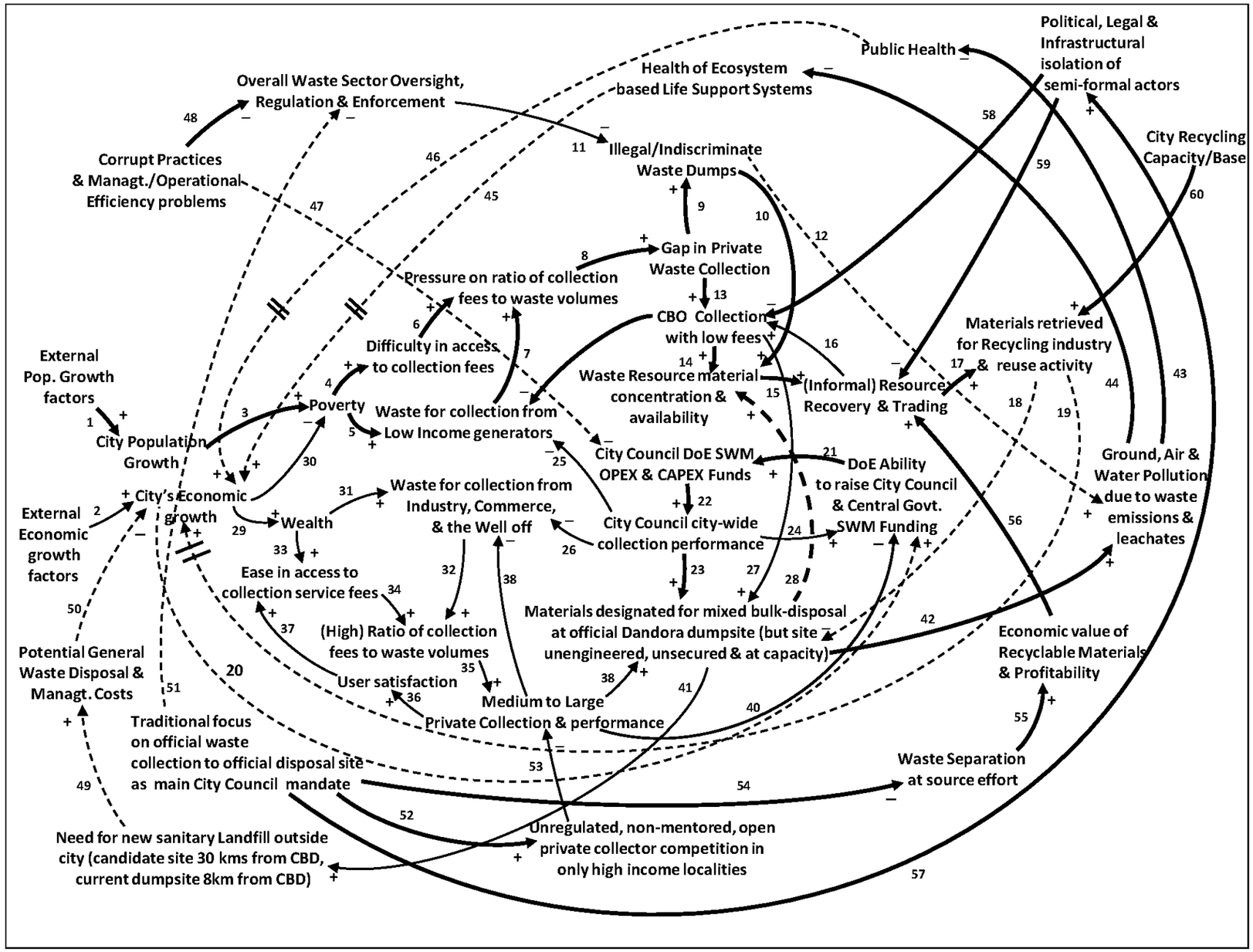

Figure 27: Causal Loop Map of Nairobi's solid waste management system (large format version)

Appendix VI: Alternate Material Balance of Organic waste degradation in Nairobi

An alternate material balance for the degradation of residential organic waste in Nairobi, using glass and not the 'other'/residual fraction as the tie component (as in Table 13) – on account of glass's declining recycling use and undesirability in informal waste recovery in Nairobi (see Section 4.3.5.1 & 4.3.5.4), is shown in Table 18 below; and confirms the sharp loss of organic waste at collection points and illegal dumps as discussed in Section 5.1.

Table 18: Residential waste material balance between immediate source, and communal collection points and illegal dumps in Nairobi using the glass fraction as a tie component (to 2 s.f.)

Residential Waste Compositions (%)

Waste type	At Immediate Source	At Collection Pts & Illegal Dumps
Organics	58.6%	46.1%
Paper	11.9%	8.9%
Plastic	15.9%	15.4%
Glass	1.9%	5.6%
Metals	2.0%	2.3%
Other	9.7%	21.7%

Waste Quantities (tonnes)

Material Quantities	At Immediate Source (tonnes)	Materials at Collection Pts & Illegal Dumps (tonnes)	Materials that disappear btn Source & Collection Pts or illegal dumps due to recovery & degradation (tonnes)
Organics	59	16 (= 46.1% x 34)	43
Paper	12	3.0 (= 8.9% x 34)	9.0
Plastic	16	5.2 (= 15.4% x 34)	11
Glass	1.9 →	1.9 (assume untouched from generation)	0.0
Metals	2.0	0.8 (= 2.3% x 34)	1.2
Other/Residual	10	7.4 (= 21.7% x 34)	2.6
SUM	**100**	**34** (= Glass 1.9 tonnes ÷ 5.6% compositional fraction at this point)	

Appendix VII: Modelling calculations and techno-economic results of hypothetical biogas-to-energy plant in Nairobi

The techno-economic modelling inputs and results described in Sections 3.3.2 and 5.3.3.4 for a hypothetical 10tonne/day biogas-to-energy plant in Nairobi are shown in detail below.

Model Inputs

Exchange Rate (KShs/US$) :	74.5	
CAPEX for 248m^3 Keekonyoike Wet Solids Biogas Plant including		
associated support Infrastrucure & Generator-Engine Set (KShs) :	8,000,000	
(US$) :	107,383	
Generator-Engine (Genset) energy conversion Efficiency:	25%	
Recommended Digester Feed Solids Concentration :	10%	
Approx. Total Solids in urban organic solid waste:	20%	
Approx. Volatile Solids in solid fraction:	90%	
Average Biogas Yield :	0.5	m^3/kg VS
Average CH_4 concentration in Biogas:	55%	
Approx. Retention time of organic substrate in digester (days) :	40	
Average Volatile Solids reduction in digester:	75%	
Digester Oversight & Maintenance		
Technician wages/month (KShs) - 1 full time technician	50,000	
Assistants/Casual Labourers wages/month (KShs) (assume 2):	15,000	(x2)

Modelling Results overleaf >>>>>>.....

Appendix VII: Modelling calculations and techno-economic results of hypothetical biogas-to-energy plant in Nairobi

Table 19: Detailed biogas-to-energy techno-economic modelling calculations and results for 10tonne/day hypothetical plant in Nairobi

Waste incentive or tipping fee (KShs/kg)	Elect. Selling Price (KShs/kWh)	Approx. TS in Feed (kg/day)	Total feed to digester (kg/day)	Total Slurry Feed Flow (m^3/day)	Total Digester Size (m^3)	Total Plant CAPEX incl. Genset		Annual OPEX (KShs)	VS (kg/day)	Biogas Yield (m^3/day)	CH_4 Yield (m^3/day)	Total Energy Potential (kWh/day)	Energy converted to Electricity (kWh/day)	Total Annual Elect. Sales (KShs)	Annual Gross Profit (KShs)	Approx. R.O.I	Approx. Payback Period (Years)
						(KShs)	(US$)										
4.0	5.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	1,869,986	-13,690,014	-33.7%	-3.0
3	5.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	1,869,986	-10,040,014	-24.7%	-4.0
2	5.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	1,869,986	-6,390,014	-15.7%	-6.4
1	5.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	1,869,986	-2,740,014	-6.7%	-14.8
0.5	5.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	1,869,986	-915,014	-2.3%	-44.4
0	5.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	1,869,986	909,986	2.2%	44.6
-0.5	5.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	1,869,986	2,734,986	6.7%	14.8
-1	5.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	1,869,986	4,559,986	11.2%	8.9
-2	5.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	1,869,986	8,209,986	20.2%	4.9
-3	5.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	1,869,986	11,859,986	29.2%	3.4
-4	5.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	1,869,986	15,509,986	38.2%	2.6
4.0	6.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	2,243,984	-13,316,017	-32.8%	-3.0
3	6.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	2,243,984	-9,666,017	-23.8%	-4.2
2	6.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	2,243,984	-6,016,017	-14.8%	-6.7
1	6.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	2,243,984	-2,366,017	-5.8%	-17.2
0.5	6.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	2,243,984	-541,017	-1.3%	-75.0
0	6.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	2,243,984	1,283,984	3.2%	31.6
-0.5	6.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	2,243,984	3,108,984	7.7%	13.1
-1	6.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	2,243,984	4,933,984	12.2%	8.2
-2	6.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	2,243,984	8,583,984	21.1%	4.7
-3	6.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	2,243,984	12,233,984	30.1%	3.3
-4	6.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	2,243,984	15,883,984	39.1%	2.6
4.0	7.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	2,617,981	-12,942,019	-31.9%	-3.1
3	7.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	2,617,981	-9,292,019	-22.9%	-4.4

Appendix VII: Modelling calculations and techno-economic results of hypothetical biogas-to-energy plant in Nairobi

Waste incentive or tipping fee (KShs/kg)	Elect. Selling Price (KShs/kWh)	Approx. TS in Feed (kg/day)	Total feed to digester (kg/day)	Total Slurry Feed Flow (m^3/day)	Total Digester Size (m^3)	Total Plant CAPEX incl. Genset (KShs)	(US$)	Annual OPEX (KShs)	VS (kg/day)	Biogas Yield (m^3/day)	CH_4 Yield (m^3/day)	Total Energy Potential (kWh/day)	Energy converted to Electricity (kWh/day)	Total Annual Elect. Sales (KShs)	Annual Gross Profit (KShs)	Approx. R.O.I	Approx. Payback Period (Years)
2	7.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	2,617,981	-5,642,019	-13.9%	-7.2
1	7.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	2,617,981	-1,992,019	-4.9%	-20.4
0.5	7.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	2,617,981	-167,019	-0.4%	-243.1
0	7.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	2,617,981	1,657,981	4.1%	24.5
-0.5	7.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	2,617,981	3,482,981	8.6%	11.7
-1	7.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	2,617,981	5,307,981	13.1%	7.6
-2	7.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	2,617,981	8,957,981	22.1%	4.5
-3	7.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	2,617,981	12,607,981	31.1%	3.2
-4	7.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	2,617,981	16,257,981	40.0%	2.5
4.0	8.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	2,991,978	-12,568,022	-31.0%	-3.2
3	8.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	2,991,978	-8,918,022	-22.0%	-4.6
2	8.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	2,991,978	-5,268,022	-13.0%	-7.7
1	8.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	2,991,978	-1,618,022	-4.0%	-25.1
0.5	8.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	2,991,978	206,978	0.5%	196.1
0	8.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	2,991,978	2,031,978	5.0%	20.0
-0.5	8.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	2,991,978	3,856,978	9.5%	10.5
-1	8.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	2,991,978	5,681,978	14.0%	7.1
-2	8.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	2,991,978	9,331,978	23.0%	4.4
-3	8.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	2,991,978	12,981,978	32.0%	3.1
-4	8.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	2,991,978	16,631,978	41.0%	2.4
4.0	9.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	3,365,975	-12,194,025	-30.0%	-3.3
3	9.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	3,365,975	-8,544,025	-21.0%	-4.8
2	9.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	3,365,975	-4,894,025	-12.1%	-8.3
1	9.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	3,365,975	-1,244,025	-3.1%	-32.6
0.5	9.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	3,365,975	580,975	1.4%	69.9
0	9.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	3,365,975	2,405,975	5.9%	16.9

Appendix VII: Modelling calculations and techno-economic results of hypothetical biogas-to-energy plant in Nairobi

Waste incentive or tipping fee (KShs/kg)	Elect. Selling Price (KShs/kWh)	Approx. TS in Feed (kg/day)	Total feed to digester (kg/day)	Total Slurry Feed Flow (m^3/day)	Total Digester Size (m^3)	Total Plant CAPEX incl. Genset (KShs)	(US$)	Annual OPEX (KShs)	VS (kg/day)	Biogas Yield (m^3/day)	CH_4 Yield (m^3/day)	Total Energy Potential (kWh/day)	Energy converted to Electricity (kWh/day)	Total Annual Elect. Sales (KShs)	Annual Gross Profit (KShs)	Approx. R.O.I	Approx. Payback Period (Years)
-0.5	9.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	3,365,975	4,230,975	10.4%	9.6
-1	9.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	3,365,975	6,055,975	14.9%	6.7
-2	9.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	3,365,975	9,705,975	23.9%	4.2
-3	9.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	3,365,975	13,355,975	32.9%	3.0
-4	9.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	3,365,975	17,005,975	41.9%	2.4
4.0	10.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	3,739,973	-11,820,028	-29.1%	-3.4
3	10.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	3,739,973	-8,170,028	-20.1%	-5.0
2	10.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	3,739,973	-4,520,028	-11.1%	-9.0
1	10.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	3,739,973	-870,028	-2.1%	-46.7
0.5	10.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	3,739,973	954,973	2.4%	42.5
0	10.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	3,739,973	2,779,973	6.8%	14.6
-0.5	10.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	3,739,973	4,604,973	11.3%	8.8
-1	10.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	3,739,973	6,429,973	15.8%	6.3
-2	10.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	3,739,973	10,079,973	24.8%	4.0
-3	10.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	3,739,973	13,729,973	33.8%	3.0
-4	10.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	3,739,973	17,379,973	42.8%	2.3
4.0	11.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	4,113,970	-11,446,030	-28.2%	-3.5
3	11.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	4,113,970	-7,796,030	-19.2%	-5.2
2	11.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	4,113,970	-4,146,030	-10.2%	-9.8
1	11.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	4,113,970	-496,030	-1.2%	-81.8
0.5	11.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	4,113,970	1,328,970	3.3%	30.5
0	11.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	4,113,970	3,153,970	7.8%	12.9
-0.5	11.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	4,113,970	4,978,970	12.3%	8.2
-1	11.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	4,113,970	6,803,970	16.8%	6.0
-2	11.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	4,113,970	10,453,970	25.8%	3.9
-3	11.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	4,113,970	14,103,970	34.7%	2.9

Appendix VII: Modelling calculations and techno-economic results of hypothetical biogas-to-energy plant in Nairobi

Waste incentive or tipping fee (KShs/kg)	Elect. Selling Price (KShs/kWh)	Approx. TS in Feed (kg/day)	Total feed to digester (kg/day)	Total Slurry Feed Flow (m^3/day)	Total Digester Size (m^3)	Total Plant CAPEX incl. Genset		Annual OPEX (KShs)	VS (kg/day)	Biogas Yield (m^3/day)	CH_4 Yield (m^3/day)	Total Energy Potential (kWh/day)	Energy converted to Electricity (kWh/day)	Total Annual Elect. Sales (KShs)	Annual Gross Profit (KShs)	Approx. R.O.I	Approx. Payback Period (Years)
						(KShs)	(US$)										
-4	11.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	4,113,970	17,753,970	43.7%	2.3
4.0	12.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	4,487,967	-11,072,033	-27.3%	-3.7
3	12.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	4,487,967	-7,422,033	-18.3%	-5.5
2	12.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	4,487,967	-3,772,033	-9.3%	-10.8
1	12.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	4,487,967	-122,033	-0.3%	-332.7
0.5	12.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	4,487,967	1,702,967	4.2%	23.8
0	12.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	4,487,967	3,527,967	8.7%	11.5
-0.5	12.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	4,487,967	5,352,967	13.2%	7.6
-1	12.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	4,487,967	7,177,967	17.7%	5.7
-2	12.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	4,487,967	10,827,967	26.7%	3.7
-3	12.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	4,487,967	14,477,967	35.7%	2.8
-4	12.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	4,487,967	18,127,967	44.7%	2.2
4.0	13.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	4,861,964	-10,698,036	-26.4%	-3.8
3	13.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	4,861,964	-7,048,036	-17.4%	-5.8
2	13.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	4,861,964	-3,398,036	-8.4%	-11.9
1	13.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	4,861,964	251,964	0.6%	161.1
0.5	13.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	4,861,964	2,076,964	5.1%	19.5
0	13.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	4,861,964	3,901,964	9.6%	10.4
-0.5	13.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	4,861,964	5,726,964	14.1%	7.1
-1	13.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	4,861,964	7,551,964	18.6%	5.4
-2	13.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	4,861,964	11,201,964	27.6%	3.6
-3	13.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	4,861,964	14,851,964	36.6%	2.7
-4	13.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	4,861,964	18,501,964	45.6%	2.2
4.0	14.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	5,235,962	-10,324,039	-25.4%	-3.9
3	14.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	5,235,962	-6,674,039	-16.4%	-6.1

Appendix VII: Modelling calculations and techno-economic results of hypothetical biogas-to-energy plant in Nairobi

Waste Incentive or tipping fee (KShs/kg)	Elect. Selling Price (KShs/kWh)	Approx. TS in Feed (kg/day)	Total feed to digester (kg/day)	Total Slurry Feed Flow (m^3/day)	Total Digester Size (m^3)	Total Plant CAPEX incl. Genset (KShs)	(US$)	Annual OPEX (KShs)	VS (kg/day)	Biogas Yield (m^3/day)	CH_4 Yield (m^3/day)	Total Energy Potential (kWh/day)	Deliverable Electricity Potential (kWh/day)	Total Annual Sales (KShs)	Annual Gross Profit (KShs)	Approx. R.O.I	Approx. Payback Period (Years)
2	14.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	5,235,962	-3,024,039	-7.4%	-13.4
1	14.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	5,235,962	625,962	1.5%	64.9
0.5	14.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	5,235,962	2,450,962	6.0%	16.6
0	14.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	5,235,962	4,275,962	10.5%	9.5
-0.5	14.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	5,235,962	6,100,962	15.0%	6.7
-1	14.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	5,235,962	7,925,962	19.5%	5.1
-2	14.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	5,235,962	11,575,962	28.5%	3.5
-3	14.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	5,235,962	15,225,962	37.5%	2.7
-4	14.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	5,235,962	18,875,962	46.5%	2.2
4.0	15.0	2000	20000	20	960	40,595,084	544,900	15,560,000	1800	675	371	4099	1024.65	5,609,959	-9,950,041	-24.5%	-4.1
3	15.0	2000	20000	20	960	40,595,084	544,900	11,910,000	1800	675	371	4099	1024.65	5,609,959	-6,300,041	-15.5%	-6.4
2	15.0	2000	20000	20	960	40,595,084	544,900	8,260,000	1800	675	371	4099	1024.65	5,609,959	-2,650,041	-6.5%	-15.3
1	15.0	2000	20000	20	960	40,595,084	544,900	4,610,000	1800	675	371	4099	1024.65	5,609,959	999,959	2.5%	40.6
0.5	15.0	2000	20000	20	960	40,595,084	544,900	2,785,000	1800	675	371	4099	1024.65	5,609,959	2,824,959	7.0%	14.4
0	15.0	2000	20000	20	960	40,595,084	544,900	960,000	1800	675	371	4099	1024.65	5,609,959	4,649,959	11.5%	8.7
-0.5	15.0	2000	20000	20	960	40,595,084	544,900	-865,000	1800	675	371	4099	1024.65	5,609,959	6,474,959	16.0%	6.3
-1	15.0	2000	20000	20	960	40,595,084	544,900	-2,690,000	1800	675	371	4099	1024.65	5,609,959	8,299,959	20.4%	4.9
-2	15.0	2000	20000	20	960	40,595,084	544,900	-6,340,000	1800	675	371	4099	1024.65	5,609,959	11,949,959	29.4%	3.4
-3	15.0	2000	20000	20	960	40,595,084	544,900	-9,990,000	1800	675	371	4099	1024.65	5,609,959	15,599,959	38.4%	2.6
-4	15.0	2000	20000	20	960	40,595,084	544,900	-13,640,000	1800	675	371	4099	1024.65	5,609,959	19,249,959	47.4%	2.1

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