Shaping and delivering tomorrow's sustainable municipal solid waste management system: proposal for a structured data management infrastructure

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Abstract: The monitoring and collection of municipal solid waste (MSW) data have been a daunting task. The development of a digital mapping, data collection, and data reporting system, allows for ease of data management and creation of a standardised system. This study develops a waste mapping and tracking system based on a structured ontological framework for an improved waste management system. The ontology is based on a four-level data framework in a zoned waste management system within a municipal area, regional or national boundaries. The waste flow system is designed to connect all facilities and activities in the zone and flexible to allow inter-zonal access to facilities that are existing outside a zone. Data tagging and collection strategies are developed to provide the vocabulary and standard for data encoding and recording of all knowledge-based information to help in the decision-making rules.

Keywords: structured data management; sustainable municipal solid waste management; waste management system flows; waste mapping and tracking system; ontological framework; activity nodes; four-levels data framework; waste management zones; zoned waste management system; data encoding and recording; knowledge-based information; decision-making rules.

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1 Introduction

According to Staniskis (2005), sustainability requires that resource conservation measures should be adopted. Therefore, in sustainable MSW management, it is necessary that attention is given to more than just existing waste. Serious attention should be given to waste minimisation through eco-design. Within the range of instruments that can lead to sustainability, waste reduction appears to be producing greater positive results than that which the traditional waste management hierarchy would suggest. Agreeing on what constitutes a waste in a system is crucial in deciding the system of material flow. So more efforts are required to evolve and further develop the theory on which to base our waste management which will help in attaining a more in-depth description of the waste management domain (Staniskis, 2005). In turn, this will assist in strategising to reduce waste generation at all stages.

Over the last few years, cities around the world have risen against waste generation and disposal, fighting landfilling and incineration and in many cases stopping them. This behaviour is in the spirit of sustainability in waste management and sustainable development. To show the seriousness in this fight against disposal, strategies have been articulated and developed to guide decision makers in municipal solid waste management which include waste management hierarchy and zero waste thinking.

The concept of zero waste which is a desire to create sustainable communities and present vast opportunities for employment and local economic development emerged at about 1985. According to Seldman (2016), zero waste started from the 'total recycling' concept of Dr. Daniel Knapp of Urban Ore, Berkeley, CA. This concept transformed to 'No Waste by 2010' in Australia and finally took the term 'zero waste' at the first Zero Waste Conference in Kataia, New Zealand in December 2000.

Waste management hierarchy is an attempt in arranging waste management in order of preference for actions focusing on waste reduction and management (Mark et al., 2013), hence establishing a hierarchy of preferred management strategies based on sustainability, as a result of environmental impact, efficiency of resource utilisation and energy consumption (Hansen et al., 2002)

Zero waste, on the other hand, is a philosophical, pragmatic, and visionary goal, strategic in maintaining natural cycles, where all discarded material are seen as a resource for others to use. Therefore, it is a practical tool seeking to eliminate waste, but not to manage it (Zero Waste Europe, 2017). Zero waste is a new brand in MSWM being adopted for change and diverse, flexible range of management policies. The zero waste concept utilises available technologies and any actions aimed at efficient resource use starting with and include; eco-design of products, industrial ecological thinking, cleaner production, extended producer responsibility (in managing the residues of their products). It also includes sustainable consumption (products that are contributing to the quality of life of the people but consume less of natural resources and less toxic release to the environment), educating the local populace and help them in domestic economic development, up to waste minimisation and resource recovery at the end of the pipe.

Therefore, the experience in the field of sustainability and waste minimisation has shown that sustainable development cannot be achieved without deliberate and fundamental changes in the ways societies produce and consume (OECD, 2001, 2002; UNEP, 2012; United Nations, 2012). Today, making a good decision for effective municipal solid waste management (MSWM) that will result in a sustainable waste management system (SWMS) is becoming more challenging. This is because MSWM (and of course, all waste management system) comprises of several parts and functions which interact with each other as in Figure 1, to produce results. The scale and level of interaction of these various parts and components differ from city to city and country to country, depending on the level of development, available funding, and the structure of the waste management system.

There is great diversity in the approach to sustainability in waste management which is hampered by lack of data (Kumar et al., 2017; Morton, 2017). Different drivers are important to different cities depending on the circumstances within the city environment. Asking decision makers what is the most important influencer in their waste management policy formulation produces a wide range of responses. Therefore, it is becoming very critical and important to provide systems that are capable of considering and representing these different elements within a complex waste management (WM) system decision tool. Knowledge management technologies (KMTs) driven by data are proving to be highly promising as a solution to these increasing complexities in WM. Hence the position of knowledge becomes very important.

Figure 1 Waste management performance and the various contributing factors (see online version for colours)

According to Liao (2003), "the power of knowledge is a very important resource for preserving valuable heritage, learning new things, solving problems, creating core competences, and initiating new situations for both individual and organisations now and in the future". The needed knowledge can be built through data consolidation resulting from a structured waste management system. This proposal incorporates this belief in a holistic assessment of the MSWM to identify the relevant data/information to be exploited in knowledge gathering, which will enrich the conceived management system and be able to produce the expected result. Hence, an ontological framework that captures the relationships between these various data/position locations and flow system and allows the inference of valid combinations of scientific resources resulting thereof, to produce new data. These various positions within the waste management system where activities are taking place are designated as ‘activity nodes’ and include waste generation points/area, waste management facilities, and may include the waste flow system, because of the incidence of pollution resulting from energy use. The identification of points of interest where data collection occurs for the purpose of ease of tagging, the definition of standards and management of generated data is quite critical.

The ‘activity nodes’ are identified as the particular point of activity within a zone. This can be defined by a point (using a pair of geographic coordinates) or polygon (using series of geographic coordinates), depending on the level of activity within the node. While a zone within a municipal area is a geographically defined area with specific boundaries, so designated for the purpose of planning to collect the necessary data and design the management of MSW generated thereof. The size and number of zones within the municipal area can be reviewed from time to time to enhance the efficiency of the waste management system.

2 Scenario for a sustainable municipal solid waste management

WM is a current burning issue globally. This is because of the concern over the economic, environmental and social-cultural impacts of unsustainable WM practices. In general, data required for effective WM are lacking. There is an increasing need for data for research and better decision making. Even where these data exist, the reliability is questionable and assumptions are applied (Bogner and Mathews, 2003). This is due to some suppositious doctrine that WM scenarios are too complex to be mapped and reduced to numerical data. This thinking being as a result of the uncoordinated nature of waste movement which makes the waste flows within municipalities look complex and impossible to be tracked. This believes and thinking has resulted in neglect and difficulty in data collection.

In this present situation, waste generation data and composition (for example), does not have the same standard of representation within the same country or even municipality (Mertins et al., 1999). And since many other related data/information resulting from WM depends on generation and composition, the uncertainties resulting from their values as determined today, leads to unreliable results from analyses carried out for the purpose of decision making. Although efforts are being made around the world regarding the systemic and syntactic heterogeneity in WM data (University of Illinois at Urbana-Champaign, 2009), the problem has persisted leading to series of assumptions and generalised data in issues concerning WM.

Added to these are increasing number of sources of waste and changing composition/characteristics, making WM and disposal a more complex adventure, coupled with the increasing demand for more processes and advanced monitoring and control systems. Hence, decision makers and practitioners are confronted by many challenges, which include data extraction, data integration, the modalities to be adopted in collecting these data and the form the data will take to make it useful in the establishment of a SWMS. Hence, a mix of general and specific elements of policy dynamics in the evolution and adoption of waste management systems in this complex scenario is important (UNCRD, UNEP-RRCAP and IGNES, 2009).

To bring together existing data sources (which have been neglected) into an acceptable information and computational system useful in managing a sustainable system, it is necessary to exploit their semantic relationship. An ontological framework that captures these relationships and permits the use of valid combinations of these scientific resources to produce new data is therefore adopted. This is showing how a knowledge-base that commits to an ontology can be used to generate a workflow for a multiplicity of resources within the system.

3 System design concepts

The existing MSWM systems being implemented around the world emerge through ad hoc arrangement to resolve emerging crises from the waste management system. MSWM has not been incorporated as part of the municipal environmental planning regime.

There is a substantial gap between the various environmental planning models and waste management in our cities and towns. The existing evidence on the negative impacts of unsustainable waste management has not changed the approach and view of decision makers and planners in conceptualising a new policy which is incorporating waste management in the planning schedule (code) of cities and towns. The result is a waste management system that results in high environmental, economic and social costs to man and the ecosystem. This understanding is the motivation for the conceptualisation of this research – to establish a link between the design of the emerging city environment and the sustainable waste management necessary to effectively manage the resultant MSW. Structuring the city framework to facilitate easy waste data collection will provide the requisite platform to achieve a sustainable MSWM system that can lead to a zero-waste scenario.

The new planning codes will incorporate waste management into the initial planning and design of our cities. This is contrary to the existing system where waste management policies are only initiated after the occupation of our cities and towns. It is also possible to upgrade the city's waste management system to conform to the proposed waste management infrastructure. The new planning codes will achieve the core environmental planning principle concepts, which include; sustainable development, low carbon development, public participation, and regional cooperation (DSPA, n.d), hence reduce the most important adverse impacts on the urban environment affecting people and the ecosystem as caused by man and nature (Williams, 2000).

3.1 Description of the ontology design concept

The core design of the MSWM is underpinned in an ontological framework based on partitioning the municipality into zones for the purpose of mapping waste generation, management and disposal activities in such a manner as to be able to monitor the flow of waste as represented in Figure 2. Each zone has activity levels 1 to 4 accordingly, depending on whether waste is generated within the zone, collected at a reuse/recycling centre (RRC), recovered/reused or managed in a material recovery facility (MRF), treated in a Waste Treatment Facility (WTF), prepared for long distance transfer in a transfer station (TS) or disposed at a waste disposal facility (WDF) (Figure 3).

Figure 2 Zoning concept within a municipal area showing possible 'activity nodes' (see online version for colours)

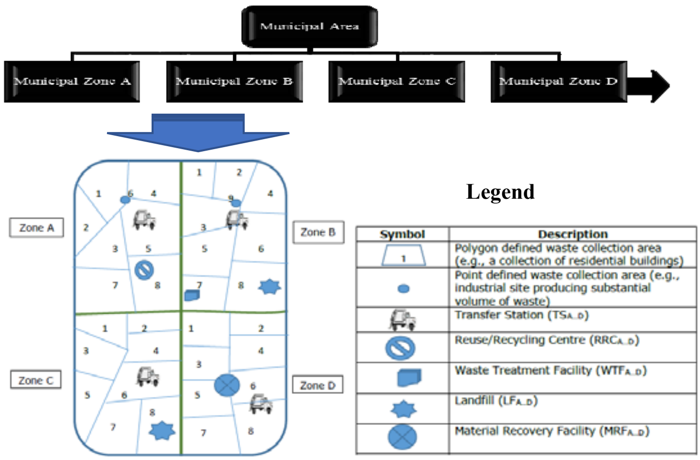


Figure 3 Waste flow between levels and activity nodes (see online version for colours)

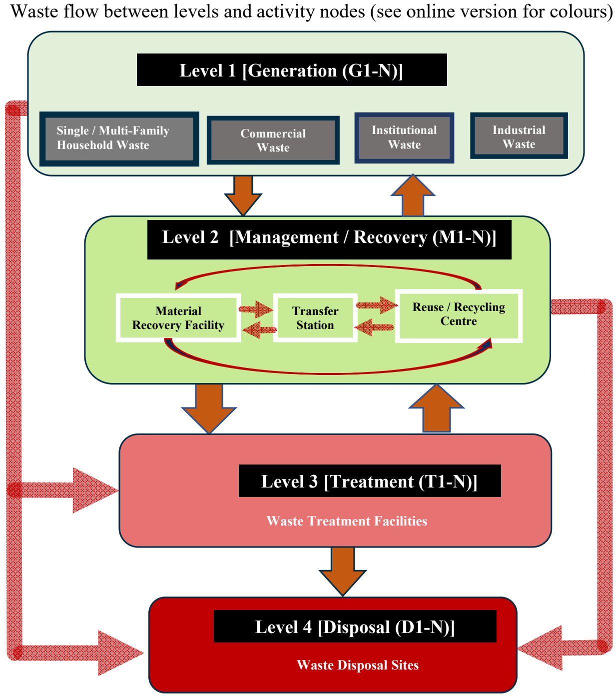
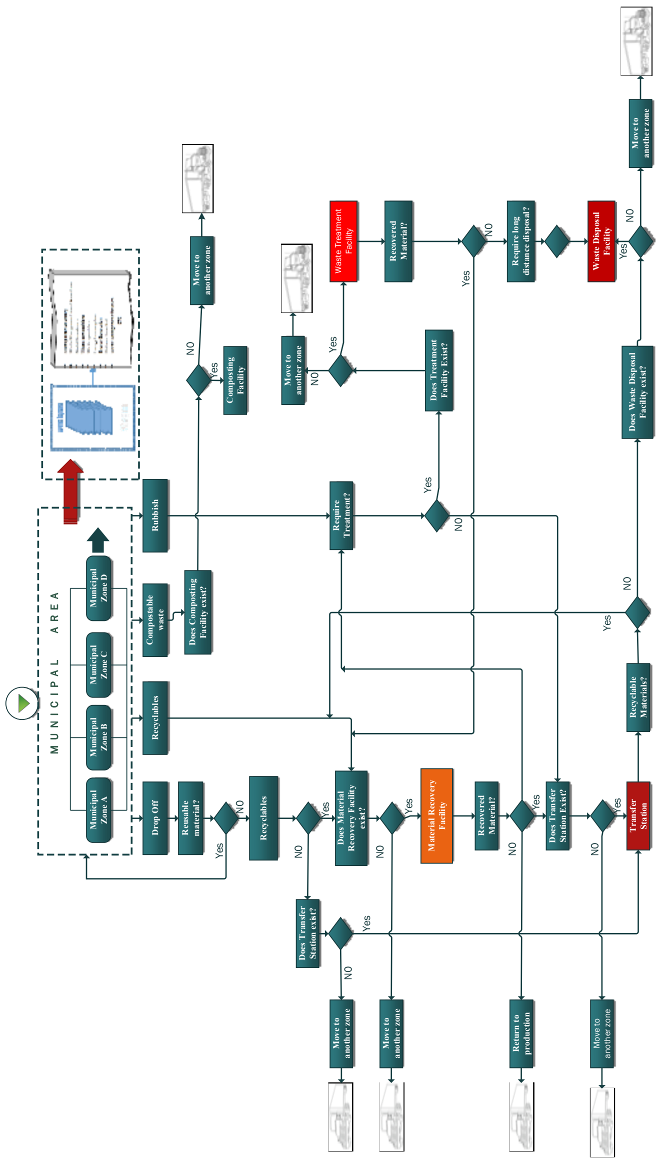


Figure 4 Ontological framework showing the waste flow system within a zonal boundary (see online version for colours)



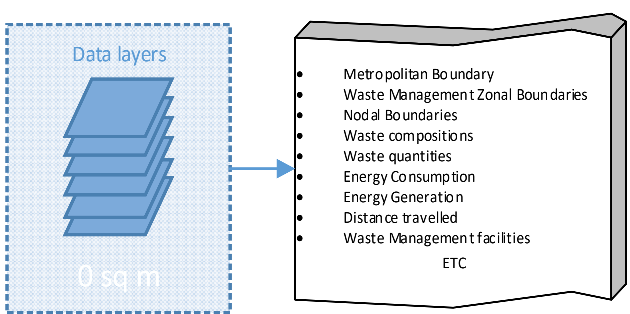
Activities within the same level have common characteristics as shown in Table 1. All the four levels of activities may not exist within a zone, depending on the size of the zone. In that case, the waste flow system as in Figure 3 allows the zone to cross over to a designated zone (as designed in the municipal waste management system) to access the activity or facility that does not exist in their zone. In this way, the destination of all waste from one level to the other is pre-determined within the ontological system as represented in Figure 4. Hence, metadata confirming such out-of-zone movement is collected for decision-making purpose.

Table 1 Activity levels for the waste management system

Activity		*Level*
Waste generation		1
Transfer station (TS)	Management/recovery	2
Material recovery facility (MRF)	Management/recovery	
Recycling/reuse facility (RRF)	Management/recovery	
Waste treatment facility (WTF)		3
Waste disposal facility (WDF)		4

Therefore, a comprehensive data system is developed through a geographic information system (GIS) approach (Figure 5), interconnecting the web of activities within a metropolitan WM system. Table 2 represents some possible data/information that may be recorded at each 'activity node'. This can be the future of tomorrow's waste data, where innovations in waste tagging will improve the availability of data, hence reducing the level of generalised and assumed data in WM.

Figure 5 GIS data concept adaptable in a municipal area (see online version for colours)

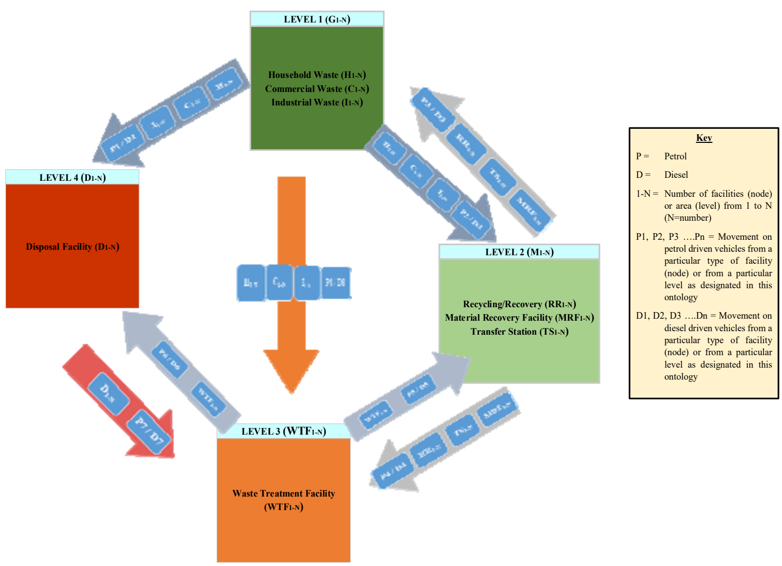


The complexity of MSWM from the environmental, economic and social point of view is therefore simplified through the implementation of a decision support system. This is achieved through the definition of a tagging system in the ontology, providing the vocabulary that is used in encoding the solid waste flow and other operational knowledge-based information to help in the decision-making rules. Figure 6. demonstrates the possible data coding principle which can be adopted to define the various data emerging from the 'activities nodes'. In this way, an ontological framework that captures the relationships between the various ‘activity nodes’ in the MSWM system is defined.

Table 2 Example of collectable data at ‘nodes’

Activity nodes	*Example of the type of data that may be recorded*									
	Waste Volume	*Waste Composition*	*Energy generation*	*Energy consumption*	*Distance travelled*	*Decomposition rate*	*Mode of transportation*	*Destination*	*Output from activity*	*Source of waste*
GP/A	X	X					X	X	X	
DOS	X	X		X	X		X	X		
MRF	X	X		X	X		X	X	X	X
WTS	X	X	X	X	X		X	X		X
WTF	X	X		X	X		X	X	X	X
WDF	X	X	X	X	X	X	X	X	X	X

Figure 6 Task-specific ontology for waste transport subsector showing movement between levels and possible data tagging for fuel consumption (see online version for colours)



The ontology allows the inference of their valid combinations of data as a scientific resource for the generation of unique new data as a solution to the present numerous unanswered questions. This is advocating for a multiplicity of resources in a data system, which have been neglected over the years. Hence developing a data standard which is currently not existing. At each of the 'activity nodes' within the levels, activities are recorded depending on the 'activity node' and the performance expectation of the system. This may include some of the activities recorded in Table 2.

The other important design concept of the ontology is the 'activity nodes'.

The ontology identified six major 'activity nodes':

- waste generation points or area (GP/A)
- drop-off station (DOS)
- material recovery facilities (MRF)
- waste transfer stations (WTS)
- waste treatment facilities (WTF)
- waste disposal facilities (WDF).

For example, at the level of waste generation; a single unit household, collection from residential apartments, an industrial site, an institution like school, a restaurant, departmental store, semi-detached unit or high rise residential apartment are examples of waste generation point or area.

The nodal area may be defined as a polygon because many addresses are combined in a collection process or as a point if single units are handled. In the case of industrial waste, this may be defined by a point depending on whether the industry is large in waste generation. This decision is taken because the volume of waste from a company may be of such a volume to warrant moving straight from the industrial site to any of the other 'nodes' in levels 2, 3 or 4 (TS, MRF, WTF or WDS), as the case may be.

These 'activity nodes' are the centre of activities and where the standards are defined. The 'activity nodes' are interconnected through a network of movement through which these wastes are moved as changes in their forms and sizes occur, before getting to their final destinations. The final destination is where they are disposed or treated. Therefore, the data standard defines the type and quality of data at each nodal point and how the data are collected. These defined standards are maintained throughout the system to facilitate comparison of information and data. In this way, the level of waste generation is monitored and recorded at each point and level, and the level of waste recovery or changes from one 'activity node' to the other is monitored and can be ascertained. The main questions are:

1. *What is* the position or characteristics of the waste on arrival at 'activity node'?
2. *How is* it leaving the 'node' in terms of quantity, quality (composition/types) and form?
3. *Where did* the waste come from and *where is* the waste going?
4. *How did* the waste arrive the 'activity node' and how is it leaving?

The definition of how these various data are reported to make comparability possible among zones, 'nodes' and levels, is very important.

4 Data and system expectation

The volume of data that is generated at the various 'activity nodes' require the adoption of a new computer-based information system capable of storing a structured data and the automation of the various activities which can only be possible through an ontological-based knowledge management framework capable of modelling generic structures in a defined waste data standard. The multiple targets of the strategy are to track and monitor waste generation, waste flow, and developments/activities in waste management and disposal facilities.

This, on another hand, will enhance and encourage stakeholder engagement and education. Policy makers with up-to-date data/information can take more robust decision to resolve MSWM challenges to achieve sustainability. This is a shift of paradigm from the current system that is based on a wide range of imposed assumptions that results from series of undecided questions of uncertainties.

To simplify the system will require a consistent research effort to establish standards and metadata at the 'activity nodes' to feed the GIS-based spatial data infrastructure. This may be generic in nature and cost saving as a strategy to creating long term data/information. For example, the approved activity within a waste generation point or area can be a pointer to the expected waste characteristics, including the recoverability and management strategy.

4.1 The knowledge-based integrated waste management system

This designed system will culminate into a knowledge-based integrated waste management system with the capability of tracking all the waste generated within a municipal area from the point of generation to the point of disposal. The result is a combination of spatial and temporal data linkages and relevant technologies, in solving the long-standing problem of waste data collection, standardisation and management.

The application of mobile application has become synonymous with modern day communication (Jambeck and Johnsen, 2015). This is advantageous in conceptualising the strategy and development of a tool to increase efficiency and reduce costs in MSWM. Structured query language (SQL) database of the municipality mapping/address system and MSW information system will be built on an MSW tracker website with an online logging. This makes it possible for data feed on various data link (WM companies and municipal authority), data retrieval and downloads. The flexibility of the design makes it possible to fit into varying scenarios and deployment in any location around the world.

Global positioning system (GPS) and form on iPhone Operating System (iOS) is also being proposed, to provide instant location information update during data upload. This provides the possibility of anywhere data upload. Hence the uploaded data is attached to the activity centre as the case may be.

Comma-separated values (CSV) files provide the flexibility for easy data import into any spreadsheet program which is used in the database and makes the data retrieval and management very easy.

Hence, municipalities can access data uploaded by registered WM companies and other service providers and provide data/information services to other stakeholders. This system provides an open and transparent WM system network leading to good decisions that will result in good system integration and sustainability.

5 Conclusions

The system identified the need for an integrated system which will help to achieve sustainability. It will also create a new level of data integrity which is expected to impact critically on the usability through improved data sharing and cost savings.

It is important to further emphasise on the paradigm shift to produce efficient combination rules that accurately capture the scope and restrictions of the system. This will lead to an interesting extension which can be implemented to produce a uniform mechanism. Combining these uniform mechanisms with appropriate metadata produces new data that have not been possible. Hence the total processing time and cost of data generation is reduced favourably.

This is expected to result in a novel technology to help gather, process, share and unlock the critical knowledge needed to provide a competitive edge in solving most of the daunting problem facing humanity in MSWM.

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