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Statistical Analysis of Determinant Factors and Framework Development for the Optimal and Sustainable Design of Municipal Solid Waste Management Systems in the Context of Industry 4.0

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Abstract

Municipal Solid Waste (MSW) generated by various natural and manmade products consumed by humans and other living creatures is amongst the most critical issues that often lead to environmental and health concerns. Within the waste management industry, there are several factors that have to be considered when a particular city needs to develop an optimal system for the collection, treatment and disposal of its MSW; and these factors differ from one city to another. Reflecting on the current trend of thinking with the Industry 4.0 in line with internet of things (IOT), Artificial Intelligence (AI), Big Data, etc. designing an optimal and sustainable Municipal Solid Waste Management System (MSWMS) has become even more challenging and city-specific. The aim of this paper is to statistically analyze demographic, geographic, economic and technical parameters that substantially affect the design of an optimal and sustainable MSWMS in the context of the fourth Industrial Revolution. South Africa is considered as a case study, and a statistical analysis methodology was applied using Microsoft Excel 2016. The analysis generated the regression equation as well as the correlation between municipal waste production and the economic, demographic and geographic variables. Finally, the paper presents a conceptual framework for the design of an optimal MSWMS for a developing city, in the context of Industry 4.0. The paper makes mainly use of secondary data collected from previous articles, official governmental reports, and Census to conduct the statistical analysis. The literature review revealed that the quantity of waste generated, available air space, city roads traffic, the distance between municipal waste production nodes and different waste treatment (disposal) facilities, the capacity of waste transportation vehicles are among the most critical parameters for the optimal design of MSWMS; and the results of this study showed that the most determinant factors impacting these parameters are the city's Gross Domestic Product contribution and its population density.

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Keywords: Waste; Statistics; Optimization; Industry 4.0; System Design.

1. Introduction

It has been said that, you cannot improve on anything unless you are able to measure it. Waste management is one of major roles of any municipality in the world, and with today's economic and geographic challenges, cities are putting more and more effort in optimizing their MSWMS in order to better serve their people and save few dollars.

One of the component of modern waste management system (WMS) is the design and use of Waste Transfer Station (WTS); these are facilities where waste is temporary stored, sorted, compacted and then loaded into long haul trucks for disposal in landfills. Considering the use of these WTS, some of the crucial questions a waste management organization or a municipality asks are as follow:

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i. When is it profitable to make use of WTS?
ii. Which WTS (Landfill) to use for each district?
iii. Which route to take?
iv. What is the ideal time and frequency for waste collection?

The concept of selecting intermediate points for transfer of materials in order to minimize transportation costs has been utilized since the 18th century. Researchers such as Marks and Leibman [1] are among the first to conduct mathematical analysis for the location of these transfer stations. After this period, several studies have been conducted and a myriad of techniques and tools have been developed and used to answer these questions.

Talebbeydokhti et al. [2] have conducted a study on the optimization of MSW collection and transportation using TransCAD software. The study resulted in an optimized system that showed a decrease in distance travelled and time of 15.7 % and 29.43 % respectively. On another research project, Chang and Lin [3] made use of Geographic Information System (GIS) and the mathematical programming to optimize the citing of a solid waste transfer station in the city of Taipei. A similar work by Yadav et al. [5] conducted a feasibility study for the location of WTS in urban centres using GIS.

Finally, in the article "Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using Particle Swam Optimization (PSO) algorithm" conducted by Hanna et al. [5], smart bins together with optimization techniques have been used to optimize the routing of waste collection in a city.

These are just some studies, among many others that have made use of optimization techniques and computer software to optimize the design of MSWMS. However, a common shortfall to most of these studies is that, they have developed models that make use of historical data to predict the best scenarios for a particular city. This paper provides a framework that incorporate the principles and tools of Industry 4.0 to design systems that use real time data and make decentralized decisions for the optimal waste collection, treatment and disposal.

The first action that needs to be taken toward the design of such a system is the analysis of determinant factors that have great impact in any SWMS. Based on the literature review, demographic, economic, geographic and other technical parameters such vehicles speeds, distances, facility capacities, etc. are among the most determinant factors for the optimal design of SWMS.

As it has been defined by Herman et al. [6], Industry 4.0, also considered as the fourth industrial revolution (4IR), is a collective term for technologies and concepts of value chain organization; and within the modular structured Smart Factories of Industry 4.0, Cyber-Physical Systems (which are systems that integrate the physical infrastructures with the cloud system) monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. The other important component of Industry 4.0 is the Internet of Things (IoT), over which CPS communicate and cooperate with each other and humans in real time. This paper presents an analysis conducted in the context of the 4IR and provides decision makers of developing cities with a framework that can assist in developing sustainable and integrated waste management plan.

2. Methodology

As in any optimization process, the collection and analysis of input data is of utmost importance because the accuracy of the optimization or simulation is only as good as the accuracy of input data. With that being said, the first step in this study is the description of demographic and economic parameters that impact the management system of waste in cities. The second step consists of conducting a detailed statistical analysis of these parameters in order to draw conclusions about the relationships they have with waste generation. Linear regression analysis and correlation techniques are the techniques used to establish these relationships; and Microsoft Excel 2016 is the software utilized to perform these analyses. A case study of South African provinces is considered and data used throughout all these analyses come from Table 1 and Figure 1 described in subsequent sections. The final step of this study is to make use of insights obtained from these statistical analyses, to describe and understand the principles and tools of Industry 4.0, and to develop a framework for the design of optimal and sustainable MSWMS within the context of the 4IR.

3. Demographic parameters

It has been mentioned in the introduction that human being, as well as all other living creatures consume all sort of products that produce waste; based on this fact, it can therefore be said that waste generation is directly linked with the demography of the population. The questions that need to be asked here are:

i. What are the effects of the population demography on waste generation?
ii. Is the correlation between these two variables positive or negative?
iii. How strong is this correlation?

The first parameter of interest in this regard is the population per province in the country as displayed in Table 1 below.

Table 1: Total Population of South Africa by Province, Census 2011.

Provinces	Population estimate	% of Total population	Land area in km2	Population Density (Hab/km2)	GDP Contribution (R'Million)
Western cape	5 822 734	11%	129 449	44.98	349 818
Eastern Cape	6 562 053	13%	169 954	38.61	189 505
Northern Cape	1 145 861	2%	362 599	3.16	57 132
Free State	2 754 590	5%	129 824	21.22	136 264
Kwazulu-Natal	10 267 300	20%	92 305	111.23	400 488
North West	3 509 953	7%	116 231	30.20	162 691
Gauteng	**12 272 263**	**24%**	**16 936**	**724.63**	**844 707**
Mpumalanga	4 039 939	8%	79 487	50.83	176 840
Limpopo	5 404 868	10%	122 816	44.01	175 313
Total	51 779 561		1 219 602	42.46	2 492 761

Source: StatsSA, [7]

As it can be seen in Table 1, the population of South African provinces is far to be proportional to the land area of the province, this is mostly due to the movement of the people from the less developed and rural arears to the big and developed cities such as Johannesburg, Tshwane, Cape town, etc. The other fact that needs to be mentioned here is that, most of immigrants coming from different neighborhood countries end up in these big cities. On the other hand, GDP contribution of provinces seems to be proportional to the population, with Gauteng province being the most populated province and with the highest contribution to the country's GDP; more detailed analysis of this trend is provided in the following sections.

4. Waste characteristics in South Africa

After looking at the demographic parameters that can directly affect the MSWMS, this section provides more information and detailed analysis of waste management in South Africa. Figure 1 below portrays waste generation per capita, per annum for every province, with Gauteng Province having the highest amount of waste generated per capita.

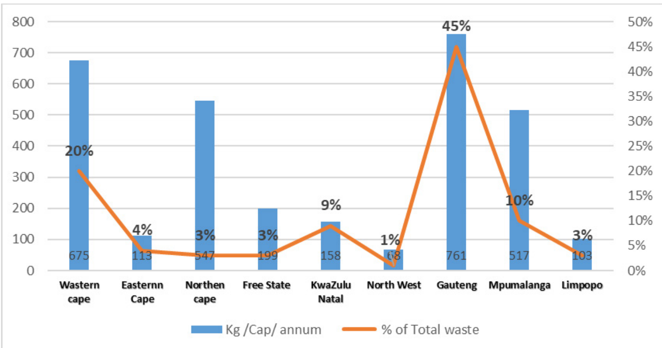

Fig.1: Percentage of municipal waste contribution by province in South Africa, 2011.
Source: Adapted from Department of Environment Affairs, SA [8].

4.1. Correlation analysis between the population and waste generation

In this first analysis, the objective is to identify the correlation that exists between the city's population and its waste generation. In this analysis, the dependent variable is waste generated, and the independent variable is the population of the province. As it is apparent in Figure 2, the results of this analysis are as follow:

- Regression Equation (RE): $y = 2.10^{-05}x + 257.42$ (1)
- Correlation coefficient: $Cor = 0.2078$ (2)

This correlation coefficient represented by equation (1), although weak, defines a positive relationship between the two variables, this means that waste generation of a city increases with the increase of the population.

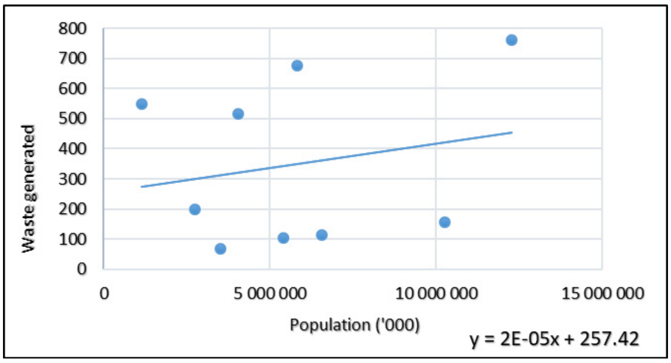

Fig. 2: Scatter Plot of Population Vs Waste Generation.

4.2. Correlation analysis between the population density and waste generation

Similarly, this second analysis establishes the relationship between the population density and waste generation; in this case, the population density is the independent variable and waste generation the dependent variable. The results of this analysis, as it is depicted in Figure 3, are expressed in equation (3) and (4) below.

- Regression Equation (RE): $y = 0.6418\,x + 272.77$ (3)
- Correlation coefficient: $Cor = 0.5380$ (4)

Just like the regression analysis of the population against waste generation, the linear regression analysis of population density against waste generation yields a regression equation with a positive slope and a positive correlation coefficient, which entails that the increase of the population density results in proportional increase of the amount of waste generated.

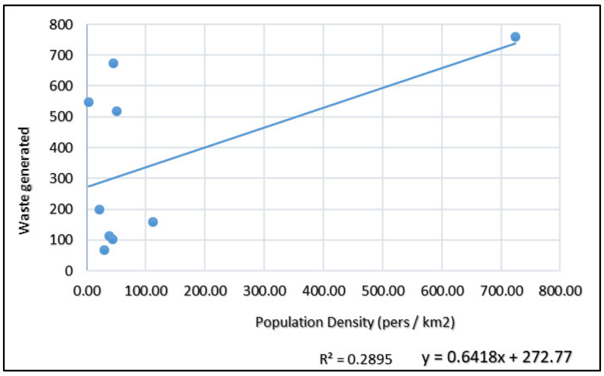

Fig. 3: Scatter plot of population Density Vs Waste Generation

4.3. Correlation analysis between the Province GDP Contribution and waste generation

The last analysis conducted is the correlation analysis between the GDP contribution of the province and waste generation. This economic factor is very important in the development of waste management system as it has been found in a study conducted by Cointreau [9] that the income level, which is directly linked to the GDP contribution of a population, affect substantially the generation of waste in countries. In this last analysis, the independent variable is the GDP contribution of the province, and the dependent variable is still waste generated. After applying the techniques described in the precedent sections, the results obtained are expressed by equation (5) and (6)

- Regression Equation (RE): $y = 0.0006\,x + 182$ (5)
- Correlation coefficient: $Cor = 0.5244$ (6)

Just like the two first analyses, the linear regression analysis produces a regression equation with a positive slope and a positive coefficient of correlation. It can then be stated with certainty that the increase of the population GDP contribution will directly cause the increase of waste generation.

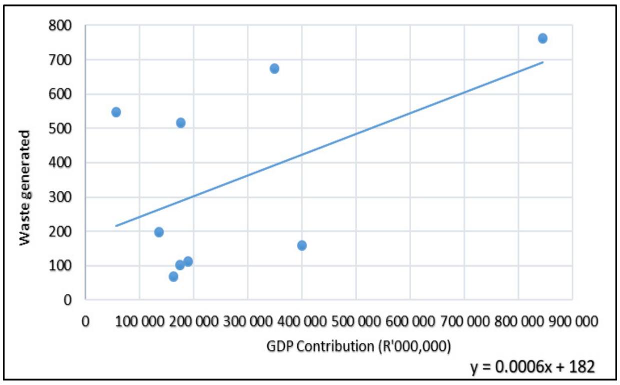

Fig. 4: Scatter Plot of GDP Contribution Vs Waste Generation

In summary, this section has conducted statistical analysis of different parameters that can affect the development and operation of SWMS. In this analysis, three parameters of interest have been considered, namely, the geographical, the demographic, and the economic parameters. Statistical analysis has been conducted to establish the relationships that exist between the generation of municipal solid waste and three principal variables, the population, the population density and the GDP contribution.

It has been established that all these three variables have a positive correlation with waste generation, which means that the increase of these variable will result in a proportional increase of waste generated. GDP contribution as well as the population density have shown a stronger correlation with the generation of waste, as compared to the city's population. In the next section, these results and insights will be used to develop a framework for the design of SWMS for a developing city in the context of Industry 4.0.

5. Overview of industry 4.0

Industry 4.0 is a trend of thinking that originated from a group of academics and industry experts from Germany, this brainstorming group gathered to discuss and think on how to improve the productivity of German industries with the use of new technologies. Since its first introduction in the academic and industrial world, Industry 4.0 has captured the attention of many scientific and industry stakeholders worldwide, and different understanding and opinions around this term has been noticed.

At the current moment, there is no doubt that industrialized countries are already thinking about and financing research for the implementation of the Industry 4.0 for the betterment of their industries. This is also the time developing countries should start thinking in the line of this fourth Industrial revolution to remain competitive in the near future. Hence, the design of product and systems of the future needs to incorporate the idea and philosophy of industry 4.0.

According to a study conducted by Herman *et al.* [6], the following are the six design principles of Industry 4.0:

i. Interoperability
ii. Virtualization
iii. Decentralization
iv. Modularity
v. Real-Time capability
vi. Service orientation

The same study has also highlighted the following 4 components of industry 4.0:

i. Cyber-Physical systems (CPS)
ii. Internet of Things (IoT)
iii. Internet of services (IoS)
iv. Smart Factories

As we progress toward the implementation and realization of industry 4.0, several academic curriculums and professional areas will need to be amended to remain relevant to the industry. As outlined by Sackey and Bester [10], of the areas that need curriculum attention, advanced analytics and system simulation, novel human-machine interfaces, digital-to-physical transfer technologies, and data-to-information conversion processes appear to be the most important. This may explain why operations research built on real-time simulation is turning out to be the most important functional area of Industrial Engineering in Industry 4.0; and all these areas are of very great importance when it comes to the design of any type of a system.

The previous sections have analyzed different input data to the SWMS design; and just like all the traditional analyses, historical data have been used to understand the current system inputs and outputs in order to provide predictions and properly plan for the future. Unfortunately, we live in a very dynamic world and things are not always static, but they change from time to time. This fact brings about the question “how much can we trust historical data to provide good inputs for the prediction of the future? This question is the basis for the development of and strive for new techniques and tools for more accurate decision support systems. Fortunately, the advancement in technology and the internet can assist modelers, data analysts, systems designers and decisions makers to develop systems that make use of these advancement in technology to perform more effectively, efficiently and sustainably.

6. Framework development

As it is depicted in Figure 4, the developed conceptual framework takes into account different stages of waste management and identifies in which stage CPS, together with IoT and Smart Factories can be implemented more effectively in order to reduce the operating time and cost of the system. Different stages of waste management are: collection, transportation, temporary storage, sorting and compaction at the Waste Transfer Station (WTS), treatment and or recycling, and finally landfilling. The framework developed is displayed in Figure 4, this conceptual framework aims to assist SWMS designers and other stake holders in designing an effective and sustainable system that will strive in the fourth industrial revolution.

5.1. Discussion of the framework

Demographic, economic and geographic parameters that affect the waste generation and management systems have already been described in section four; and technical parameters considered in the framework include: traffic delays, distance between different nodes, vehicle speed, loading and unloading time at WTS and Landfill, etc.

The stages of waste management system as depicted in this framework start with collection, where Waste Collection Vehicles (WCV) travel within the city, from household to household collecting waste deposited in the bins; the second stage is the transportation; after waste is collected, WCV transport it to the next stage, which is Waste Transfer Station (WTS) where waste is sorted, compacted and loaded into long haul truck. At this stage waste is directed either to Material Recovery Facility (MRF) for material recovery and recycling, or to landfill. The next stage is again transportation, where waste is transferred to different final disposal sites. The last stage is landfill, this is the final destination of waste that comes either directly from households, from WTS or from MRF.

This framework has identified three stages where the application of CPS, IoT and Smart Factories will be of utmost importance for the optimal design and operation of the system; the positions, Inputs/Outputs, and functionalities of these CPS are described below:

- CPS 1: The first Cyber-Physical System is at the first stage (collection). The function of this system is to inform the WCV of the optimal time and frequency of collection.
  It will make use of smart bins and sensors to collect information, that will be processed in Data Processing (DP) software and then provide useful information. The aim of this system is to send WCV to only full waste bins and to determine optimal waste collection frequency.

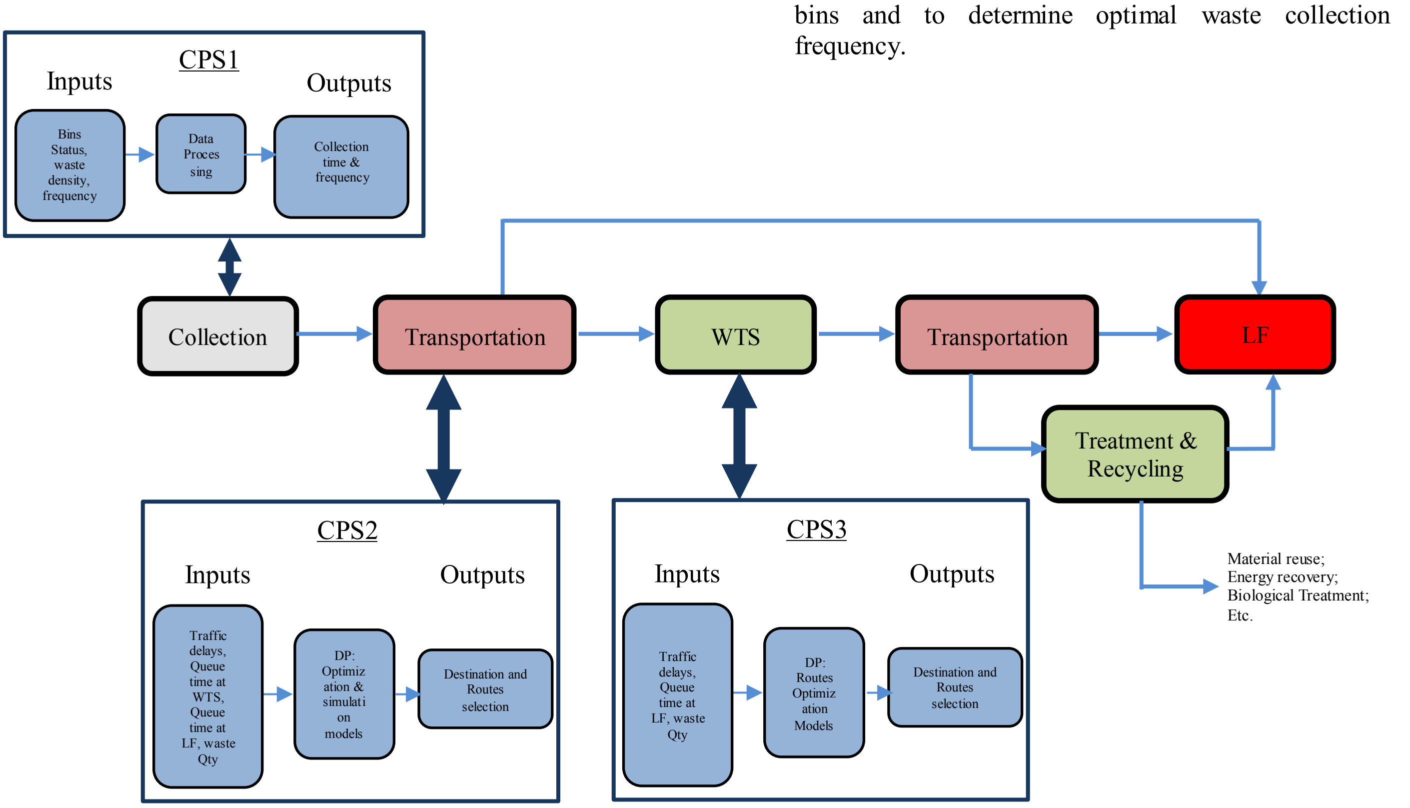

Fig. 5: Conceptual Framework for the Optimal Design of SWMS in the context of Industry 4.0

- CPS 2: the second CPS should be implemented at the first transportation stage, at which decision needs to be made whether to send waste directly to landfill or to WTS. The inputs for this information system will be traffic delays, road blocks, queue time at different WTS's and landfills and municipal waste quantity. Data processing instruments of this CPS will be optimization and simulation models and tools; and the outputs will be the optimal destinations and routes.

- CPS 3: This last CPS will be implemented at stage 3 of the waste management system to integrate the WTS and the information in the cloud in order to determine what is the best final destination and routing of waste. In the same analogy, the inputs to this CPS will be traffic delays, queue times at different landfills and municipal waste quantity. Data processing tools will consist of routes optimization and facility selection models together with optimization and simulation software's.

6. Conclusion

In conclusion, this paper has presented a statistical analysis of factors contributing to the generation of waste in cities; a case study of waste generation in South Africa has been used. The analysis has shown that population density together with GDP contribution have a higher correlation with waste generation as compared to the population size; the coefficient of correlation of population density and GDP contribution against waste generation is about 0.5 and the one for the population size is about 0.2. Nevertheless, all these parameters have shown a positive correlation with waste generation, which means an increase in these parameters will result in an increase in the quantity of waste generated, and vice versa.

The insight obtained from these statistical analysis, along with technical parameters such as waste collection and transfer vehicles speeds, distances between different MSWMS nodes, roads traffic, and performances at different waste facilities have been used to develop a framework for the optimal design and operation of waste management systems in the context of Industry 4.0.

In this framework, three stages of the waste management system have been identified, where the implementation of Industry 4.0 principles, components and tools will provide the greater result in terms of reducing the time and cost of waste collection, treatment and disposal.

Acknowledgement

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This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.