Sustainable solid waste management in urban areas of Pakistan: A system dynamics based approach

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Abstract— Pakistan, like other developing countries, faces serious environmental problems, especially those related to Solid Waste Management. Waste management systems involve interconnections among physical infrastructure, financial, and socio-political factors. Several interacting feedback loops are formed due to these interconnections and make the management of solid waste a complex and dynamic problem. A system dynamics approach is used to develop a demonstration model for solid waste management system. A detailed causal loop diagram for management of solid waste is presented. Based on this causal loop diagram, a system dynamics model is developed. Policy levers are included in the model to facilitate formulation of different strategies. Simulation results indicate that different financing strategies can achieve varying impacts for consumers in terms of collection efficiency and financial burden.

Index Terms— Causal loop diagram, Solid waste management, Sustainability, System dynamics, Stella, Stock flow diagram, Environmental problems.

1 Introduction

Sustainability of solid waste management in Pakistan, like other developing countries, is a growing challenge (Shoaib et al., 2017). Rapid population growth (2.61 percent a year) and economic growth has contributed to increase in solid waste pollution and this situation continues to exacerbate (Pakistan EPA, 2005). Efficient disposal of solid waste is essential to maintain a high quality of life and promoting economic activity in urban areas. Solid Waste Management System (SWMS) includes solid waste generation, storage, collection, transfer and transport, processing and disposal. Sustainable Solid Waste Management System consists of five main components i.e. technical, environmental, economic/financial, social, and institutional (Shoaib et al., 2017). The technical, financial, institutional, environmental and social elements involved in the management of SW systems do not remain static but rather evolve over time. To properly understand system behavior, a holistic framework is needed that integrates the above mentioned elements of the system in a dynamic framework.

Many efforts have been made to study solid waste systems, however, almost all of the existing studies focus on various aspects of SWMS, and a holistic approach towards addressing the sustainability of complete system is lacking. Available studies are mostly based on linear approaches from generation to disposal. But a sustainable SWMS is complex, dynamic and multi-faceted. System Dynamics approach (Forrester, 1958) adopted in this study is considered as one of the appropriate options to deal with such complex systems.

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2 Literature Review and Conceptual Framework

2.1 Sustainability

Sustainability (noun) represents the ability of a system to sustain, and the word sustainable (adjective) implies the capability of being sustained (Jha et al., 2019). Technical, environmental, economic, social and institutional contributes to five main elements of sustainability.

2.2 Solid Waste Management System

The primary purpose of solid waste management is to address environmental, social, economic, technical and institutional issues that arise from improper practices of solid waste management. Solid Waste Management (SWM) includes preparing, organizing, financing, and implementing strategies for efficient generation, storage, collection, transporting, processing, recycling and its final disposal in a scientific sanitary manner.

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2.3 System Dynamics

System dynamics is a methodology for analysis of problems with "time" as an important factor, and which involves the study of how the system can be benefitted or protected against the external shock that fall from the outside world. A system dynamics model is built from assumptions in a "mental model". The ability of system dynamics to explore the actions linked with solid waste management system that are dependent on time makes it a much needed technique (Chang & Pires, 2011). Jay Forrester in late 1960s introduced System dynamics in Massachusetts Institute of Technology as a methodology for modeling and simulation (Chaerul et al., 2008).

2.4 System Dynamics modeling

System dynamics describes cause and effect relationship with stock and flows, which are the basic building blocks of SD models. Stocks (or levels) represent accumulations within the system both physical and non-physical. At any instant, the magnitudes of the stocks give us a snapshot of the system. Their values can only be changed by flows. Examples of stock are population, public awareness, etc. Flows represent activities or actions in a stock that transport quantities into or out of a stock instantaneously or over time. Examples of stock are births or deaths in population, public awareness build up or dissipation, etc. ("STELLA v9 Tutorial 1," n.d.).

2.4 Application of System Dynamics in solid waste management

Study on solid waste management using system dynamics methodology began in 1973 and up till now many study achievements have been observed (Lin, n.d.). These achievements can be found in various environmental issues such as: environmental change, world water management, global green house gas emissions, forecasting of waste generation and composition in relation to lifecycle trends. (Alcamo and Kreileman, 1996; Alcamo et al., 2000; Alcamo et al., 1996; Leemans et al., 1996; Cosgrove and Rijsberman, 2000; Nakicenovic et al., 2000;Fell and Fletcher, 2007).

3 Methodology

Identification of major variables that contribute to sustainability of SWMS followed by an overview of system dynamics and finally modelling process for applying system dynamics approach.

3.1 Identification of key variables

From the review of literature major variables that contribute to the sustainability of solid waste management system were identified and were grouped under three main headings encompassing solid waste generation, collection and transport, and final disposal.

3.2 System description

After identification of the problem next step is to identify and include all the key variables in the model that influence the behaviour of the system.

3.3 Model formulation

Quantitative analysis by constructing stock-flow diagram in a software package which helps to understand the problem better with the help of defining equations and running computer simulations.

3.4 Model validation

Model is tested first to make sure all the variables included are meaningful in the real world and then entire model is tested to examine if it fits reality.

3.5 Scenario Analysis

After validation, the model is simulated under different scenarios to evaluate and examine the response of the system under these for making timely decisions and policies.

4 Model development

Model for solid waste management was developed containing three sectors: consumer sector, Solid waste management utility, and financial sector. The model developed is not complete in every respect containing all elements of solid waste management but is sufficient for development of a model that can be used for decision making in short and long term planning.

4.1 Causal loop diagram for solid waste management system

The consumer sector estimates solid waste generated by constant population that needs to be collected. Total *solid waste generation* is determined by product of *population* (stock) and *per capita generation rate* (convertor). *Average per capita generation rate* is a function of *economic development level* and with increase in economic development level solid waste generation rate increases.

Modified_per_Capita_Generation_Rate = MAX(Avg_Per_Capita_Generation_Rate*PA_multiplier_for_Gen_Rate,Avg_Per_Capita_Generation_Rate*0.5) (1)

Solid waste management utility sector includes processes of solid waste formal collection, informal collection, and waste spillage and calculates efficiency of collection. The financial sector comprises of 02 separate but interconnected stock-flow structures i.e. Funds Balance and SW Fee

5 Conclusions

Management of solid waste is shown as a complex and dynamic system which comprises of several interconnections and feedback loops. The existing system of solid waste management in Pakistan does not capture this dynamic complexity. Simulation results shows that the feedback loops identified have a noteworthy influence on system behaviour and through different strategies, better efficiency and service delivery can be achieved

6 Contributions

Original contributions made by this research are presented below:

1. Management of solid waste is framed as a complex and dynamic problem.
2. Causal loop diagrams are developed for sustainable solid waste management system.
3. System dynamic models are developed for management of solid waste system including a number of policy levers allowing formulation of different strategies that can be used for achieving best efficiency.

It is hoped that the models developed in this research will help municipalities develop short and long term management plans to meet the requirement of waste disposal with justifiable user fee.

7 RECOMMENDATIONS

Specific recommendations for future research are presented below:

1. Research is needed to better understand the impact of public awareness on solid waste generation rate, which can be then incorporated in the model for improved results.
2. Unit cost collection is modelled as a constant value, as an improvement, it can be replaced by a value that varies with time for more realistic representation.
3. Debt service charges may be included in the model for improved financial sector results.
4. Disposal of solid waste is needed to be incorporated in the model.

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