Revista Brasileira de Gestão e Desenvolvimento Regional
G&DR. V. 19, N. 1, P. 687-710, Jan-Abril/2023. Taubaté, SP, Brasil.
ISSN: 1809-239X

PROPOSTA DE UM MODELO DE DINÂMICA DE SISTEMAS DA GESTÃO DE RESÍDUOS SÓLIDOS URBANOS DOMICILIARES: UM ESTUDO APLICADO A CURITIBA (BRASIL) A LUZ DA POLÍTICA NACIONAL DE RESÍDUOS SÓLIDOS (PNRS)

PROPOSAL FOR A SYSTEM DYNAMICS MODEL FOR URBAN HOUSEHOLD SOLID WASTE MANAGEMENT: A STUDY APPLIED TO CURITIBA (BRAZIL) IN LIGHT OF THE NATIONAL SOLID WASTE POLICY (PNRS)

Received: 05/01/2022
Accepted: 03/15/2023

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Resumo

O aumento da geração dos resíduos sólidos urbanos se tornou um problema para a gestão das cidades e necessita de formas para o seu equacionamento e disposição ambientalmente segura. Trata-se de um problema presente em todos os países que buscam diferentes formas de equacionar. No Brasil, estes preceitos decorrem da Lei Federal nº. 12.305, que instituiu a Política Nacional de Resíduos Sólidos (PNRS), em 2010. A gestão brasileira aplicada atualmente não consegue atender as prioridades estipuladas pela Lei, sendo caracterizada por ser ineficaz e onerosa, como demonstra a pesquisa que avalia a política municipal da gestão integrada de resíduos sólidos urbanos das capitais brasileiras. A falta de gestão de resíduos gera uma série de problemas ambientais, sociais e econômicos. O objetivo foi propor um modelo de dinâmica de sistemas da gestão de resíduos sólidos urbanos aplicado ao município de Curitiba a luz dos preceitos da PNRS. O estudo é descritivo e utilizou entrevistas semiestruturadas, pesquisa bibliográfica e documental como técnicas para obtenção de dados primários e secundários para elaboração da proposta do modelo. A elaboração do modelo seguiu a metodologia da dinâmica de sistemas com aplicação do

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estudo de caso em Curitiba. A execução do modelo possibilitou demonstrar a integração e interação entre as diversas variáveis que envolvem a questão da gestão de resíduos sólidos urbanos. Em comparação ao modelo em vigor, pode-se verificar que a estruturação desta dinâmica de sistemas permitiu compreender que há alternativas para uma gestão mais alinhada com os preceitos da PNRS.

Palavras-chave: Gestão de resíduos sólidos urbanos. Dinâmica de sistemas. Política Nacional de Resíduos Sólidos. Cidades. Curitiba.

Abstract

The increase in urban solid waste generation has become a problem for municipal management to solve in order to dispose of waste in an environmentally safe way. The problem exists in all countries and each country seeks different ways to address it. In Brazil, the guidelines of Federal Law 12.305 are followed, with the enactment of the National Solid Waste Policy (PNRS) in 2010. Brazilian management today cannot comply with the priorities stipulated in the Law, which are characterized as ineffective and costly, as demonstrated in research that evaluates municipal policy for the integrated management of the urban solid waste system in Brazilian capital cities. The lack of waste management leads to several environmental, social and economic problems. The aim of this study is to propose a system dynamics model for urban solid waste management applied to the municipality of Curitiba, supported by the precepts of the PNRS. The study is descriptive in nature, and semi-structured interviews and bibliographic and documentary techniques were used to obtain primary and secondary data to construct the proposed model. The design of the model followed the system dynamics methodology, with the application of a case study in Curitiba. The execution of the model demonstrated the integration and interaction among the variables involved in urban solid waste management. Compared with the existing model, the structuring of the system dynamics methodology showed that there are alternatives for management that are more closely aligned with the precepts of the PNRS.

Keywords: Urban solid waste management. System dynamics. National Solid Waste Policy. Cities. Curitiba.

Introduction

Cities are characterized as “the main centers of waste production, due to their economic concentration and number of inhabitants” (PEREZ 2012, p. 98). The behavior of purchasing products and the consequent generation of waste is encouraged by consumerist advertisements, shown in the various forms of mass media (HORKHEIMER; ADORNO, 1991). They create needs, some artificial, encouraging people to acquire new products (MATTOS, 2006), doing so naturally and on a daily basis, without giving it much thought (BAUMAN, 2008).

The generation of different kinds of waste and its growth is a harsh reality in Brazil. In 2010, the average per capita generation collected from the urban population was 0.93 kg/inhabitant per day, and by 2021, this number had increased to 1.01 (BENSEN, JACOBI, SILVA, 2021; SNIS, 2021). This demonstrates that one of the basic indicators (non-generation) continues to show negative results, and other indicators are far below expectations after more than 10 years since the enactment the National Solid Waste Policy. Solid waste management requires the attention and action of both public authorities and society (MONTEIRO *et al*., 2001), and new alternatives must be sought to plan and manage this process (SILVA, 2019).

Othman *et al*. (2012) and Economopoulos (2012) presented waste management models applied in developed countries, with energy recovery and the use of different technologies, which reduce the amount of waste sent to landfills. However, these studies on proposing models involve realities that do not include some Brazilian characteristics, although some research has been conducted in Latin American countries (GUERRERO *et al*., 2013). Other studies have dealt with specific situations, such as recycling, but not specifically on how to analyze the development of municipal solid urban waste policies, considering the predominantly organic composition of waste and the lack of correct segregation (MASSUKADO, 2008).

Silva *et al*. (2015) proposed key variables to understand the dynamic of municipal solid waste management, but did not propose an analysis model. Furthermore, Silva (2016) stressed the need to understand the Brazilian reality and pointed out the high cost of urban solid waste management, in addition to the low levels of recovery and recycling. The author drew attention to a double financial loss: materials of economic value are buried; and gains from resources that could return to the productive system following circular economy logic are lost.

However, the proposition of an analysis model in light of the Brazilian reality is relevant, as it would enable a better understand of the dynamics of municipal policies following the implementation of the National Solid Waste Policy (Jacobi and Besen, 2011; Massukado, 2008; Monteiro *et al*., 2001; Silva *et al*., 2015).

The aim of this study is to propose a system dynamics model of urban solid waste management applied to the city of Curitiba, based on system dynamics in light of the precepts of the PNRS. One of the assumptions of the model is that it enables improvements to the current management of urban solid waste by separating it for reuse and thereby reducing the amount sent to landfills.

The theoretical alignment between the National Solid Waste Policy and system dynamics models is presented in the following section. The third section presents the methodology, and the construction of the model is discussed in the fourth section. The conclusions are presented in the final section.

Public policy for waste management in light of system dynamics

The public policy that instituted the National Solid Waste Policy (PNRS) (Law 12.305/2010) was negotiated and discussed for 21 years, with the participation of public agencies, representatives from the private sector, social movements and civil society. Even so, its outcome did not live up to expectations (BENSEN, JACOBI, SILVA, 2021; FUGII; BOLSON; SILVA, 2018). After being passed by the Chamber of Deputies, on March 11, 2010, and by the Federal Senate, on July 7, 2010, the President of the Republic, Luís Inácio Lula da Silva, sanctioned Federal Law 12.305/2010 (FUGII; BOLSON; SILVA, 2018).

In general, the National Solid Waste Policy (PNRS) It is composed of four sections, comprising over ten chapters: object and field of application, definitions, general provisions, principles and objectives, instruments, preliminary provisions, solid waste plans, responsibility of generators and public authorities, hazardous waste, economic instruments, prohibitions and transitional and final provisions (BRASIL, 2010).

According to Article 4 of the PNRS, the Law contains the set of goals, principles, instruments, directives, guidelines and actions adopted by the Federal Government, alone or in cooperation with the states, Federal District, municipalities or individuals, with a view to achieving integrated and environmentally appropriate solid waste management (BRASIL, 2010a).

In Article 6 of the Law, the principles of the PNRS are listed, which include, among other aspects, the polluter-pays and protector-receives principle, sustainable development and the “recognition of reusable and recyclable solid waste as an economic asset of social value, generator of work and income and promoter of citizenship” (BRASIL, 2010a – Article 6 Principle VIII). These principles are demonstrative of the breadth of the discussion and show that waste management involves interaction and integration with the region and sustainable development, which are fundamental in discussions and aligned with national policies, as stated in Lopes (2016).

Meanwhile, Article 7 of Law 12.305/2010 describes the objectives of the National Solid Waste Policy, addressing relevant and integrated issues, such as the protection of public health and environmental quality and concern over the principles of the circular economy, namely: non-generation, reduction, reuse, recycling and treatment of solid waste, as well as environmentally appropriate final disposal of waste (Objective II). In addition, the other goals integrate topics such as training, sustainable standards, incentives for industry, articulation of different public spheres and integrated management, aligned with a complex and highly dynamic model (BENSEN, JACOBI, SILVA, 2021).

Article 8 presents the instruments of the PNRS, and item VII mentions scientific and technological research, which is related to the present study. The complexity of these objectives, principles and instruments is related to the various flows and players involved. In this respect, it is important to understand them as a system dynamics process.

According to Aracil (1983), decision making occurs from several possible alternatives. In this way, the relationship that links possible actions with their effects is precisely a system model. A model constitutes an abstract representation of a certain aspect of reality, and its structure is formed by elements that characterize the aspect of the modeled reality and the relationships between the elements that comprise the model (ARACIL, 1983).

To Forrester (2013), a model should be able to achieve several objectives and describe any statement of cause-and-effect relationships that the user wishes to include, as well as being mathematically simple in nature and a synonym in nomenclature for industrial, economic and social terminology. It should also cater for a large number of variables, without exceeding practical limits and be capable of handling continuous interactions, in the sense of any artificial discontinuities introduced by time intervals. However, it must be able to generate discontinuous changes in a decision when necessary (FORRESTER, 2013).

According to García (2004), the main applications of system dynamics are found in complex and poorly defined environments, in which human decisions are guided by logic. The recent trends in system dynamics aim to change the mental models that people use to represent the real world.

To this end, it is necessary for a person to be sufficiently involved in the modeling process to internalize lessons on dynamic feedback behavior (FORRESTER, 1995).

Churchman (2015) claimed that systems are made up of sets of components that interact to achieve a goal. Von Bertalanffy (2015) defined a system as a complex of interacting elements. According to Bardach (2006), the structure of a system consists of: (1) its constitutive elements; (2) the rules of its interactions; and (3) the information required by the system to apply the rules.

Analyzing a system means dissecting it, at least conceptually, to define the parts that constitute it. However, merely analyzing a system is not sufficient. To understand its behavior, it is necessary to know how the parts (variables) fit in, the relationships between the variables and how they develop over time (ARACIL, 1995).

Studying a system includes analyzing and synthesizing it. The analysis enables becoming familiar with the parts of a system, and the synthesis provides the integration of these parts within the system (ARACIL, 1995). System dynamics deals with expressing how the structure and behavior are related.

System dynamics is specially designed to deal with linear and non-linear interactions and large-scale, complex and dynamic systems. It is capable of dealing with system configuration assumptions and dynamic structures, facilitating the control of the effects of changes in subsystems and the interrelationships of elements in the holistic system (SUKHOLTHAMAN; SHARP, 2016).

To build a system dynamics model, it is necessary to identify a problem and develop a dynamic hypothesis to explain the cause of the problem. A simulation is performed in a system dynamics model, with time displacement (DYSON; CHANG, 2005). Simulation analysis over time enables a series of long-term simulation steps to update the status of variables in the system of interest, generating results of system activities (DYSON; CHANG, 2005). A study of system dynamics can be carried out in several steps, as shown in Table 1.

Table 1 – Steps for the study with system dynamics

Steps	Characteristics
Step 1	Observation of the behavior modes of the real system to attempt to identify its fundamental elements
Step 2	Seeking the feedback structures that can produce the observed behavior
Step 3	Construction of a mathematical model of the behavior of the system in a suitable way.

Step 4	Simulation
Step 5	Modification of the structure until its components and the resulting behavior are in step with the observed behavior
Step 6	Modification of the decisions that could be introduced into the simulation model until acceptable and useful decisions are found that pave the way for improved real behavior

Source: Aracil (1983).

Stocks and flows, in feedback loops, are two central concepts of system dynamics theory (GEORGIADIS, 2013). Other elements are: arrows (direction), the complementary variables and the external source (ARACIL, 1995). A better definition of the elements is presented in Table 2.

Table 2 – The basic elements used in the system dynamics models.

Elements	**Description**
Variables (circles)	Represent parameters used in the system
Constant variables (rhombus)	Variables that assume a value that does not vary
Flows	Represent the transport of resources
STOCKS (rectangles)	Represent accumulations/non-accumulations of a resource
Information (channel)	Link the elements in the system and explain relationships between them. It is important to note that information, unlike flows, does not withdraw or place resources in stocks. Information can also have a “double dash”, meaning that it will only be available at a point in time in the future and not immediately.
External sources (clouds)	Represent a source of resources that lies outside the scope of interest of the model under study. In other words, in the above example, the flow withdraws resources from the external source and throws them into the stock. The details of the external source are not considered in the study of the system represented by the model.

Source: Villela (2005).

A model can present the impact and consequences of unrecognized causal relationships, structural delays and dynamic complexity that could lead to less intuitive and informed results to improve the situation (FAN *et al.*, 2018). Sterman (2000) presented five steps for the modeling process, as described in Table 3.

Table 3 – Steps in the modeling process

Step	Name	Questions/Action
1	Articulation of problems (Selection of limits)	**Selection of theme:** What is the problem? Why is it a problem? **Main variables:** What are the main variables and concept? **Time horizon:** How far ahead should we look? How far back do the roots of the problem go? **Dynamic definition of problems (modes of reference):** What is the behavior of the key concepts and variables? How will this behavior look in the future?
2	Formulation of dynamic hypotheses	**Generation of initial hypotheses**: What are the current theories of the problematic behavior? **Endogenous focus**: Formulate a dynamic hypothesis that explains the dynamic as endogenous consequences of the feedback structure. **Mapping**: Develop causal structure maps based on initial hypotheses, key variables, reference modes and other available data, using tools such as: model contour diagrams; subsystem diagrams; causal circuit diagrams; stock and flow maps; policy framework diagrams; and other facilitation instruments.
3	Formulation of a simulation model	Structure specification, decision rules. Estimation of parameters, behavioral relationships and initial conditions. Test consistency with a purpose and a limit.
4	Test	Comparison with reference modes: Does the model adequately reproduce the problem behavior for its purpose? Robustness under extreme conditions: Does the model behave realistically when forced by extreme conditions? Sensitivity: How does the model behave with regard to parameter uncertainty, initial conditions, model limit and aggregation?
5	Planning and assessment of policies	Scenario specification: What environmental conditions might arise? Policy design: what new decision rules, strategies and frameworks can be tried in the real world? How can they be represented in the model? “And if. . .” Analysis: What are the effects of the policies? Sensitivity analysis: How robust are the policy recommendations in different scenarios and given uncertainties? Policy interactions: Do policies interact? Are there synergies or compensating responses?

Source: Sterman (2000).

The study sought to present a model with the main variables and their simulation, generating graphs that facilitate comparisons of different futures, allowing for alternatives. This can aid decision-making in urban solid waste management and propose new public policies.

Research methodology

The study was developed in 3 phases, and this article focuses on the last two phases. The first was exploratory and descriptive research, using bibliographic research to define the variables. This step was defined and published in Silva, Fugii and Santoyo (2017). The second phase was explanatory and analytical because it developed the model from the 5 steps for modeling presented in Table 3, from the precepts of system dynamics (MATOS, 2012). The third phase involved explanatory and analytical research using the model built in Phase 2 to establish scenarios and modeling (Table 4).

The first phase was a qualitative study, with data collected through a literature review. The second and third phases were qualitative, using quantitative techniques to establish a system dynamics model, with experimental analysis.

This research is documentary and experimental, with a case study regarding the methodological procedures. The first phase involved the documentary procedure and the second and third phases focused on the case study and experimental study. As for the approach, it is quali-quantitative because the variables were defined through bibliometric and documentary research (Phase 1) and quantitative because data analysis was used to establish the scenarios. The nature of this research is applied because it aims to generate new knowledge to solve specific problems.

The research followed the five steps for establishing a system dynamics model proposed by Sterman (2000), as shown in Table 3. An explanation of each step for the case under study is presented below.

First step: the problem is related to the current management practiced in Brazil and the deficiencies found in Curitiba in past research. In this way, the work proposed an urban solid waste management model applied to the municipality based on the National Solid Waste Policy and Circular Economy theory.

The current study is the unfolding of the first phase, published in Silva, Fugii and Santoyo (2017), which provided the variables for the development of the presented model.

Second step: this is related to the general goal of the study, which was to present an urban solid waste management model based on system dynamics to anticipate the future, generating scenarios and aiding decision making. From the variables stipulated in the first step and the existing relationships between the variables, assumed in theory, the theoretical model was constructed.

Third and fourth steps: these are, respectively, the formulation of a simulation model and a test using Vensim® software. From the theoretical model, the system dynamics for the simulation were developed. At this stage, the model was tested and validated through interviews with experts to update the current scenario in Curitiba, as well as provide the primary data needed to develop the system.

Obtaining the primary data involved the participation of individuals directly or indirectly linked to waste management in Curitiba, that is, people from the Municipal Secretariat for the Environment, Waste and Citizenship Institute and Municipal Secretariat for Supply.

The primary responses for the execution of the scenarios included the current cost of collection, the cost of final disposal, amount of waste generated per capita, and gravimetric composition of the waste that is generated. Other responses included the final destination, existing treatments, future actions and the analysis horizon, which is the duration of the next tendered service.

In addition to the primary data, the study was complemented by official secondary data from the National Sanitation Information System (SNIS), the 2017 Integrated Solid Waste Management Plan for Curitiba, and the Urban Solid Waste Plan for the Management of Treatment and Disposal of the Intermunicipal Consortium for the Management of Urban Solid Waste, in addition to the electronic portal of the city of Curitiba.

These sources provided information on the number of inhabitants, population growth rate, past strategies, future actions and historical management data since 2010. From the data and variables, a model was built based on the system dynamics methodology.

In this way, the generated scenarios have greater circularity of materials through the recycling of dry and wet matter, less waste sent to landfills, shared responsibility for waste, alternative treatment technologies, and better packaging and segregation, in addition to avoiding waste generation.

Fifth step: policy planning and evaluation, which were discussed based on the results obtained from applying the model simulating the city of Curitiba. This simulation spanned a period of 27 years, which corresponds to the duration of the next tendered service. The first scenario presented how the current situation of the waste management system will unfold until the year 2045, that is, it continues with the present problems and limitations and generates future consequences, as will be presented in the results section.

Table 4 presents the structure of the research with the main activities developed with regard to the methodology.

Table 4 – Structure of the research methodology

Research	Technique/ Activity	Materials	Theme	STEP	Actors-Object of study
Exploratory/ descriptive phase	Bibliographic research/ Literature review	Books, articles, theses, dissertations	Urban solid waste management	Step 1 – Table 3	Economopoulos (2012); Jacobi and Besen (2011); Lohri *et al.*, (2017); Massukado (2008); Monteiro *et al.*, (2001); Othman *et al.* (2012); Tchobanoglous and Kreith (2002); Zanta and Ferreira (2003). SNIS (2021); Leis; Dyson and Chang (2005); Georgiadis (2013); Kolekar, Hazra and Chakrabarty (2016); Simonetto and Löblerb (2014); Sukholthaman and Sharp (2016)
		Books, articles, theses, dissertations	Public policies		Dye (2011); Kraft and Furlong (2010); Souza (2006); Trevisan and Van Bellen (2008)
		Articles, books, theses	System dynamics		Aracil (1995); Dyson and Chang (2005); Forrester (1971); Simonetto and Löblerb (2014); Sterman (2000)
Explanatory/ analytical phase	System dynamics/ Construction of models	Portfolio of main works, books, theses	System dynamics methodology	Step 2 to 5 – Table 3	Matos (2012); Simonetto and Löblerb (2014); Sterman (2000)
Explanatory/ analytical phase	System dynamics/ Modeling and simulation	Vensim® software	Application of system dynamics	Step 5 – Table 3	Garcia (2003, 2008); Simonetto and Löblerb (2014); Sterman (2000)

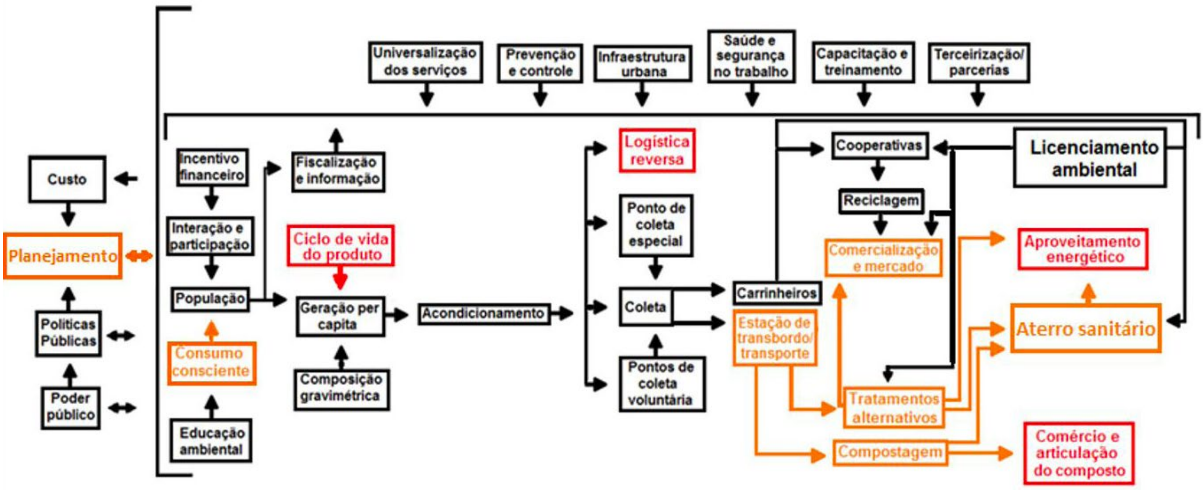
Source: Prepared by the authors (2022).

Results: constructing the model and simulation

The variables used in the model are from the study by Silva, Fugii and Santoyo (2017), who evaluated the actions of the municipal government of Curitiba in terms of urban solid waste management policies for the Brazilian context. Among their findings, the authors pointed out that the municipality has a universal service and provides basic services of selective collection and final disposal in landfills. However, the authors drew attention to the need to improve management, considering that the municipality does not have treatment for wet waste, in addition to a low recycling rate of dry waste (SILVA; FUGII; SANTOYO, 2017).

Further studies are required to evaluate the real situation of services provided *in situ* for the improvement of management in the city. The variables used in other works by these researchers were established through an evaluation by specialists, using a questionnaire, with the responses undergoing a reliability test. This result is presented in Silva, Fugii and Santoyo (2017), who structured a theoretical model to evaluate the municipal policy of Integrated Urban Solid Waste Management (GIRSU) applied in the city of Curitiba (Figure 1).

Figure 1 – Evaluation model of the municipal GIRSU policy enacted in Curitiba



Source: Silva, Fugii and Santoyo (2017).

The variables in black are those aligned with the National Solid Waste Policy. Those in orange are actions that partially comply with the PNRS, and those in red are the variables that are not aligned with Federal Law 12,305/2010. The current model applied in Curitiba has two forms of waste collection: wet compostable with refuse and dry. The wet way is mixed with refuse, dry material and humid compostable material, which makes treatment difficult (MASSUKADO, 2008) and is aggravated by the lack of incentives (HOORNWEG, THOMAS and OTTEN, 1999). Wet waste and refuse with dry material today account for 95% of the total generated and are sent to landfills without any treatment.

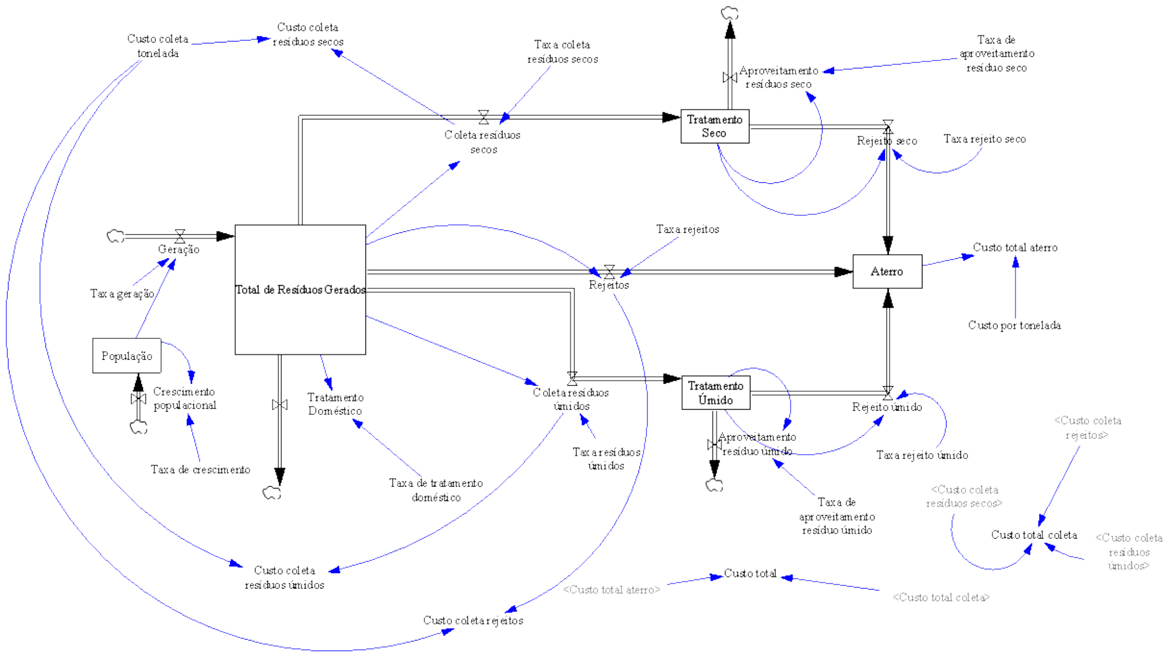
The integrated system proposed and published by Silva, Fugii and Santoyo (2017) served as the basis for the development and proposition of a new model for urban solid waste management in the capital of Paraná State: a model that seeks to align the orange and red variables shown in Figure 1. Among the variables worked on, directly or indirectly, in the model are: conscious consumption, planning, product lifecycle, reverse logistics, alternative treatments, composting, transport, transfer stations and landfills.

The model was built based on the system dynamics methodology, considering the concepts of the circular economy, the National Solid Waste Policy, the problems found in past research and the current scenario of urban solid waste in the city of Curitiba.

The works of Garcia (2003), Garcia (2008), Kolekar, Hazra and Chakrabarty (2016), Dyson and Chang (2005), Babader *et al*. (2016), Guo *et al*. (2016), Liu *et al*. (2014), Sukholthaman and Sharp (2016), Georgiadis (2013), Karavezyris, Timpe and Marzi (2002), Elia, Gnoni and Tornese (2016), Tozan and Ompad (2015), Matos (2012), Fan *et al*. (2018), Sufian and Bala (2007), Dace *et al*. (2014), Long *et al*. (2012), Tsolakis and Anthopoulos (2015), Eriksson *et al*. (2005), Simonetto and Löblerb (2014) and Simonetto (2014) aided both the development of the system and its application.

The model is the basis for developing future scenarios for a twenty-seven-year horizon, making it possible to demonstrate the management panorama in the medium and long term, anticipating future problems, presenting alternatives and aiding the strategic planning of future public policies and decision making. The period of 27 years was established in order to have a perspective for 2050. Figure 2 presents the system dynamics model built for the management of urban household solid waste. The success of such a system depends on society, which is responsible for the correct segregation of materials. The model has a decentralized treatment, which includes a home/community treatment, followed by a centralized treatment, with the collection of waste in three forms: wet compostable, dry and refuse.

Figure 2 – Urban Household Solid Waste Management Model based on system dynamics



Source: Prepared by the authors.

The model uses the treatment of wet compostable waste in a decentralized manner, at both the domestic and community level. This initiative represents a double reduction, that is, in the cost of collection, which is R$ 177.97 (one hundred and seventeen reais and ninety-seven cents) per ton and in the cost of waste destined for landfills, which is R$72.89 (seventy-two reais and eighty-nine cents) per ton. The flows of this model are detailed and justified below (Figure 2).

The composting or vermicomposting system has a low investment and construction cost compared with other treatment methods, in addition to being considered clean and sustainable, and converts waste into value-added products (AMORIN *et al*., 2016; DA SILVA *et al*., 2018; DA Silva *et al*., 2016; LIM; LEE; WU, 2016).

In this way, the proposed model shows that waste treatment can contribute to more efficient waste management, due to the lack of a better technological system for treating and collecting waste, as well as a material production system, changing habits that encourage recycling (COSTA, 2010) and the segregation and reduction of waste at the source.

As for refuse which, according to the gravimetric study, represents around 20% of the waste that is generated, it was not simulated in this work, as it focuses mainly on the treatment of compostable organic waste. Some possibilities for this kind of waste are their replacement by humid or dry compostable materials, in addition to the use of other technologies such as thermal ones, which are also not addressed in this work.

One of the treatments that require heat is incineration, which is not used by the municipality in the treatment of domestic solid waste nor in the model due to the high cost of investment, maintenance, operation and monitoring. In addition to the need for specialized labor and the use of fuels, the system can generate products as or more dangerous than the waste itself when operated incorrectly (MARCHEZETTI; KAVISKI; BRAGA, 2011).

Incineration and other forms of energy recovery, although useful to reduce the amount of waste destined for landfills, prevent the recycling of materials (TISSERANT *et al*., 2017). Promoting the recycling resource industry and post-consumer products increases landfill life and reduces the need for incineration (JUN; XIANG, 2011).

Several authors have addressed the issue of solid waste recycling models. Kolekar, Hazra and Chakrabarty (2016) discussed and reviewed models for predicting waste generation, Dyson and Chang (2005) also worked on waste generation. Babader *et al*. (2016) addressed social behavior and packaging reuse, Guo *et al*. (2016) worked on intervention for behavior change in Baltimore, United States and Liu *et al*. (2014) researched consumption and impact.

Sukholthaman and Sharp (2016) worked on waste segregation in Bangkok, Thailand. Georgiadis (2013) discussed a recycling network, focusing on the role of industry, and Karavezyris, Timpe and Marzi (2002) used two tools for forecasting solid waste management.

Elia, Gnoni and Tornese (2016) evaluated waste collection through the product service system and Tozan and Ompad (2015) worked on issues related to urban health. Matos (2012) worked on reverse logistics networks, Fan *et al*. (2018) modeled recycling in Taiwan and Sufian, and Bala (2007) researched waste management in Dhaka, Bangladesh. Dace *et al*. (2014) analyzed the effect of a packaging development policy, and Long *et al*. (2012) worked on the generation of plastic waste in Beijing, China.

Tsolakis and Anthopoulos (2015) addressed the issue of smart cities and development, while Eriksson *et al*. (2005) explored the assessment of product lifecycles. Simonetto and Löblerb (2014) evaluated scenarios for the generation and disposal of urban solid waste, and Simonetto (2014) analyzed scenarios for solid waste. Silva, Weins and Potinkara (2019) discussed the issue of formal and informal relationships in the waste chain in BRICS countries (Brazil, Russia, India, China and

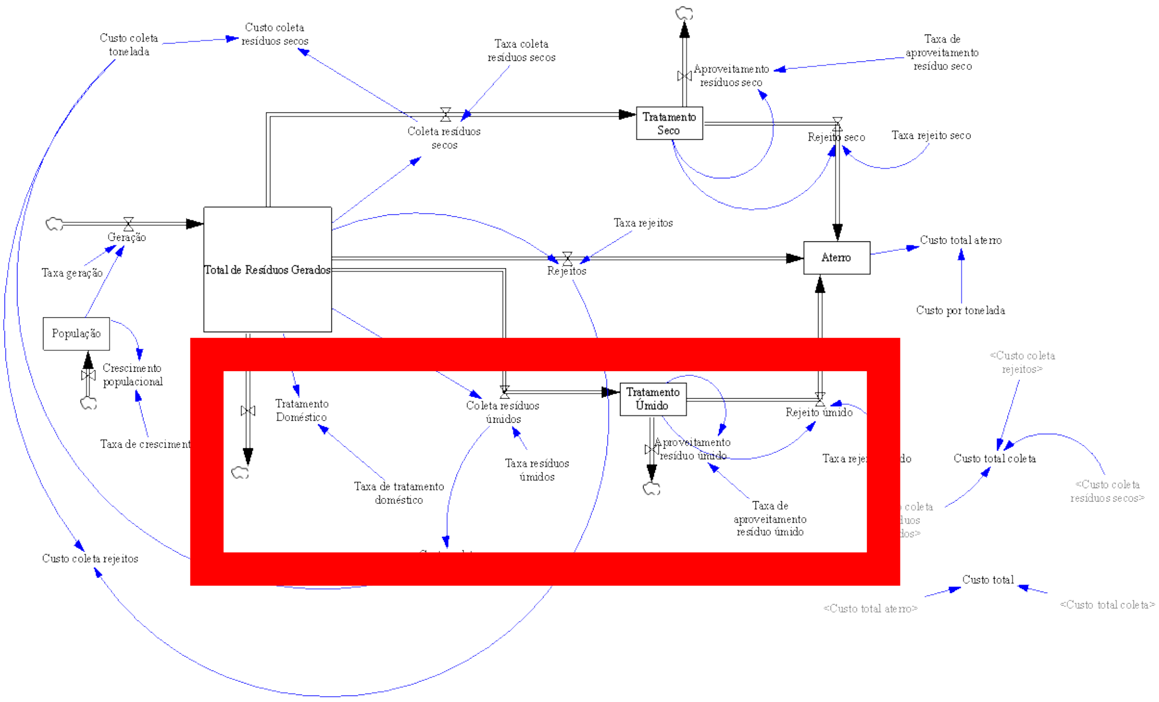
South Africa), and Silva (2018) presented a model focusing on Curitiba, but concentrating on recycling.

Thus, the presented model differs in some aspects from the other models by proposing a decentralization of composting, participation of society, the segregation of waste into three types, and the exclusion of incineration. The model also considers the characteristics of the city of Curitiba, seeking to follow the precepts of the National Solid Waste Policy in Brazil and the concepts of the Circular Economy.

Validation of the model

To validate the model validation, simulations were carried out based on current data. Only variables outside the box in red were used, as shown in Figure 3. In this way, the panorama predicted the development of the current service provided over a 27-year horizon.

Figure 3 – Partial use of the model to simulate the current scenario



Source: Prepared by the authors.

The data for simulating the current scenario are shown in Table 5, extracted from interviews, Municipal Plans and historical data from the National Sanitation Information System. It is the basis for the other scenarios, changing only the treatment and reuse rates and the year of the changes. Therefore, it can be applied to other municipalities.

Table 5 – Data used for the simulation of the model

Population	1,917,185	Recycling rate of dry waste	0.05%
Population growth rate	0.99	Reuse rate of dry waste (over the percentage of dry waste)	0.055%
Per capita generation	0.8 kg	Refuse rate	0.95%
Decentralized composting rate	0%	Collection and transport cost	177.97 per ton
Centralized wet treatment rate	0%	Landfill cost	72.89 per ton

Source: Prepared by the authors.

Figure 4 shows the costs of the current model forecast until 2045. If the service provided is maintained, the total cost over a 27-year horizon will be R$ 4,327,274,227, with increasing costs over the years, without adjusting for future inflation.

The projected population of Curitiba in 2045 is 2,501,381 inhabitants, with expenditure of R$ 181,631,730.20. To validate this simulated value, it was compared with other municipalities with a current population close to that projected for Curitiba at the end of the scenario (2045). Thus, based on data from the National Sanitation Information System (SNIS, 2021), the closest capitals are Fortaleza and Belo Horizonte. Table 6 shows that the cost trend and the amount of waste disposed of in landfills vary little among the three municipalities, remembering that Curitiba is the projected value and Fortaleza and Belo Horizonte the actual values for validating these findings.

The same occurs with the unit values (disposal per capital per day and cost of disposal per ton), indicating a variation between the projected scenario for Curitiba close to the current values for Fortaleza and Belo Horizonte.

Table 6 – Comparison of the results of the Curitiba Waste Management Policy (projected for 2045) with current data from Fortaleza and Belo Horizonte

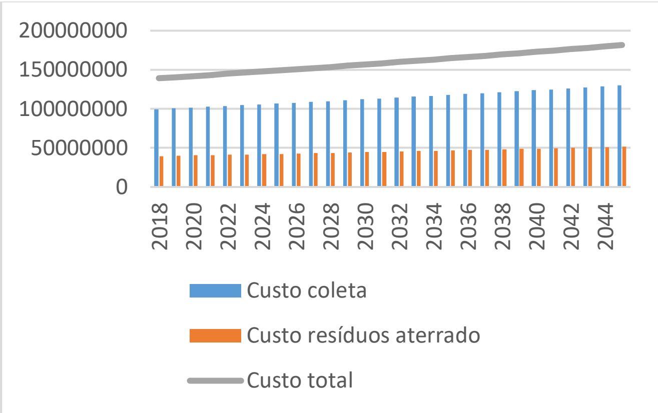
City (Brazil)	Year	Population	Cost of Service (Millions R$/ Year)	Amount of waste sent to landfills (Tons/Year)	Disposal per capita (kg/day)	Cost of disposal (R$/ton)

Curitiba	2045 (projected by the model)	2,501,381	182	730,403	0.80	249.18
Fortaleza	2013	2,551,806	196	857,161	0.92	228.66
Belo Horizonte	2015	2,502,557	135	822,064	0.90	164.22

Source: Prepared by the authors.

From this validation of the model, Figure 4 shows the evolving cost of the service over time for Curitiba, dividing between collection and disposal cost and total cost.

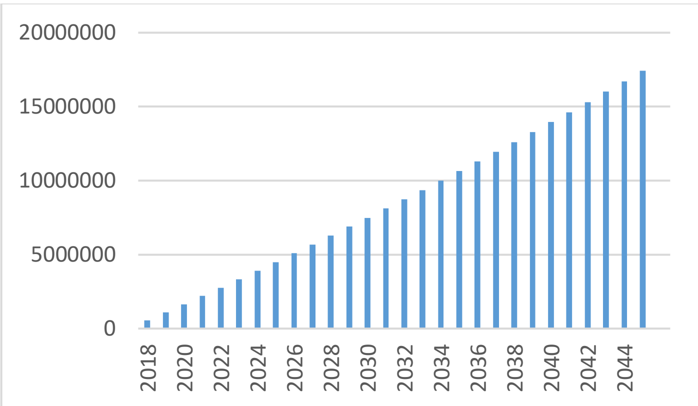
Figure 4 – Application of the Dynamic Waste Management Model to project service costs over a 27-year horizon – Curitiba



Source: Prepared by the authors.

Figure 5 shows the growing amount of waste sent to landfills, with a total of 16,879,392 tons of waste accumulated in 27 years, with a yearly total of 708,491 tons in 2045.

Figure 5 – Amount of waste sent to landfills in the current model



Source: Prepared by the authors.

Since 2010, the municipal government has had an Integrated Solid Waste Management Plan that is reviewed at the beginning of every new mandate. This plan includes actions and strategies to reduce the amount of waste sent to landfills through composting, increased reuse of dry waste and recycling cooperatives.

However, the National Sanitation Information System, which provides historical data from municipal governments, has shown that Curitiba sends over 96% of its waste to landfills (SNIS, 2021).

In view of this, the application of the model can allow the preparation of scenarios of public policy actions that relate the cost and benefit of each action. As an example, some possible scenarios can be given: an analysis of the reduced cost of collection and transport using a transfer station; treatment of dry waste with circular economy features and reduction of waste sent to landfills; decentralized treatment of compostable organic waste carried out with the participation of the population at home or in community areas; and management trends in other countries, with 50% of wet waste treated in a decentralized manner (20% of total waste) and 5% reuse of dry waste.

Conclusion

For the proposed model, the systems dynamics methodology was considered, along with the National Solid Waste Policy and possible destinations based on the Brazilian context. The interviews and bibliographic and document research provided current data for the application of the model and to propose scenarios. The model presented in Figure 2 provides a basis for future scenarios, considering the most up-to-date values, that is, it projects the future according to the current model in use.

The scenarios that were developed aid planning, decision making and the implementation of public policies. The proposed model contributes to projecting, in the medium and long term, the amount of waste sent to landfills and the costs of a certain form of management, as well as the relations between the variables that make up the dynamic system.

This model can be applied to other municipalities, aiding strategic planning, decision making and the implementation of public policies. The scenarios provide an inkling of future consequences and how to proceed to achieve a certain goal, be it financial (reduction in the cost of waste management), or the reduction of materials sent to landfills or both (financial and physical). The model also demonstrates that intentions alone cannot change a reality. The Municipal Plan mentions the alternatives developed in the model. However, there is a lack of demand, participation and evaluation by society in the public policy processes involving the urban household solid waste chain.

The validation of the model allows it to be used to examine various scenarios, support public managers in their decision-making processes, and encourage greater social participation in this process. There are public alternatives to this problem, which is growing in several developing countries, such as Brazil, but there is also an opportunity to transform these problems into alternatives for the better use of natural resources. A crisis creates opportunities and this is no different when it comes to solid waste. Nevertheless, it is necessary to understand this problem from another perspective, as proposed in this article. A suggestion is to apply this model with the analysis of scenarios for Curitiba, as well as the use of its reasoning for application to other municipalities.

Finally, it should be highlighted that the model allows the creation of new forms of waste management in Brazilian municipalities, considering that it is one of the main items of municipal public expenditure and that there is a need to comply with the National Solid Waste Policy. This new way of understanding waste management turns the problem, as it currently stands, into an opportunity for regional development.

Therefore, it is important to understand the public policy issue of solid waste as an opportunity. The model makes it possible to establish scenarios, which use the assumptions of the circular economy, and can show that in the long term this policy will be better socio-economically, environmentally and institutionally than the current waste management model.

The use of the model for waste management is socially and economically better because it generates income for cooperative organizations, reduces the cost of "burying" waste and generates more public resources that municipal governments can invest in other social functions. Furthermore, it is environmentally better because it has a softer impact and aids compliance with the National Environmental Policy. It is also important because it is better from an institutional viewpoint, as it complies with the National Solid Waste Policy.

Acknowledgements: CAPES for the scholarship and the CNPq for supporting this research project (Process 306960/2019-2 and 304937/2022-3).

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