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Assessment of Energy Saving in Waste Recycling using System Dynamics

Uso de Systems Dynamics para avaliação de cenários sobre a reciclagem de resíduos sólidos e seu impacto na economia de energia elétrica

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ABSTRACT

This paper presents a computer simulation model to analyze energy saving in waste recycling. This simulation aims to support environmental decision-making process especially in regards to issues as agenda setting for Environmental Policy and its evaluation. The proposed model is based on the following parameters: population growth rate, solid waste and recycling rates, gravimetric composition of the material in the total waste generated, Per capita waste generation and, electrical energy saving materials. . For modeling and system implementation the Vensim software from Ventana Systems was used. Through the results generated by the model, it is expected that environmental managers will be able to, for example, set incentives to reduce the total generation of waste and produce campaigns emphasizing reuse and recycling. Model validation was made through the analysis of future scenarios for a given city in southern Brazil.

Keywords: Computer Simulation; Municipal Solid Waste; Environmental Management; Waste Management; Saving Energy; Population Growth.

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RESUMO

A reciclagem é um tópico de grande importância na gestão integrada dos resíduos, prova disso é sua importância na Política Nacional dos Resíduos Sólidos. Nesse artigo apresenta-se um modelo de simulação computacional, desde seu desenvolvimento até sua validação, que tem por objetivo auxiliar gestores ambientais em suas decisões com relação à definição e/ou manutenção de políticas de reciclagem de resíduos sólidos, bem como avaliar os benefícios do processo no meio ambiente (nesse artigo foi avaliada a economia de energia elétrica). Para a construção do modelo considerou-se: a taxa de crescimento natural populacional (nascimentos e mortes), percentual de resíduo sólido reciclado (para cada tipo de material), composição gravimétrica do material no total de resíduo gerado, quantidade de resíduos gerada por habitante e a economia de energia elétrica ocasionada por cada tipo distinto de material. Através dos resultados gerados pelo modelo, os usuários finais (gestores ambientais) do mesmo poderão, por exemplo, definir incentivos à redução da geração total de resíduos sólidos, produzir campanhas valorizando o reuso e a reciclagem e avaliar os benefícios relativos à economia de energia elétrica ocasionados pela reciclagem. A validação do modelo foi através da análise de cenários futuros para um determinado município da região sul do Brasil. Para a modelagem e execução do sistema foi utilizado o software Vensim da Ventana Systems.

Palavras-Chave: *Simulação Computacional; Reciclagem de Resíduos; Gestão Ambiental.*

1 INTRODUCTION

The evolution of integrated solid waste management in recent years turned it into an important and critical area for municipal and environmental managers, and general population. These developments have also led to new problems to be considered, such as environmental, economic and legal problems. Among them are the results of misuse and waste disposal, which can cause major adverse impacts to the environment, featuring a waste of the material originally used.

In order that the waste generated by population and industries be reused, and contribute to reducing the use of natural resources becoming more and more scarce, it is essential to have accurate and reliable information on the physicochemical characteristics of the waste, the amounts generated, collected, as well as its destination. Waste recycling is an excellent alternative in the search of sustainable development in the integrated management of solid waste, for it allows electrical energy saving as well as a lower use of natural resources in the production of steel, aluminum, paper/cardboard, plastic and glass. Another aspect denoting the importance of waste recycling is that it is considered a priority action by the Brazilian Policy for Solid Waste - PNRS (Ministry, 2011).

The study of integrated management solid waste has catch the attention of researchers in the area of decision support systems in recent years, because through the use of this tools it is possible to represent a real-world situation, to study their behavior and take decisions based on the conclusions drawn (Bani et al., 2009). Proof of this are the numerous studies published, which range from the allocation of vehicles to collect waste (Bhat, 1996; Everett and Shahi, 1997) to build models of environmental impact assessment caused by the disposal of waste, taking into account the disposition type, the type of waste and the area where it was deposited (Perrodin et al., 2002).

Other authors (Huang et al., 1998; Chang and Wei, 2000; Chang et al., 2008; Costi et al., 2004; Sufian and Bala, 2007; Tanskanen, 2000; Tung and Pinnoi, 2000; Weintraub et al., 1998) have used techniques and methods of decision support systems to develop researches in this specific area, although these researches are few in Brazil.

The aim of this paper is to present the modeling, development and validation of a computer simulation model that allows decision-makers in the environmental area, more specifically in the area of solid waste to assess and analyze scenarios regarding solid waste recycling, both in terms of the amount of waste recycled as the benefits generated by recycling; in this paper it was evaluated the electrical energy saving achieved with the recycling process of different types of recycled materials. To illustrate the energy saving achieved by recycling we can point out aluminum (Hisatugo and Marçal Jr., 2007): to produce 1 ton from raw material 17.6 Mwh is used, and to produce the same amount, from recycled aluminum only 0.75 Mwh is used, thus generating saving of 16.85 MWh (95% of electrical energy saving).

For such problem, this research consisted of investigation, definition and validation of the variable components of the simulation model as well as its design and validation. To develop the computer model, techniques of the *system dynamics* area were used (Gharajedaghi, 2011; Daellenbach and McNickle, 2005). The use of decision support systems tools seeks to add quality to the decision-making process because, even today, many decisions on solid waste management are based only upon the experience of managers (Chang and Wei, 2000).

The paper is organized as follows: Section 2 presents the research methodology, as well as the formulation of the dynamic hypothesis used in the development of this study and describes the problem of modeling, the variable components and the model developed. Section 3 presents the validation, the simulation scenarios, and the experiment using the model as well as the discussion of results. Final considerations and conclusions are presented in section 4.

2 MATERIAL AND METHODS

Simon (1990) states that modeling systems can be classified into two types, prediction and prescription. Although the fascination with predicting the future, which is natural in human beings, after all it is about its own future, a model that takes the prediction of timing behavior of large systems has no chance of complete success. The modelling with the highest chance of success is the prescriptive one. According to Simon (1990) taking the issue raised by the Club of Rome, about the prediction of "nuclear winter", approaching it as a prescriptive problem and not as a predictive problem, would be the most appropriate way, since important issues would arise in order to be answered. What is the population that can be maintained on earth in "steady state" with a reasonable standard of living, and what is the steady-state amount of energy produced possible to be maintained without serious damage to the environment.

In this study the research methodology used to develop the computer model was based on the methodology proposed by Law and Kelton (1991) and consisted of the following steps: (1) exploratory studies in scientific papers, reference manuals and interviews with managers from solid waste area, in which the problem was characterized and structured, as well as the dynamic hypothesis was formulated, which is presented in section 2.3; (2) developing the solution, through the construction of formal models able to describe the problem; (3) computer implementation of the solution, using the Vensim simulator (Vensim, 2012) from system dynamics area; (4) solution validation, through laboratory and field tests, to verify if the results are in accordance with the reality observed, as well as through simulation of an experiment by using three scenarios.

The scenarios used to validate the model were generated from analysis, where historical data regarding the population censuses of 2000 and 2010 (IBGE, 2010) were used, as well as the Overview of Solid Waste in Brazil-2010 (ABRELPE, 2011), the Brazilian Plan for Solid Waste (Ministry, 2011), as well as the Diagnosis of Solid Waste Management (Ministry, 2010) and also through the participation of researchers and experts in the field. The concepts involved in the development of this research (system dynamics and waste recycling) are presented below in sections 2.1 and 2.2.

2.1 System Dynamics

The system dynamics method (SD) allows studying the system behavior over time, so as to permit assessing the consequences of our decisions (Daellenbach and McNickle, 2005). For this reason and the need to study the waste recycling at a future time horizon it was decided to use it in computer modeling and simulation. An SD model can be interpreted as the structure resulting from the interaction of policies. This structure consists of two main components, which are the stocks and flows, so that Ford (2009) defines SD as a combination of stocks and flows using a computer structure to be simulated. Stocks describe variables that are accumulated and flows work as decision functions or policies of a system.

These components may be arranged in circular relationships of cause and effect, known as balance feedback or reinforcement, and they are subject to time lags in the system. Sufian and Bala (2007) used this approach for modeling the solid waste management system of the city of Dhaka, Bangladesh. Several other authors have also used this method, among which can be cited Abeliotis et al. (2009); Dyson and Chang (2005); Kum et al. (2005).

2.2 Waste Recycling

Recycling, according to O'Leary & Walsh (1999), is the process by which the waste intended for final disposal are collected, processed and reused. Monteiro et al. (2001) defines recycling as being the separation of household waste materials such as paper, plastics, glass and materials, in order to bring them back to industry to be benefited. These materials are reprocessed into marketable products.

The recycling of solid waste is an excellent alternative to provide the preservation of natural resources, energy saving, reduction of the area demanding the landfill, generation of jobs and income, as well as public awareness for environmental issues. However, for the better functioning, it is very important to implement a wide system of selective collection in the cities, where recyclables MSW (municipal solid waste) be segregated in homes and collected by the municipal selective collection system. Despite being a good alternative for the reduction of waste intended to landfills, only a small portion (about 10%) of waste are reused or recycled in the cities of Rio Grande do Sul, according to CEMPRE (Non-Governmental Organization of Business Commitment for Recycling) (Netto, 2001). One of the reasons for such low recycling is the poor packaging waste by population, due to the lack of information about selective collection.

Other factors contributing to low waste recycling rates is the high cost of selective collection for municipalities (O'Leary et al., 1999; Monteiro et al., 2001), as well as the lack of a properly sized system in terms of storage capacity and processing waste at the sorting units. But despite the problems faced, cities are investing and supporting increasingly waste recycling, either through selective collection or through the construction of recycling plants, due to the fact of excessive time in waste decomposition and to a continued search for a better use of these waste (Chang and Wei, 2000).

2.3 Formulation of Dynamic Hypothesis

According to Silva (2006), dynamic hypothesis aims to deal with the problem theory, analyzing its behavior and noticing what variables are parts of the system. In this article, four (4) basic variables were included: population change, waste generation, electrical energy saving and the types of materials that can be recycled (aluminum, steel, paper / cardboard, glass and plastic).

The first one (population change) is understood as the most difficult to control, since the place used already grows at a diminutive rate of 0.7% per year, and this rate remained fixed within the three scenarios. The current average of waste generation is 1.223 kg/person (ABRELPE, 2012); in two scenarios this rate was modified, considering the annual increase (about 1%). In another, the amount of 1.223 kg / person remained static throughout the simulated time. As for recycled materials and their recycling rates as well as their participation in the gravimetric composition of solid waste, we used those presented in the Brazilian Plan for Solid Waste (Ministry, 2011). The energy saving rates for each type of recycled material were achieved in technical articles (Hisatugo and Marçal Jr., 2007) and sites of organizations that work on integrated solid waste management (Waste Management, 2012).

The aim of this step is to formulate a hypothesis to explain the dynamics as a result of the internal structure of the system through the interaction between the variables and the agents represented in the model, including decision rules (Strauss, 2010). Therefore, the dynamic hypothesis of the systems dynamics model of this study is defined below as:

- The population variation regarding the amount of waste generated by the component elements of the population influences directly on the total amount of solid waste generated and recycled, influencing the electrical energy saving resulting from the recycling of aluminum, steel, paper / cardboard , glass and plastic.

3 SIMULATION MODEL AND VARIABLE COMPONENTS

The Brazilian Policy for Solid Waste (PNRS) (Ministry, 2011) defined the order of actions to be followed in waste management, among which was included recycling as one of the main actions. Recycling, under the law, is the process of transforming waste involving change of its physical, physicochemical or biological properties, in order to transform them into inputs or new products. (ABRELPE, 2012)

Associated with the priority given by PNRS, there is a growing generation of solid waste by the population (ABRELPE, 2012), so demanding that viable alternatives to the better utilization of solid waste be created and put into practice. In this regard, waste recycling becomes a viable alternative, since in the moment in which material is recycled it does not require space in a landfill, it does not pollute the environment and do not use natural resources excessively in its transformation.

Basing the priority given to recycling by PNRS and the environmental gains incurred, this study aimed to develop a simulation model that allowed both to environmental managers, as to solid waste recycling area evaluate waste recycling policies referring to recycled materials and environmental gains, aiming at a sustainable development. In the model developed, the recycled materials considered were aluminum, steel, paper / cardboard, glass and plastic.

On the question regarding the environmental gains in the model, the electrical energy saving caused by the recycling of such materials was evaluated. Other resources could be evaluated, such as: reduction of the felling of trees, water consumption reduction, minimizing of use of oil, etc.

Decisions, from the analyses generated by the model, may involve the pursuit of raising the recycling rate (with awareness campaigns from population), efforts to reduce consumption, incentives to increase "green consumerism" (reducing organic waste in the environment) (Mansvelt, 2010), as well as other analyses and observations of environmental managers and / or municipal governments interest, since they are feasible in the simulation model. The model was implemented aiming to simplify the computer-user interaction so that what-if analyses, usual in simulation models, be quickly and simply implemented.

For the definition of the simulation model variables (Figure 1) academic and governmental studies form solid waste area were used (ABRELPE, 2012; IBGE, 2010; Kum et al., 2005; Ministry, 2010; Ministry, 2011; Monteiro et al., 2001; UNEP, 2005). The validation of these variables was made with the participation of environmental managers and professionals from solid waste area. The selected variables and their interrelationships with other variables, which influence the total values of generation and final disposal of urban solid waste, are:

- The **annual birth rate (*BirthRate*)**, the ***annual mortality rate*** (***DeathRate***), the **annual immigration rate (*ImiggRate*)** and **the annual emigration rate (*EmiggRate*)**, all these directly influencing the flow of **input** and **output population** (***InputPop and OutputPop***), which determine the **total population** (***Population***) of the city. In the model, the natural growth or vegetative rate was used (total births - total deaths), which corresponds to the only possible way to increase or decrease the world's population and, when it is analyzed the growth of specific areas should be considered, too, migration. These variables are represented by equations (1), (2) and (3) in the mathematical formulation of the ordinary differential equations model. (Figure 2)

- The average waste amount (***SWPerCapita***) generated per capita multiplied by the total population results in the total waste amount (***SWGeneration***) of the city. The variables described are represented in equation (4) of the mathematical model in Figure 2;

- The **input streams of recyclable waste in different types of recyclable material (*SteelRecyc, AluminumRecyc, PaperRecyc, PlasticRecyc, GlassRecyc*)**, which represent the total annual recyclable solid waste from each of the different types of material and are obtained through the product from the total waste amount (***SWGeneration***) by **the percentage rate of solid waste in total waste generated** (gravimetric composition) and also its product by the material recycling rate under analysis. Equations (Figure 2) representing the variables on the input streams are described in the mathematical model by equations (5), (6), (7), (8) and (9);

- The total accumulated amount of each type of recycled material is represented by ***Steel* (Steel), *Aluminum* (Aluminum), *Paper* (Paper/Cardboard), *Plastic* (Plastic) and *Glass* (Glass)** variable levels. The variables regarding the cumulative totals of recyclable waste are described in equations (10), (11), (12), (13) and (14), in Figure 2;

- The amount of energy saved (***SavingEnergy***) through the recycling process is obtained by equation (15) described in Figure 2, which for its calculation uses data regarding the saving achieved by different types of materials, as well as the total generation of each of them.

The simulation model using systems dynamics (Figure 1) and its mathematical formulation (Figure 2) help us to understand the variables and their interrelationships, thus facilitating the understanding of it.

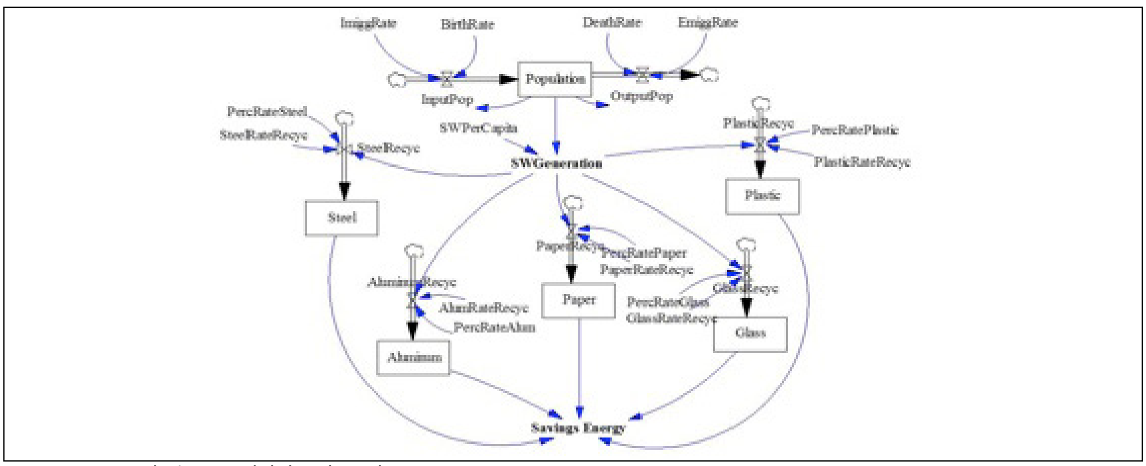

Figure 1 – Simulation model developed
Source: Authors

(1)	Population(t) = InputPop(t) – OutputPop(t)
(2)	InputPop(t) = (ImiggRate*Population(t))+(BirthRate*Population(t))
(3)	OutputPop(t) = (EmiggRate*Population(t))+(DeathRate*Population(t))
(4)	SWGeneration(t) = Population(t)*SWPerCapita
(5)	Steel(t) = SteelRecyc(t)
(6)	Aluminum(t) = AluminumRecyc(t)
(7)	Paper(t) = PaperRecyc(t)
(8)	Plastic(t)= PlasticRecyc(t)
(9)	Glass(t) = GlassRecyc(t)
(10)	SteelRecyc(t) = (SWGeneration(t)*PercSteelRate)*SteelRateRecyc
(11)	AluminumRecyc(t) = SWGeneration(t)*PercAluminumlRate)*AluminumlRateRecyc
(12)	PaperRecyc(t) = (SWGeneration(t)*PercRatePaper)* PaperRateRecyc
(13)	PlasticRecyc(t) = (SWGeneration(t)*PercRatePlastic)* PlasticRateRecyc
(14)	GlassRecyc(t) = (SWGeneration(t)*PercRateGlass)* GlassRateRecyc
(15)	SavingEnergy(t) = ((Paper(t)/1000)*3510) + (Aluminum(t)/1000)*16850)+((Steel (t)/100000)*27) + ((Plastic(t)/1000)*5300)+((Glass(t)/1000)*42)

Figure 2 – Mathematical formulation of the simulation model developed
Source: Authors

3 RESULTS AND DISCUSSIONS

The validation has been given attention in several research areas, such as Operational Research, intelligent systems, and also in decision support systems. Consequently, it is difficult to find a standard definition for "what validation is." In this study, we adopted the definition given by Pidd (1998), which states that "*a model is a representation of the real world or at least part of it. Therefore, validation is really straightforward - in principle. All validation needs to do is to check whether the behavior of the model and the real world occurs under the same conditions. If they do, the model is valid. If they don't, then the model is not valid.* "

For developing of validation of the simulation model we used the approach proposed by Finlay (1994) for validation of decision models and decision support systems (DSS). The approach of Finlay (1994) proposes the validation of decision models by combining two methods:

Analytical Validation - Each part of the decision-making model is checked individually and also its integration with other parts of the system components.

Validation Synoptic - In this type of validation, the decision-making model is examined as a whole and then the system performance is tested. The validation is performed by comparing the real world results (outputs) with the model results. If the system produces "acceptable" results in accordance with the supplied inputs, we can say that the system is valid.

In the first validation phase, that is, the validation conceptual problem, the functional requirements are validated, non-functional and variable components of the model. In this initial stage, we used data from scientific articles, from the Brazilian Policy for Solid Waste (Ministry, 2011), technical manuals regarding the area of solid waste and, with the participation of specialists in environmental management. In the second validation phase, when implementing the Vensim simulator (Vensim, 2012), we used historical data on the Brazilian population and RSU (urban solid waste) management (ABRELPE, 2012; IBGE, 2002; IBGE, 2010; Ministry, 2011) for the verification individual modules and their integration with other model component modules (analytical validation). The results generated by the simulation model and its compliance with data and results in the real world were also verified and validated, reflecting the correctness of the model (synoptic validation). In both phases the results met the expectations of simulation projectors and experts (environmental managers).

In the subsequent validation phase, for the experiment construction, data and real rates (population, population growth and data on solid waste management), of a city of Rio Grande do Sul, were used.

For such, we generated two (2) scenarios to be simulated in the model: (a) Current scenario with varying current rates and (b) positive scenario, which is based on increasing rates of waste recycling and static maintenance rate of solid waste generation by population. This type of validation can be recognized as a sensitivity analysis of the simulation model, since the variables were used in *inputs* and changes in results were checked. The detailing and quantifying rates for each simulated scenario are presented below in subsection 4.1.

3.1 Scenarios simulated in the model

To best describe the scenarios simulated in Table 1 are presented the basic rates for the population growth, the waste generation, the gravimetric composition of recycled materials in the total waste generated, and the recycling rate for each material analyzed by the model. To obtain such data the Population Census (IBGE, 2010), the Overview on Solid Waste in Brazil-2011 (ABRELPE, 2012) and the Brazilian Policy for Solid Waste (Ministry, 2011) were analyzed. The scenarios generated were conceived by the researchers, with the aid of environmental managers.

Table 1 – Base rates considered in the simulation

Population Growth	We considered current birth and death rates, where the average population growth in a city in Rio Grande do Sul was 0.7% (Ibge 2010).
Waste Generation	The average of daily urban waste generation is approximately 1,223 kg/person (Abrelpe 2012). The annual generation evolution is 2%.
Gravimetric Material Composition in the Waste Generated	Rates were achieved in (Ministry 2011): Steel – corresponds to 2.3% of solid waste generated. Aluminum – corresponds to 0.6% of solid waste generated. Paper / Cardboard – corresponds to 13.1% of solid waste generated. Plastic- corresponds to 19% of solid waste generated. Glass – corresponds to 2.4% of solid waste generated.
Recycling Rate for Material	Rates were achieved in (Ministry 2011): Steel – 35% of the recycled steel are collected. Aluminum – 36% of the aluminum collected are recycled. Paper / Cardboard – 43% of the paper collected are recycled. Plástico- 19% of the plastic collected are recycled. Glass – 21% of the glass collected are recycled.
Energy Saving by Recycling	Rates were achieved in (Garbelini et al. 2011; Hisatugo and Marçal Jr 2007; Waste Management 2012): Steel – 27 Kwh /100 t. Aluminum – 16850 Kwh / t. Paper / Cardboard – 3510 Kwh / t. Plastic – 5300 KWh / t. Glass – 42 Kwh / t.

Source: Abrelpe (2012), Ibge (2010), Ministry (2011), Hisatugo and Marçal Jr (2007), Garbelini et al. (2011), Waste Management (2012).

Positive Scenario

In designing the positive scenario, increasing rates of the recycling of the materials analyzed and their gravimetric composition in total waste generated were simulated, however, the *per capita* generation rate of solid waste remained static. Population growth was maintained for the purposes of this simulated scenario. The scenario description can be seen in Table 2.

Table 2 – Rates used in the simulation with a positive scenario

Population Growth	We considered current birth and death rates of the city analyzed.
Waste Generation	In this scenario, the generation rate remained static until the end of the time simulated and the annual evolution rate of 2% was not considered.
Gravimetric Material Composition in the Waste Generated	In this scenario, we considered an increase of 30% of the gravimetric composition for the past ten years simulated (20° to 30°).
Recycling Rate for Material	In this scenario, we considered an increase of 30% in the recycling rate for each material in the first ten years simulated. From the 11th year to 30th year we considered an increase of 50% in the recycling rate for each type of material.

Source: Authors

Current Scenario

In the current scenario the recycling rates of population growth and the waste generation *per capita* were considered, but the gravimetric composition remained static, and it was considered a small increase in levels of material recycling. The scenario details can be seen in Table 3.

Table 3 – Rates used in a simulation with a current scenario

Population Growth	We considered current birth and death rates of the city analyzed.
Waste Generation	In this scenario we considered an annual evolution of 2% in the generation rate.
Gravimetric Material Composition in the Waste Generated	In this scenario, the gravimetric composition index of the recycled materials regarding solid waste generation remained unchanged.
Recycling Rate for Material	In this scenario, we considered an increase of 0.3% in recycling rates (per year) for each type of recycled material.

Source: Authors

3.2 Experiment

Once the scenarios for the experiment using the model were defined, simulations were performed. As described earlier, the data used in both scenarios were a city with about 265,000 inhabitants in Rio Grande do Sul, which has selective collection of solid waste, as well as screening units aiming at solid waste recycling. The other rates were obtained in technical documents, as can be seen above in section 4.1. The simulated time horizon of the study was 30 (thirty) years, but setting this variable is responsibility of managers (potential end users) and / or the simulation projectors.

In performing the simulations we used the Vensim simulator (Vensim, 2012) in a computer framework with Intel Core (*i5 2450*) 2.5 Ghz, 4 Gb of RAM and the runtime simulation of two scenarios occurred in the order of millionths of a second. The results obtained using the models are presented below in subsection 4.3.

3.3 Results Achieved

With the implementation of the model, the results generated are several, but the article will discuss aspects regarding the amount of waste recycled in relation to the total generation of solid waste, as well as those related to electrical energy saving generated by waste recycling.

First of all, it will be analyzed the amount of waste recycled in both scenarios; for such, it was considered the last years simulated in the model, that is, 30th year. In this analysis there is a high rate of recycling caused by the positive scenario, where it reaches the mark of 27.33% of waste generated recycling (42,670 tonnes). In this same analysis, the current scenario reaches an 11.76% rate of waste generated recycling (24,503 tonnes), which shows a growth of 9.3% to the current recycling rate (about 10.7%). The results generated, and the detailment of the simulated amount for each waste can be seen in Table 4.

The positive scenario with a recycling rate of 27.33% provides an excellent growth of 153% if related to the current recycling rate, but with all this growth, this rate is still lower than that recorded in many European countries. For example, the Netherlands has a percentage of 32% of waste recycling (EUROSTAT, 2011). To demonstrate how small is the amount of waste recycled in Brazil, a comparative chart between the paper / cardboard recycling (waste of greatest recycling rate) with the total waste generation throughout the simulated period is presented in Figure 3. At the end of the simulated time, in the positive scenario, the paper recycling rate was 14.28% (22,203 tonnes), while in the current scenario the recycling rate was 6.14% (12, 800 tonnes).

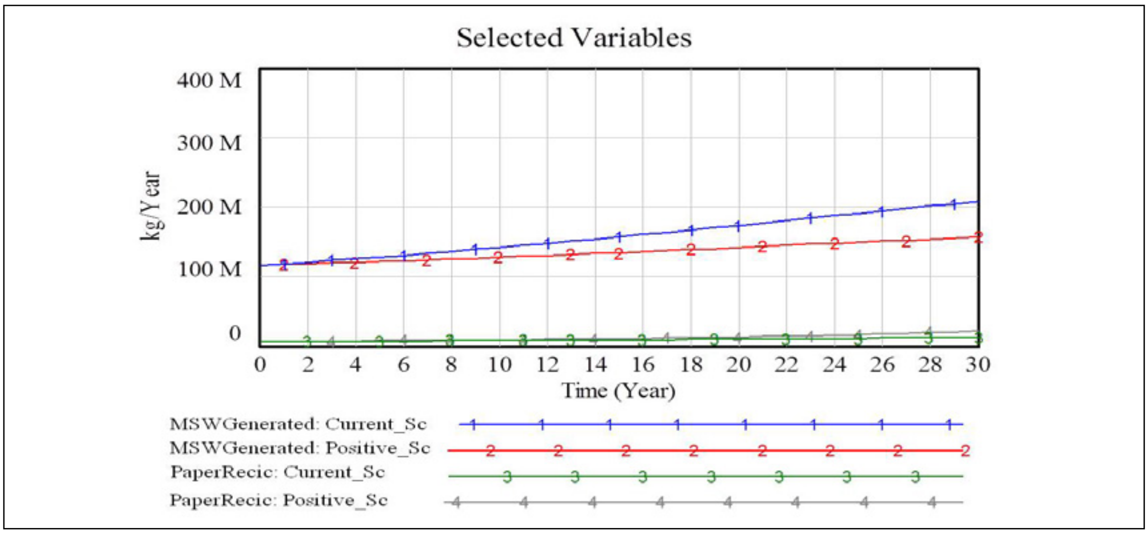

Figure 3 – Relation between the amount of recycled paper and the total waste generated
Source: Authors

Table 4 – Results of scenarios in the latest simulated year and the relation to the total generated waste

	Current Scenario (Year 30)		Positive Scenario (Year 30)	
Material	Recycled Amount	Relation Total Generation	Recycled Amount	Relation Total Generation
Steel	1,830,390 kg	0.88%	3,196,550 kg	2.05%
Aluminum	489,992 kg	0.24%	876,769 kg	0.56%
Paper/Cardboard	12,799,600 kg	6.14%	22,293,400 kg	14.28%
Plastic	8,233,200 kg	3.95%	14,306,400 kg	9.16%
Glass	1,149,980 kg	0.55%	1.997.090 kg	1.28%
TOTAL	24,503,162 kg	11.76%	42,670,209 kg	27.33%

Source: Authors

Another analysis performed on the simulation model was the amount of electricity saved over the thirty years simulated, according to the results presented (Garbelini et al., 2011; Hisatugo and Marçal Jr., 2007; Waste Management, 2012) for each material analyzed. In this analysis the benefits of recycling solid waste to the environment and the conservation of natural resources are clear, for example, the positive scenario gets a monthly average saving of 7,500 MWh, and in the current scenario, a monthly saving of 5,800 Mwh. These values are considered as excellent, for the total approximated consumption of a city the size of the analyzed one is 82,000 MWh / month (CEEE, 2012), therefore, it is estimated in the positive scenario an electrical energy saving of 9.1% per month and in the current scenario a saving of 7%. Figure 4 shows the total cumulative of electrical energy in the simulated years, where it is noticed that for the positive scenario the value is 2,694,280 MWh and 2,108,060 MWh for the current scenario.

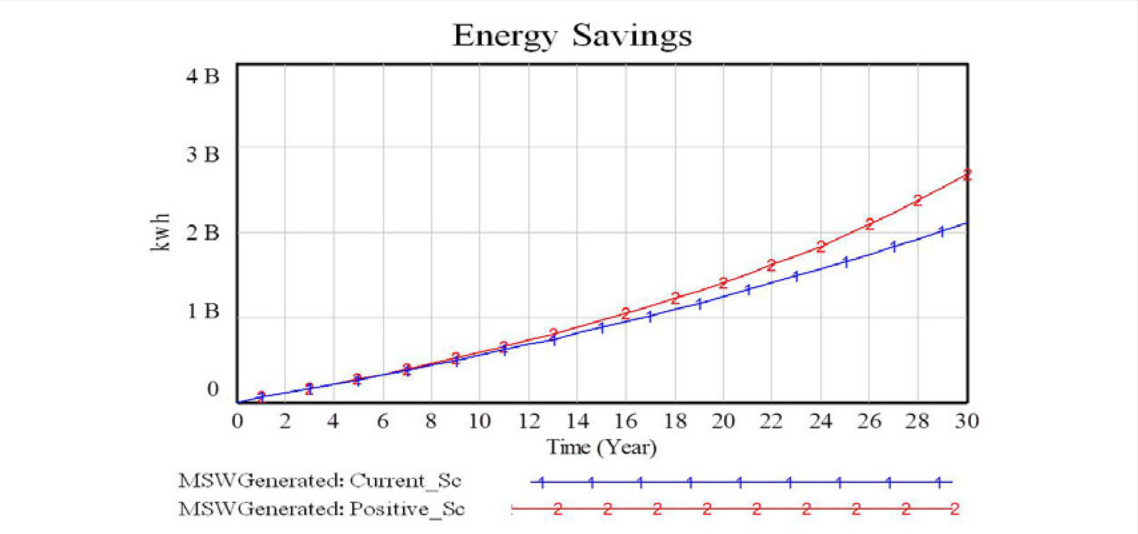

Figure 4 – Electrical energy saving throughout 30 years.
Source: Authors

4 CONCLUSIONS

The aim of this paper was to present the development, the validation and the use of a computer simulation model to aid environmental managers in the decision-making process, regarding solid waste recycling policies. To develop the model we used variables such as the population growth rate (births and deaths), percentage of solid waste recycled (for each type of material), gravimetric composition of the material in the total waste generated, the amount of waste generated *per capita* and electrical energy saving caused by each different type of material in a given period of time (which, in the model developed can vary from minutes to years).

Through the results generated by the model, end users (environmental managers) will be able to, for example, set incentives to reduce the total solid waste generation, incentives to increase rates of green consumption, produce campaigns emphasizing reuse and recycling of materials and evaluate the benefits regarding electrical energy saving provided by recycling.

In this paper two scenarios were presented, in which the model was verified and validated by using data from a city in Rio Grande do Sul. The generated results were presented to environmental managers, who tested the model again and had their aims fulfilled with it. The scenarios presented in this paper were generated exclusively for the model validation, but it can be configured according to the end user's need in order that the model is open and reconfigurable.

Regarding the results produced by the model, we highlight the positive scenario, because it sought to portray a profile of people concerned about environmental issues, that is, about generating less solid waste, increasing the amount of potentially recyclable waste and recycling rates. In this analysis, the amount of recycled waste would have an increase of 153% compared to current standards. As for the current scenario, the amount of waste recycled at the end of the simulated time would grow by 9.3%. Despite all the growth caused by the positive scenario, with a recycling rate of about 27%, it is below the European community countries, such as Germany, Belgium, Sweden, Holland and Ireland, which present rates upper to 30% of solid waste generated recycling.

As for energy savings, despite the positive scenario generates a higher saving (7500 MWh / month), the current standards (current scenario) show a considerable possibility of reduction of 5,800 MWh / month, which demonstrates the vital importance of recycling solid waste in search for sustainable development and in the Brazilian Policy for Solid Waste.

As a future research, we intend to evaluate, together with recycling, the reuse for discarded material and waste composting. Finally, we emphasize that the model, after being evaluated by environmental area managers, fulfilled their need for information.

REFERENCES

Abeliotis, K, Karaiskou K, Togia A, Lasaridi K (2009). Decision Support Systems in Solid Waste Management: A Case Study at the National and Local Level in Greece. Global NEST J. 11(2): 117-126.

ABRELPE – Brazilian Association of Special Waste and Public Cleaning (2012). Overview of Solid Waste in Brazil – 2011, ABRELPE, São Paulo. (In Portuguese).

Bani MS, Rashid ZA, Hamid KHK, Harbawi ME, Alias AB, Aris MJ (2009). The Development of Decision Support System for Waste Management; a Review, World Academy of Science, Eng. Technol. 49: 161-168.

Bhat VN (1996). A model for the optimal allocation of trucks for the solid waste management. Waste Management & Research. 14: 87-96.

CEEE. State Company for Electric Power (2012). Energetic balance of 2011. Available at: http://www.ceee.com.br/pportal/ceee/component/Controller.aspx?CC=46490. (Accessed in 14 August 2012). (In Portuguese).

Chang N, Parvathinathan G, Breeden JB (2008). Combining GIS with fuzzy multicriteria decision-making for landfill sitting in a fast growing urban region. Journal of Environmental Manage. 87: 139-153.

Chang N, Wei Y (2000). Siting recycling drop-off in urban area by genetic algorithm-based fuzzy multiobjective nonlinear integer programming modeling, Fuzzy Sets and Syst. 114: 133-149.

Costi P, Minciardi R, Robba M, Rovatti M, Sacile R (2004). An environmentally sustainable decision model for urban solid waste management. Waste Manage. 24(3): 277-295.

Daellenbach HG, McNickle DC (2005). Decision making through systems thinking. Palgrave MacMillan, New York.

Dyson B, Chang NB (2005). Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling. Waste Manage. 25(7): 669-679.

EUROSTAT- European Commission Statistical (2011). Environment in the EU27 - Recycling accounted for a quarter of total municipal waste treated in 2009. Available at: http://epp.eurostat.ec.europa.eu/cache/ITY_PUBLIC/8-08032011-AP/EN/8-08032011-AP-EN.PDF. (Accessed in 07 June 2011).

Everett JW, Shahi S (1997). Vehicle and labor requirements for yard waste collection. Waste Management & Res. 15: 627-640.

Finlay PN (1994). Introducing decision support systems. Blackwell Publishers, Oxford.

Ford A (2009). Modeling the Environment. Island Press.

Garbelini SM, Borges DM, Silva RC. (2011). Practise Selective Collection. Public Prosecution Service of Goiás. (In Portuguese).

Gharajedaghi J (2011). Systems thinking: managing chaos and complexity, 3rd. Ed., Elsevier, Burlington.

Hisatugo E, Marçal Jr. O (2007). Selective Collection and Recycling as Tools for Environmental Conservation: A Case Study in Uberlândia – MG. Sociedade & Natureza 19(2): 205-216. (In Portuguese).

Huang GH, Baetz BW, Patry GG (1998). Trash-Flow Allocation: Planning Under Uncertainty, Interfaces 28(6): 36-55.

IBGE a. Brazilian Institute of Geography and Statistics (2002). National Survey of Basic Sanitation. Available at: http://www.ibge.gov.br/home/estatistica/populacao/condicaodevida/pnsb/pnsb.pdf. (Accessed in 12 June 2011). (In Portuguese).

IBGE b. Brazilian Institute of Geography and Statistics (2010). Census 2010. Available at:

http://www.ibge.gov.br/home/download/estatistica.shtm. (Accessed in 12 June 2011). (In Portuguese).

Kum V, Sharp A, Harnpornchai N (2005). A System Dynamics Study of Solid Waste Recovery Policies in Phnom Penh City. The 23rd International Conference of the System Dynamics Society, Boston. Proceedings... Boston: SDS.

Law AM, Kelton WD (1991). Simulation Modeling & Analysis. 2ª Ed., McGraw-Hill, New York.

Mansvelt J (2010). Green Consumerism: An A-to-Z Guide. SAGE Publications.

Ministry of Cities - Department of National Environmental Sanitation (2010). National Information System on Sanitation: Diagnostic management of municipal solid waste - 2008**.** MinisterioCidades, Brasília. (In Portuguese).

Ministry of Environment (2011). Brazilian Policy for Solid Waste. MinisterioMeioAmbiente (MMA), Brasília. (In Portuguese).

Monteiro JHP et al. (2001). Handbook for Integrated Management of Solid Waste, Brazilian Institute of Municipal Administration, Rio de Janeiro. (In Portuguese).

Netto A (2001). The Wasteful Waste. Zero Hora Newspaper, Edited in 09 September 2001, p.32. (In Portuguese).

O'Leary PR, Walsh P (1999). Decision Maker's Guide to Solid Waste Management. Vol. 2, U.S. Environmental Protection Agency, Washington DC.

Perrodin Y, Gobbey A, Grellier-Volatier L, Canivet V, Fruget JF, Gilbert J, Texier C, Cluzeau D, Gros RL, Poly F, Jocteur-Monrozier L (2002). Waste ecocompatibility in storage and reuse scenarios: global methodology and detailed presentation of the impact study on the recipient environments. Waste Manage. 22:215-228.

Pidd M (1998). Computer Simulation in Management Science. John Willey.

Silva ECP (2006). The impact of management on the size of the police force in the rate of violence in Curitiba: A qualitative approach under the reference of system dynamics. Dissertation (Master of Science in Product and System Engineering) - Pontifical Catholic University of Paraná, 2006. (In Portuguese).

Simon HA (1990). Prediction and prescription in systems modeling. Operations Research, 38: 7-14.

Straus LM. A system dynamics model for higher education (2010). Dissertation (Master of Science in Management Science) – Federal University of Rio Grande do Sul. (In Portuguese).

Sufian MA, Bala BK (2007). Modeling of urban solid waste management system: The case of Dhaka city, Waste Management. 27(7): 858-868.

Tanskanen JH (2000). Strategic planning of municipal solid waste management. Resourc. Conserv. and Recycl. 30: 111-133.

Tung DV, Pinnoi A (2000) Vehicle routing-scheduling for waste collection in Hanoi, Eur. J. Oper. Res. 125: 449-468.

UNEP - United Nations Environment Programme. (2005). Solid Waste Management, Vol.1, CalRecovery Inc, New York.

Ventana Systems (2012). Vensim Simulation Software**.** Available at: http://www.vensim.com. (Accessed in 14 August 2012).

Waste Management (2012). Recycling Facts and Tips. Available at: ttp://sacramentovalley.wm.com/recyclingfacts.asp. (Accessed in 05 August 2012).

Weintraub A, Martell D, Gunn E (1998). Forest Management Challenges for Operational Researchers'. Eur. J. Oper. Res. 104(1): 1-17.