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ADIÇÃO DE DIFERENTES PERCENTUAIS DE BIODIESEL NO TRANSPORTE DE RESÍDUOS SÓLIDOS; ANÁLISE DE CENÁRIOS

ADDITION OF DIFFERENT PERIOD OF BIODIESEL IN THE TRANSPORT OF SOLID WASTE; SCENARIO ANALYSIS

ADICIÓN DE DIFERENTES PORCENTAJES DE BIODIÉSEL EN EL TRANSPORTE DE RESIDUOS SÓLIDOS; ANÁLISIS DE ESCENARIOS

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Resumo: Os Resíduos Sólidos Urbanos (RSU) se configuram como uma problemática tanto no Brasil como em outras partes do mundo, exigindo que se pense em alternativas de como amenizar seus impactos negativos. No Brasil, a coleta e o transporte dos RSU é feita por meio de veículos movido a diesel. Neste contexto, foi formulada a seguinte hipótese: "A adição de maiores percentuais de biodiesel gerará maior economia financeira para a empresa, além de diminuir a geração de gás carbônico?" Assim, o objetivo deste estudo é comparar o impacto de adição de diferentes percentuais de biodiesel na composição do combustível de veículos de transporte de resíduos sólidos, levando-se em consideração a projeção de mistura de biodiesel do governo brasileiro, comparando cenários com 10%, 15% e 20% de biodiesel nessa composição. Esta comparação foi realizada por meio de simulação de um modelo computacional desenvolvido pelos pesquisadores baseado na , metodologia proposta por Sterman (2000). Na definição das equações e suas relações do modelo de simulação, foi considerado um horizonte de tempo de dez anos. Os resultados revelam que, visto de uma perspectiva financeira, há uma grande diferença existente entre os diferentes percentuais de biodiesel na composição do combustível, demonstrando vantagens na utilização de biodiesel com maior percentual.
Palavras-chave: Biodiesel; Modelagem Computacional; Resíduos Sólidos Urbanos

Abstact: Urban Solid Waste (RSU) is a problem both in Brazil and in other parts of the world, requiring that we think of alternatives for mitigating their negative impacts. In Brazil, the collection and transportation of RSU is done by means of diesel-powered vehicles. In this context, the following hypothesis was formulated: "Will the addition of higher percentage of biodiesel generate greater financial savings for the company, in addition to reducing the generation of carbon dioxide?" Thus, the objective of this study is to compare the impact of adding different percentages of biodiesel in the fuel composition of solid waste transport vehicles, taking into account the Brazilian government's biodiesel blending projection, comparing scenarios with 10%, 15% and 20% of biodiesel in this composition. This comparison was carried out by means of simulation of a computational model developed by the researchers based on the methodology proposed by Sterman (2000). In the definition of the equations and their relations of the simulation model, a time horizon of ten years was considered. The results show that, from a financial perspective, there is a

great difference between the different percentages of biodiesel in fuel composition, showing advantages in the use of biodiesel with higher percentage.
Keywords: Biodiesel; Computational modeling; Urban solid waste.

Resumen: Los Residuos Sólidos Urbanos (RSU) constituyen un problema tanto en Brasil como en otras partes del mundo, lo que requiere la consideración de alternativas para mitigar sus impactos negativos. En Brasil, la recolección y el transporte de RSU se realizan mediante vehículos diésel. En este contexto, se formuló la siguiente hipótesis: "¿Añadir mayores porcentajes de biodiésel generará mayores ahorros financieros para la empresa, además de reducir las emisiones de dióxido de carbono?". Por lo tanto, el objetivo de este estudio es comparar el impacto de añadir diferentes porcentajes de biodiésel a la composición del combustible de los vehículos de transporte de residuos sólidos, teniendo en cuenta la proyección de mezcla de biodiésel del gobierno brasileño, comparando escenarios con 10%, 15% y 20% de biodiésel en esta composición. Esta comparación se realizó mediante la simulación de un modelo computacional desarrollado por los investigadores, basado en la metodología propuesta por Sterman (2000). Para definir las ecuaciones y sus relaciones en el modelo de simulación, se consideró un horizonte temporal de diez años. Los resultados revelan que, desde una perspectiva económica, existe una diferencia significativa entre los distintos porcentajes de biodiésel en la composición del combustible, lo que demuestra las ventajas de utilizar biodiésel con un porcentaje mayor.
Palabras clave: Biodiésel; Modelado computacional; Residuos sólidos urbanos

1. INTRODUCTION

In Brazil, despite its regional differences, the per capita generation of solid waste urban waste (RSU) increased in all regions and a large part of this waste does not have a destination appropriate sanitary and environmental (IBGE, 2018). It is also noteworthy that waste urban areas are disposed of in open skies in so-called dumps, and not in the proper and less harmful waste, in controlled landfills, where waste is covered by land, or in landfills that, by the method of treatment adopted, reduces environmental impacts and damage to health from its disposal (FROTA et al., 2015).

Urban solid waste has received greater attention practically all over the world, being an area of study in evolution. The treatment of solid waste also contributes to the emission of a variety of greenhouse gases, from carbon derivatives (such as carbon Carbon Monoxide, Carbon Dioxide and Methane), passing through the causative elements acid rains, such as sulfur, for example, to dangerous nuclear waste, which is still continue to be disposed of in the untreated environment in several countries.

The collection of solid waste is a continuous activity, mainly in large centers, and features diesel vehicles, causing damage to the environment, like those previously mentioned. Aiming to reduce this damage, with the use of cleaner energy and renewable, the Government of Brazil requires the mixture of Biodiesel and diesel. The National Agency for Petroleum, Natural Gas and Biofuels (ANP) is the body that regulates the use of biodiesel in the fuel oil throughout Brazil. Current laws require that, starting in 2018, diesel oil contains 10% biodiesel (acronym B10), and in some

Brazilian regions, truck fleets have already use the B20 blend (20% biodiesel) as fuel (MIRANDA et al., 2018).

The use of biodiesel, considered a renewable fuel, with possible mixtures with the commercial diesel (fuel from non-renewable sources) had its origin motivated by the crisis of the world supply in times of war. The need to insert biofuel in the market is necessary not only to balance the supply and demand relationship, but also for environmental feasibility regarding the reduction of atmospheric polluting gases. The main method of biodiesel production is the transesterification method that consists of using a tri glycerol which reacts with an alcohol in the presence of a catalyst, which results in the by-product glycerol and methyl ester (biodiesel). This renewable fuel can be used in the 4-stroke engines of the diesel cycle (MENDES, 2015).

According to Mendes (2015), the concept of Biodiesel adopted by the ANP is a fuel used in diesel engines, produced from renewable sources and which meets the needs of specifications of ANP Resolution No. 14, of May 11, 2011. To determine the percentage of biodiesel in diesel oil the standards EN 14078 and ABNT NBR15568 are used, which use the spectroscopy in the infrared region. This method is based on the fact that the substances carbonyl compounds, specifically esters, have two characteristic absorptions that have originated in the stretches of the connection, but there is no standard percentage to be adopted, being able to execute different percentages (COSTA et al, 2015).

In view of the above, the present study aims to compare the impact of adding different percentages of biodiesel, taking into account the projection of the biodiesel mixture Brazilian government, comparing scenarios with the addition of 10%, 15% and 20% biodiesel in the fuel from solid waste collection vehicles. This comparison was performed via simulation, from a computational model developed by the researchers. For easy access the data this research will only study the collection of solid waste.

As for the structure of this study, after this introductory chapter the referential is presented theoretical. Next, there is the research method adopted. Following is the description of the development of the model and experiment and, later, ends with the final considerations accompanied by recommendations for future research.

2. THEORETICAL REFERENCE

For the purposes of constructing the theoretical framework of this work, first, the issue is addressed of Urban Solid Waste, after Biodiesel and finally the definitions on modeling computational.

2.1 URBAN SOLID WASTE

The issue of solid waste in Brazil was, for a long time, placed in second place plan, without due attention. The intense urbanization process associated with the lack of investments in sanitation led to the proliferation of landfills across the country. With the worsening socio-environmental problems, the theme of garbage was raised in discussions on sanitation in the late 1980s (MONTAGNA, 2012).

There are several definitions of solid waste. According to the Research Program in Basic Sanitation (PROSAB), solid waste is any and all material resulting from activities of human beings in society, and that is discarded (PROSAB, 2013). According to the National Solid Waste (PNRS), solid waste is discarded materials, substances, objects or goods resulting from human activities in society, whose final destination proceeds, it is proposed to proceed or is obliged to proceed, in solid or semi-solid state, as well as gases contained in containers and liquids whose particularities make their release into the public sewer network or into bodies of water unfeasible, or require technical or economically unfeasible solutions in view of the best available technology (PNRS, 2010).

Urban Solid Waste (RSU), under the terms of the National Solid Waste Policy, encompass household waste, that is, waste originating from domestic activities in urban residences and urban cleaning residues, that is, those originating from sweeping, cleaning of public places and public roads, as well as other urban cleaning services.

As for their classification, there are several ways to proceed, the most common being those related to their physical nature (dry or wet), chemical composition (organic or inorganic), origin (Household waste and urban cleaning waste / Commercial waste), as to the potential risks of contamination of the environment (CEMPRE, 2010).

According to the Solid Waste Manual (IBAMA, 2001) and the Waste Sanitation (BRASIL, 2006), the characteristics of the residues vary according to social aspects, economic, cultural, geographical and climatic, that is, vary from community to community of according to the habits and customs of the population, as well as the number of inhabitants, purchasing power and local development.

According to the 2018 Solid Waste Panorama in Brazil, the figures referring to the generation of RSU show an annual total of 78.4 million tons in the country, which demonstrates a resumed the increase of about 1% compared to 2016. The amount collected in 2017 was 71.6 million tons, registering a collection coverage index of 91.2% for the country, which shows that 6.9 million tons of waste were not collected and, consequently, they had an improper fate. With regard to the final disposal of collected RSU, the Panorama made no progress compared to the previous year's scenario, practically maintaining the same proportion between what goes to suitable and inappropriate places, with about 42.3 million tons of RSU, or 59.1% of the collected, disposed of in landfills. The rest, which corresponds to 40.9% of the collected waste, was dumped in inappropriate places by 3,352 Brazilian municipalities, totaling an additional 29 million tons of waste in landfills or landfills controlled companies, which do not have the set of systems and measures necessary to protect the environment environment against damage and degradation, with direct damage to the health of millions of people. (ABRELPE, 2018).

Regarding the generation of RSU in Brazil, the population presented a per capita growth of 0.48% in waste generation, between 2016 and 2017 the total generation of waste increased 1%, reaching about 214 tons per day in the country. Analyzing the collection of RSU in 2017 grew in all regions compared to the previous year, and maintained coverage just above 90%. The Southeast region continues to account for about 53% of the total waste collected, and has the highest percentage of coverage of collection services in the country (ABRELPE, 2018). The table 1 shows the amount of RSU collected by region.

Table 1: Amount of RSU collected by regions and Brazil

REGIONS	2016 Total RSU (t/day)	2017 Total RSU (t/day)
NORTH	12.500	12,705
NORTHEAST	43.555	43.871
CENTER-WEST	14.175	14.406
SOUTHEAST	102.620	103.741
SOUTH	20.987	21.327
BRASIL	**193.637**	**196.050**

Source: Adapted from ABRELPE (2018)

The figures show that even with more restrictive legislation and efforts undertaken in all governmental spheres, the inappropriate destination of RSU is made present in all Brazilian regions and states. These usual practices provoke, among others impacts, contamination of soils and bodies of water, silting, flooding, proliferation of vectors that transmit diseases, atmospheric emissions of greenhouse gases, in addition to visual pollution, bad smell and unavailability of the affected areas for economic purposes (MONTAGNA, 2012).

According to Resol (2008), efforts should focus on the four main areas of waste-related programs: (a) reducing waste to a minimum; (b) increase in maximum environmental reuse and recycling of waste; (c) promotion of environmentally sound deposit and treatment of waste; and (d) expanding the reach of services dealing with waste. These areas are related to each other, but a well-defined structure designed for sustainable management.

In Brazil, the official selective collection has usually been carried out with trucks and teams collectors. To carry it out, the government uses its own structure (trucks and personnel) or that of contracted companies. Under public domain, traditionally, the vehicle fleet used in the collection and transport of recyclables is powered by fossil fuel energy, specifically diesel, which contributes to increasing air pollution in urban centers.

2.2 BIODIESEL

Biodiesel is often referred to as "the fuel of the future" because it is biodegradable and non-toxic, with diesel-like properties. Biofuels are derived from resources renewable and used as transport fuel (MADHESHIYA; VEDRTNAM, 2018). Mendes (2015) pointed to the need for new sources of energy as an alternative to the use of fossil fuels. Gas emissions, such as CO, HC and SOx, are extremely harmful and lead to the need for an alternative, safer and cheaper than petroleum-based diesel (Ranjan et al., 2018). The environmental benefits resulting from emissions inherent to the use of biodiesel in engines, as opposed to diesel oil, are evident. Biodiesel is sulfur-free, non-toxic, and biodegradable. Reduces emissions gaseous pollutants, reduces global warming, is economically competitive and can be produced by small companies (MIRANDA et al., 2018).

Biodiesel arose from an invention at the world exhibition that took place in Paris in 1900. On the occasion, Dr. Rudolf Diesel presented to those present a diesel injection engine indirectly using peanut oil as fuel (KNOTHE et al, 2006). At this time, according to Tavares and Da Silva (2008), engines with this characteristic were powered by filtered oil, vegetable oils and even fish oil. Difficulties such as accumulation of fatty residues generated by vegetable oil led to the abandonment of studies to produce a viable fuel through vegetable oils (RODRIGUES et al., 2016).

The studies on Biodiesel were forgotten until the moment when the countries had to think about the development of alternative energy sources, which could replace, in part or in part, totally, the primacy of fossil fuels (CARIOCA; ALMEIDA, 2011). The increase in the barrel of oil in 1973 and 1979 made the development of a new source economically viable alternative fuel, such as ethanol (MENDES, 2015). Another important factor is the Kyoto Protocol, which aims to promote a systematic reduction in gas emissions cause of the greenhouse effect. The qualitative and quantitative reduction in the levels of environmental and by substituting diesel oil, make Biodiesel a great strength of the Kyoto. Studies prove that the use of Biodiesel has presented great advantages for the decrease in greenhouse gas (GHG) emissions (TAVARES; DA SILVA, 2008).

A variety of oils can be used to produce biodiesel. However, the efficiency of yield of raw material per unit area affected the feasibility of raising production to industrial levels needed to supply the automotive market.

2.3 COMPUTATIONAL MODELING

Computational Modeling is a multidisciplinary area of knowledge that deals with the application of mathematical models and techniques from computing to analysis, understanding and study of phenomenology of complex problems in areas as comprehensive as engineering, exact sciences, biological, human, economics and science. They are incomplete representations and simpler than the object or system in question (COSTA, 2004). For Andrade et al (2006), computational modeling is one of the tools of systemic thinking that add learning to the process and through from it, micro-worlds of the real system are built.

For researchers like Andrade (2006), Maani and Cavana (2000) among others, the models can present two types of modeling, distinctly called soft and hard. The soft modeling refers to conceptual approaches that seek greater realism, pluralism and a more holistic intervention than hard modeling. The soft and hard concepts are also related to the ideas of qualitative and quantitative, respectively.

A computational model is constructed with basically four components: Stocks, flows, connectors and auxiliary. They will be detailed in the following section.

2.3.1 Model Components

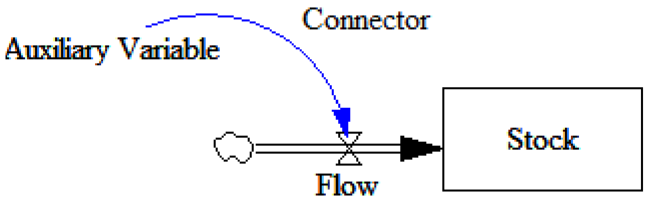
Inventories are state variables and can be considered as repositories for accumulate or store for other elements of the system (DEATON; WINEBRAKE, 2000), main importance to provide a view of how the system is at any time, changes in inventories are not instantaneous, they take some time and occur due to the action flows.

In turn, flows are action variables, they can increase or decrease the volume determined in stock. It produces stock growth or reduction, the movement of materials and information within the system.

Auxiliary variables are components for performing algebraic operations, which process information about stocks and flows or represent sources of information external to the system (BLOIS; SOUZA, 2008). There are helpers who can also modify other auxiliary variables, are often used to model information and not physical flow, being able to change instantly without delays (COVER, 1996).

Finally, there are the connectors that represent the interrelationships between all components, that is, it is these interconnections that connect the components that form the expression mathematics (STRAUSS, 2010). They have function of information links that describe the relationship between stocks, flows and auxiliaries. Figure 1 shows each component of a model of System Dynamics.

Figure 1: Model components -



Source: Simonetto and Lobler (2013)

3. RESEARCH METHOD

The methodology adopted in this study is based on the system dynamics modeling approach proposed by Sterman (2000), which emphasizes that modeling must be embedded within the organizational and social context of the problem being studied. The process involves a sequence of structured stages, including the definition of the problem, the formulation of a dynamic hypothesis, the construction and simulation of a computational model, validation through testing, and the evaluation of scenarios to support decision-making and policy development.

The central hypothesis of the model is that increasing the percentage of biodiesel in the fuel composition used by solid waste collection vehicles can result in financial savings and a reduction in carbon dioxide (CO_2) emissions. To test this hypothesis, a system dynamics model was developed using Vensim software, structured over a ten-year time horizon and composed of four interconnected submodels: population growth, waste generation, fuel consumption, and environmental impact (CO_2 emissions).

The population submodel was constructed based on birth and death rate projections provided by the Brazilian Institute of Geography and Statistics (IBGE, 2020). This allowed for the

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annual estimation of the number of inhabitants and, subsequently, the quantity of municipal solid waste (MSW) generated per year, calculated as the product of population and per capita waste generation.

The transportation submodel used real data collected from the waste collection company operating in the region of Santa Maria, RS. This data included average fuel consumption per kilometer, number of trips, and distance to the regional landfill. The total annual fuel consumption was calculated based on the number of trucks, distances covered, and engine efficiency. Fuel use was then divided into diesel and biodiesel according to the proportions defined in three simulated scenarios: a current scenario with 10% biodiesel (B10), an intermediate scenario with 15% biodiesel (B15), and an optimistic scenario with 20% biodiesel (B20).

Cost estimation included fuel prices and driver salaries, with total operational cost calculated annually as the sum of fuel and labor expenses. Additionally, the CO_2 emissions submodel calculated total emissions based on the type and quantity of fuel consumed, using emission factors derived from the Brazilian National Agency for Petroleum, Natural Gas and Biofuels (ANP, 2018).

The mathematical logic of the model was organized into equations grouped by function: equations 1 to 4 referred to the population and MSW generation submodel, equations 5 to 8 addressed fuel consumption and biodiesel blending, equations 9 to 12 dealt with financial costs, and equation 13 represented the environmental impact through CO_2 emissions. These equations, along with historical and empirical data, enabled the simulation of realistic scenarios and the evaluation of their outcomes.

The clarity and robustness of this modeling approach allowed for the comparison of different biodiesel blending policies over a decade, offering valuable insights into both economic performance and environmental sustainability in municipal waste management logistics.

3.1 DYNAMIC HYPOTHESIS FORMULATION

According to Silva (2006), the dynamic hypothesis aims to work on the problem theory, analyzing their behavior and observing which variables are part of the system. The objective of this step is to formulate a hypothesis that explains the dynamics as a consequence of the internal structure of the system through the interaction between the variables and the agents represented in the model, including rules of decision (STRAUS, 2010). Thus, the dynamic hypothesis of the systems dynamics model in this work is defined as follows: "The addition of higher percentages of biodiesel will generate greater financial savings for the company, in addition to reducing the generation of carbon dioxide ".

4. MODEL DEVELOPMENT

Melquiades (2015) points out that both the collection and transport of RSU is a problem critical in most cities in Brazil. According to Souza and Guadagnin (2009), the collection steps and transport spend between 60% and 80% in terms of overall costs when it comes to waste management. In this research, the RSU transport logistics was simulated, prospecting the generation of RSU based on population variation according to data collected in IBGE's online platform (IBGE, 2019), analyzing the impacts caused by the insertion of biodiesel on trucks collecting urban solid waste in the ten-year time horizon simulation. The model must react to different factors, such as: population growth, average generation of solid urban waste per capita and the cost of transportation.

For the construction of the sub-models it was necessary to deepen the knowledge about the area the road modal and also the area of urban waste management. Truck consumption took into account the daily loaded ton in addition to the distance covered, whose data were collected in reports such as National Agency of Land Transport (ANTT, 2013), National Association of Vehicle Manufacturers Automotores (ANFAVEA, 2014), Ministry of Environment (MMA, 2014), Petrobras (2018), and also, directly in the bank data from the company responsible for collecting RSU in the region considered here for analysis purposes. Values referring to internal collections and shipping to Santa Maria / RS (single landfill licensed in the region) are shown in Frame 1.

Frame 1: Monthly collection data

City	n. collections	Landfill Shipping	spent diesel	internal collection	Shabby Diesel
Agudo	6 for week	3403.2 km	1361.28 liters	500 km	200 liters
Cacequi	6 for week	5952 km	2380.80 liters	480 km	192 liters
Restinga Seca	6 for week	2827 km	1130.88 liters	493.4 km	197.36 liters
São Francisco	6 for week	6672 km	2668.80 liters	515.6 km	206.24 liters
Faxinal	3 for week	1406 km	562.56 liters	133.6 km	53.44 liters
Maa	3 for week	1992 km	796.80 liters	109.8 km	43.92 liters
São Martinhi	2 for week	472 km	188.80 liters	42.8 km	17.12 liters
Total		19321.6	9089.92	2275.2	910.08

Source: Company responsible for collecting RSU in the region studied (2025).

Collections are normally carried out from Monday to Saturday for the municipalities of 10,000 inhabitants or more. The cities of Agudo, Cacequi, Restinga Seca and São Francisco fall into in this collection model. The municipalities from 5 (five) to 10,000 (ten thousand) inhabitants have collection 3 (three times a week; in this case, the municipalities of Faxinal do Soturno and Mata. São Martinho da Serra +collects urban waste twice a week, since it has a population of less than 5,000 (five thousand) inhabitants. The collection is brought to Santa Maria, where the only landfill is located licensed health facility in the region. The municipalities focused on this study do not have transshipment nor screening. Only few municipalities have selective collection and in these collection is carried out in a very disorganized and very inefficient.

To simulate the behavior of the variable that comprises the population of the studied region, it is necessary to understand the number of births and annual deaths. To back up the data inserted in these two rates, the IBGE projection platform was used. The rate projections that involve the size of the Population of Brazil and the Federation Units are elaborated with based on information on the components of demographic dynamics from the censuses demographic data, household sampling surveys and administrative records of births and deaths investigated by IBGE. Given the changes in the dynamics population, projections are monitored continuously and undergo periodic reviews, both for the incorporation of new information, when changes in the hypotheses are detected foreseen for the components, as well as for the update of its calculation methodology, being these improvements duly explained in the respective methodological reports. The values of the projection of rates that influence inhabitants are shown in frame 2.

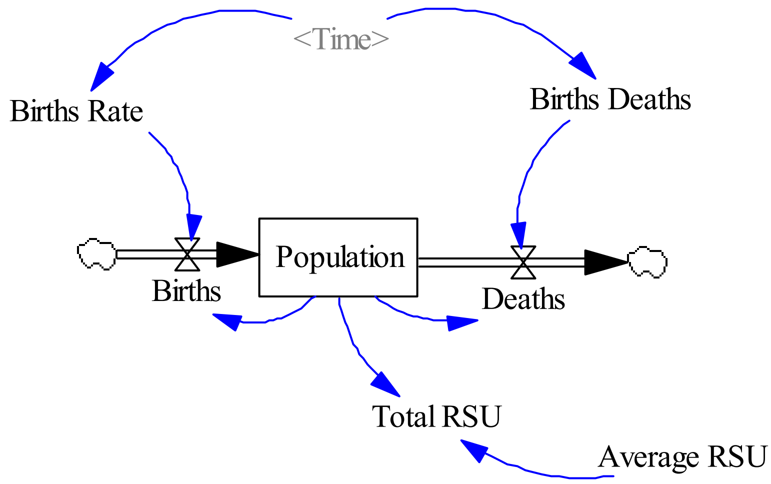
Frame 2: Rates for each 1000 people

Year	**Rate**	
	Births	Deaths
0	12.34	7.27
1	12.20	7.36
2	12.03	7.45
3	11.85	7.54
4	11.67	7.65
5	11.50	7.76
6	11.30	7.87
7	11.16	7.99
8	11	8.12
9	10.84	8.26
10	10.70	8.4

Source: Elaborated by the authors from the data from IBGE (2020).

The first sub-model developed (Figure 2) represents the logic for generating the population and consequently the amount of waste generated annually. For the definition of the variables of the submodel academic and governmental works in the solid waste area were used, more specifically, Brazilian Association of Cleaning Companies (ABRELPE, 2018), Ministry of the Environment (2018) and IBGE (2019). The selected variables, as well as their interrelationships with other variables, which influence the total values of generation and final disposal of solid urban waste are: births rates and deaths rates directly influence the inflow and outflow of the stock variable (inhabitants) of the studied region. The rate of natural or vegetative growth (total births - total deaths) which corresponds to the only possible way of growth or reduction of the world population. The average amount of waste (average RSU) generated by each inhabitant multiplied by the inhabitants of the region results in the total amount of waste (total RSU).

Figure 2: Sub-model Population



Source: Authors (2025)

For the configuration of the sub-model responsible for representing the logic of consumption data for the transportation of solid waste, data from ANTT reports were used (2013) and the Ministry of the Environment (MMA 2014). It should be noted that in road transport there are various types of trucks with different sizes and capacities. Thus, in this research, trucks responsible for collecting RSU are classified as light trucks, because according to the Ministry of the Environment report (MMA, 2014), trucks capable of loading between 6 and 10 tons fall into this nomenclature.

The pick-up variable CaminhõesColeta has two auxiliary variables at its input (TotalRsu and Capacity), in order to add trucks according to the quantity population increases and consequently its generation of RSU per capita is higher, enabling the sub-model to simulate without a fixed number of trucks.

Transport is measured in the Annual Transport variable, where the consumption of fuel by the trucks, by multiplying the variable CaminhõesColeta by the variable auxiliary (Distance) which stores the number of kilometers traveled by trucks. O result of this is again multiplied by the number of kilometers that each truck consumes per liter (Engine Yield), resulting in the amount of liters of fuel consumed, this annual value is stored in the auxiliary variable (ConsumoCombustível).

As determined by ANP (2018), diesel already contains 10% biodiesel in its composition and this article will simulate the composition of diesel with 15% and 20% biodiesel. To separate the consumption of diesel and biodiesel in the collection, the submodel presents two variables responsible for controlling the exact percentage of each type of fuel (DieselRate and BiodieselRate) that when multiplied by the Diesel and ConsumoBiodiesel variables will result in the quantity (in liters) consumption of each fuel. Figure 3 shows the submodel described above.

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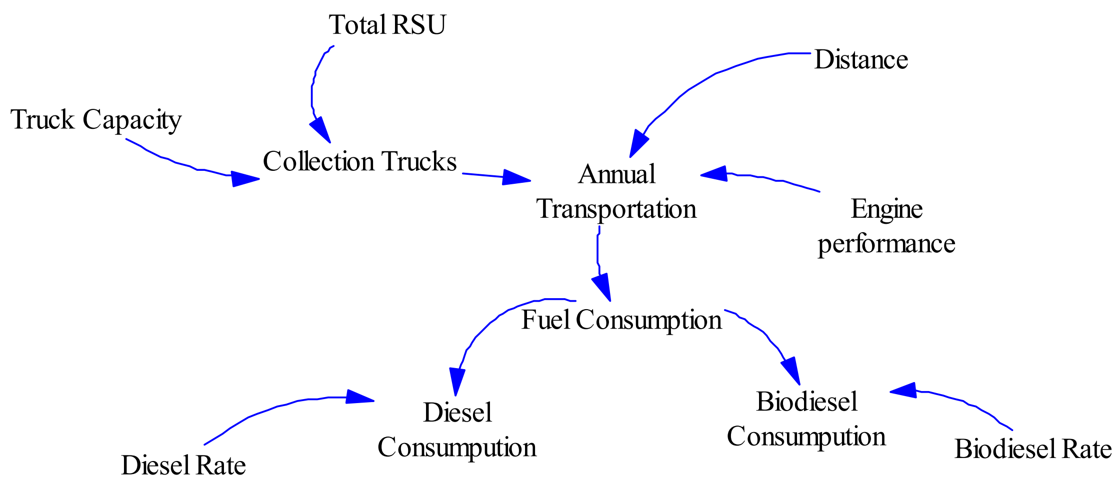
Figure 3: Fuel Consumption Submodel



Source: Authors (2025)

This submodel (Figure 3) aims to observe the financial impact related to the use of different portions of biodiesel in the collection, providing area managers with the benefits the use of biodiesel in the collection. The auxiliary variables BiodieselPrice, DieselPrice, ConsumoBiodiesel and ConsumoDiesel are responsible for storing the cost of fuel in the 10 years modeled, your data is stored in the Flow CostDiesel and BiodieselCost. Shadow Variable (CollectionTrucks) combined with auxiliary variable DriverSalary is responsible for storing the cost of the professionals who carry out the transportation of the RSU and its value is stored in the DriverCost stream.

The central stock variable of this sub-model (OperatingCost) has the function of presenting the operation cost through the sum of the costs that involve the collection, as presented previously. Through the Vensim software it is possible to visualize the variation in cost over ten years. These interactions are shown in figure 4.

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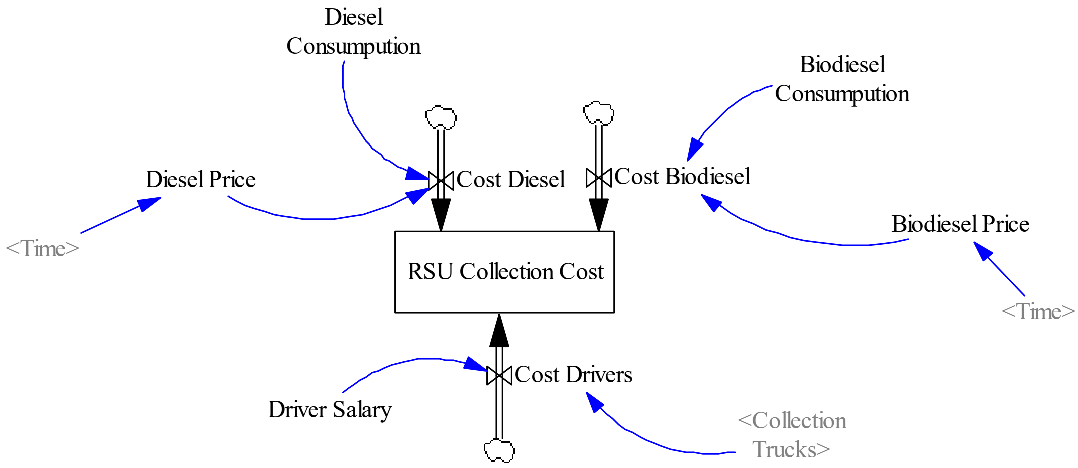
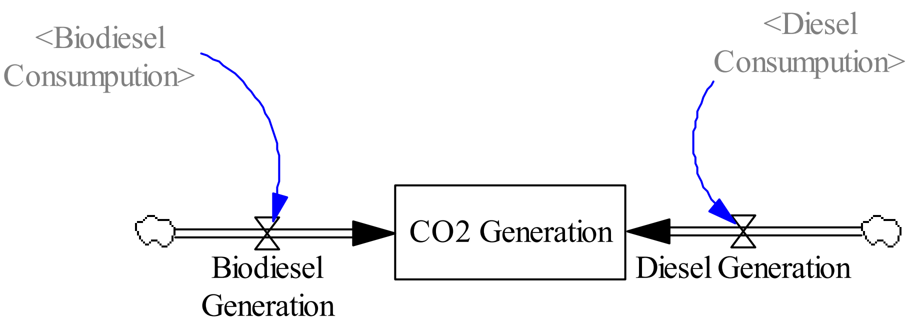
Figure 4: Cost



Source: Authors (2025)

To analyze the environmental impact generated by garbage collection in the cities studied, the Geracao CO2 submodel, represented in figure 5, was created, whose objective is to compare the reduction of generation of CO2 by collecting vehicles using biodiesel. The CO2 generation inventory variable stores the interaction between flow variables (BiodieselGeneration and DieselGeneration), both variables are fed by variables already existing in other submodels (ShadowVariables).

Figure 5: CO2 Generation - Authors (2018).



Source: Authors (2025)

Equations 1, 2, 3 and 4 are components of the Population submodel. In turn, the Fuel Consumption sub-model, to represent its mathematical logic, uses equations 5 to 8. In order to make the submodel Cost viable, in order to simulate the financial issue of the article, equations 9, 10, 11 and 12 were developed. Finally, equation 13 is responsible for representing the Environmental analysis of the study.

For the simulation of the model, three scenarios were generated in order to compare the scenario current waste collection, where diesel is used with a mixture of 10% biodiesel, with two proposals created by modelers. The first scenario proposes the current scenario with 10%, the second scenario the addition of 15% biodiesel, while the third scenario presents the proposed add 20% biodiesel. The table below details the percentage of each fuel.

Table 3. Scenarios

	Diesel Quantity (%)	Biodiesel Quantity (%)
Current Scenario	90	10
Average Scenario	85	15
Optimistic scenario	80	20

Source: Authors (2025)

5. EXPERIMENT OF COMPUTATIONAL SUB-MODELS

The first analysis to be developed using the model refers to the amount of inhabitants in the studied region, thus, in year zero or initial year of simulation, it was 80,729 the following year (year 1) there is an increase of 3,326 people. In the simulated ten years there was an average variation of approximately 3.84% reaching 108,781 inhabitants in year 10. Knowing the possible population of the region and considering the average generation of RSU per capita it became possible to estimate the generation of garbage per capita for eleven years. Therefore, in year 0 (zero) about 30,644 tons of garbage will be produced, reaching 41,293 tons in the year 10, with an average generation of RSU per year of approximately 35,000 tons. Ensure that in Frame 4 the projection of population growth in the ten years of analysis beyond the generation of RSU in the region studied.

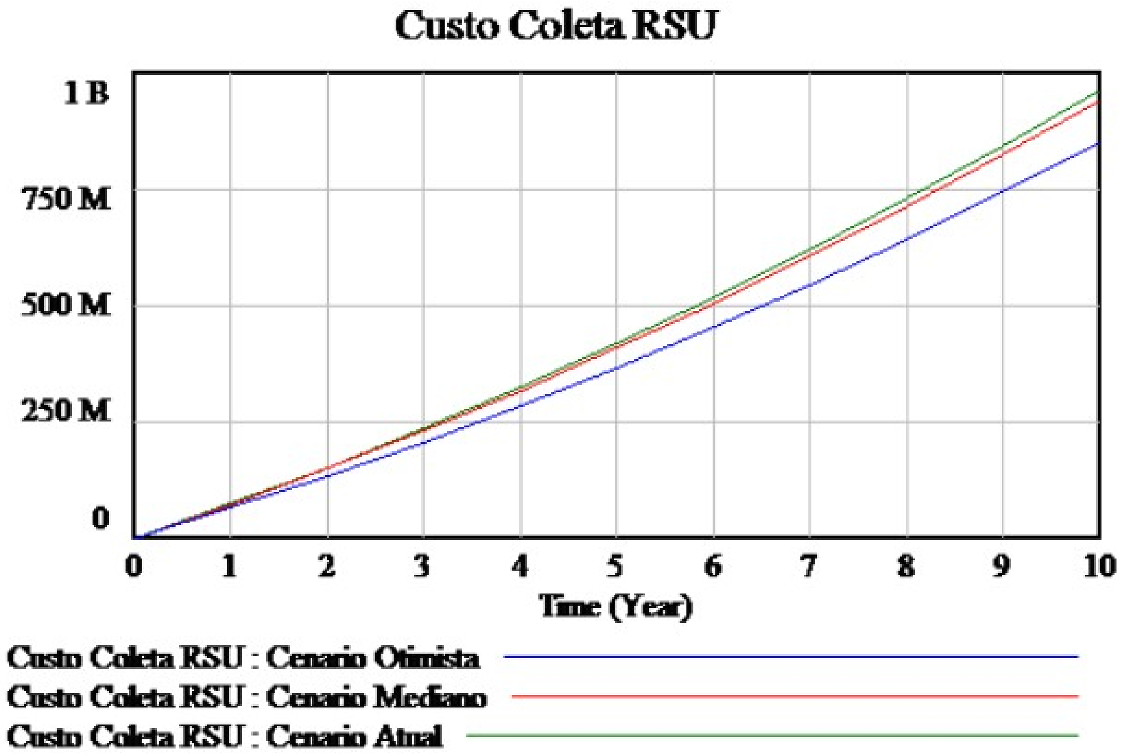
Frame 4: Inhabitants and RSU

Year	Population	Urban Solid Waste
0	80.729	30.644
1	84.055	31.907
2	87.527	33.225
3	90.643	34.408
4	93.679	35.560
5	96.668	36.695
6	99.490	37.766
7	102.117	38.763
8	104.598	39.705
9	106.836	40.554
10	108.781	41.293

Source: Authors (2025)

The cost to transport the urban waste projected in Table 4 is represented in figure 6, where the scenarios were compared using three different concentrations of biodiesel in the diesel-based fuel. The Current Scenario - which represents the collection with 10% biodiesel - is the most expensive transport: reaching R $ 96 million per year, totaling around R $ 10 in year 10 962 million. The scenario with the best financial performance is the Optimistic Scenario, which will save about R $ 11 million per year compared to the scenario with the worst financial income. If applied the optimistic scenario, the company will spend around R $ 848,778 million. The median scenario it will also present savings when compared to the Current Scenario and may generate, approximately R $ 2.2 million per year, being able to spend on transporting the waste up to R $ 940,068 million.

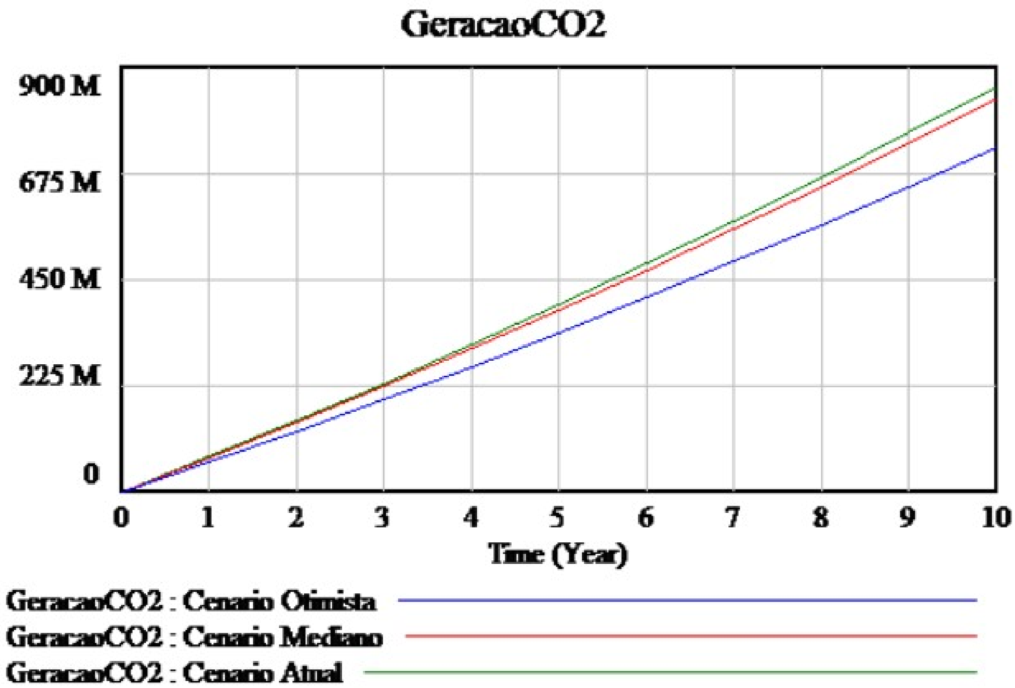
Figure 6: Collection Cost RSU



Source: Authors (2025)

Air pollution is one of the biggest environmental problems in the world, being a factor concerning both today and for the next generations (Instituto Estadual do Ambiente [INEA], 2012). Therefore, the second analysis of the model is related to the emission of carbon dioxide carbon (CO2) resulting from the complete combustion of carbon. Figure 7 shows the simulation performed, in which it is perceived that the Optimistic Scenario is the one with the lowest index of emissions of CO2, totaling in 7 years simulated here, approximately 728 tons. That represents 129 tons less than the scenario with the highest emission index (Current Scenario), because in year 10 will emit up to 857 tons of CO2. The Modal Scenario also has lower CO2 emissions when compared to the Current Scenario, it will emit approximately 831 tons, about 26 tons less than the Current Scenario.

Figure 7. Generation CO2



Source: Authors (2025)

It is observed by the simulations generated in this work that there is a big difference in financial and environmental terms between the proposed scenarios. This demonstrates the importance of using more sustainable fuels in the collection and transportation of Solid Waste.

6. FINAL CONSIDERATIONS

RSU issues have become a problem both in Brazil and elsewhere in the world. world and, in addition to significant financial expenses, environmental damage must be considered caused by the collection, since the collection trucks burn tons of fuel from the Petroleum. Consequently, this requires looking for ways to alleviate these problems, seeking alternatives to reduce both negative financial impacts and from the RSU.

Thus, considering the proposal of this article and among the analyzes carried out, it was verified in the ten simulated years that the number of inhabitants in the region considered for study purposes reaches a total of 108,781 at the end of the simulation period. From that, it became possible to make an estimate of the generation of waste per capita in the period, where it was found that the average generation of RSU per year will be approximately 35,000 tons.

As for the simulated scenarios, it was observed that the Optimistic scenario obtained the best financial performance - saving about R $ 110 million reais - compared to the which presented the worst financial performance (current scenario). Furthermore, investigating the environment, it was found that the Optimistic Scenario is the one that presented the lowest emission index of CO2 in the simulated period - approximately 728 tons - a total of 129 tons less compared to the scenario with the highest emission index. Finally, based on the research It is remarkable, seen from a financial perspective, that there is a big difference between the current percentage, which is 10%, and the optimistic proposal of 20%.

At the end of this study, it is expected that it will have contributed to the managers and governments to seek new options in view of the problem faced with the RSU and, at the same time, find ways to take advantage of the advantages provided by biodiesel as alternative fuel. In order to continue this study, as a recommendation for future research, it is indicated an investigation that contemplates the environmental part, taking into account the benefits that could be achieved by using other means of transporting Urban Solid Waste in Brazil.

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