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Planning A Village Waste Management System using System Dynamics Modelling and Simulation: TPS 3R Case Study in Aceh, Indonesia

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Planning A Village Waste Management System using System Dynamics Modelling and Simulation: TPS 3R Case Study in Aceh, Indonesia

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Abstract. The increasing amount of waste every year leads to the increasing capacity load and the decreasing life cycle of the landfill. In Banda Aceh, the official landfill is no longer able to accommodate garbage by 2018. Thus, in order to reduce the load on the landfill, waste reduction activities from sources must be conducted as mandated in the constitution UU No.18 2008. TPS 3R (Waste Processing Facility Reduce Reuse Recycle) is introduced by Ministry of Public Works as a waste management system from its source in villages. It has been planned to be built at several points in Banda Aceh villages, including Rukoh. In order to achieve the target of waste reduction according to Permen PU No.3 2013 and the Government of Aceh by 30% in 2020, the appropriate TPS 3R specification is required to achieve such number. In this research, system dynamics modelling and simulation using software Stella Architect used to develop the best-case scenario for waste management system in Rukoh Village in the form of TPS 3R. The main result is that the facility should be built with combination of 1 unit of composter, 2 units of plastic counters, and minimum participation of 131 households.

1. Introduction

1.1 Background

Based on Indonesian law UU 18 of 2008, waste is the remaining material from daily activity and/or a solid natural process. Based on the Act, reduction waste must be done from the source. This is done so that the waste is not directly transported to the Final Disposal Site (TPA) because it will provide a buildup load on the TPA and decrease its service life. In order to reduce waste from its source, a village waste management system is introduced by Indonesia government in 2013 called “Tempat Pengolahan Sampah Reduce Reuse Recycle” or TPS 3R. The program was formally established by the Ministry of Public Works in Permen PU No. 3 of 2013 that TPS 3R is a waste processing facility for carrying out activities, sorting, reusing, and regional scale recycling at village level and its development approval depends on the readiness of the village community.

In Banda Aceh, the main landfill, TPA Gampong Jawa, receives an average of 160 tons of trash every day and now as high as 26 m above sea level. It is already overload in 2017 and planned to channel Banda Aceh City garbage to a new landfill further in TPA Blang Bintang. To overcome this problem, the Aceh Government is targeting to build TPS 3R in several villages, one of which is in Rukoh. The Government of Aceh aims to reduce waste from sources through TPS 3R as much as 30% in 2020. To achieve this target, appropriate specifications are needed for the TPS 3R development



plan. An approach is needed to help us understand the structure and dynamics of the system that can be used to simulate models that can be used for better planning of the dynamic systems (Sterman, 2000). Thus, this study was conducted to set the correct specification of TPS 3R that can reduce Rukoh Village waste by 30% in 2020. The Rukoh Village waste management model was built and carried out using several TPS 3R scenarios into the simulation.

1.2 Research Questions

1. What variables affect the behavior of the waste management system in Rukoh Village using system dynamics modelling?
2. How is the waste generation behavior model generated in Rukoh Village through simulation results from the system dynamics model?
3. What is the best scenario of TPS 3R interventions on the simulation model that can achieve the waste reduced in Rukoh Village?

1.3 Methodology

The research was conducted as a case study in Rukoh Village, Syiah Kuala District, Banda Aceh City. Data collection was carried out during July 2017 obtained from Central Statistics Agency and Environmental Engineering UIN Ar-Raniry. The methodology applied was System Dynamics modelling and simulation using software *Stella Architect* in order to formulate the best-case scenario of the village waste management system which is in a form of a TPS 3R specification plan. Figure 1 describes the main steps of System Dynamics methodology.

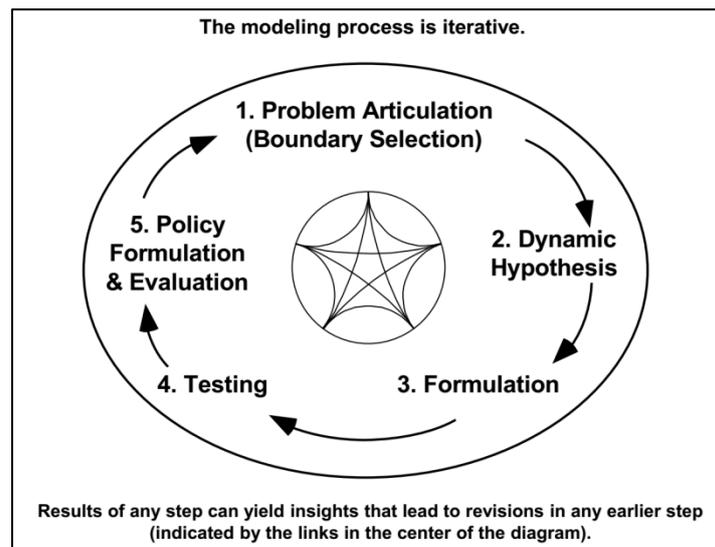


Figure 1. System Dynamics Life Cycle (Sterman, 2000)

According to Mai and Smith (2016), the dynamic hypothesis after clarifying the problem articulation in System Dynamics is the construction of Causal Loop Diagram (CLD). There are 3 main stages that must be passed in developing the CLD in this study, which firstly is building a preliminary CLD model based on literature studies on the issues raised. Then the second step is adding new variables into the initial CLD model based on the results of the problem identification stage with stakeholders so that a new model in the form of a working CLD is produced. This model is reviewed and verified by stakeholders directly during in depth interview and focus group discussion so that the final model in the form of final CLD is obtained.

Then the next step is to model formulation using *Stella Architect* based on the final CLD. This model is also called a Stock and Flow Model (SFM). One of the advantages of *Stella Architect*

software is that the model can be divided into sub-model and can also be run partially in accordance with the desired sub-model focus (Binder and Mosler, 2007). The division of the model into several sub-models in order to facilitate workmanship, understanding system behavior, and more thoroughly analyzing a series of relationships for each variable.

2. Results and Discussions

2.1 Problem Articulation

Banda Aceh as the capital city of Aceh Province produces significant amount of waste. The waste management implemented by the city today is a classic system of Gather - Transport - Throw which is carried out continuously and ultimately adds a buildup load in the city Final Disposal Site (TPA), namely the Gampong Jawa Landfill. Over time, there is also rising trend of waste that is worrying and calls for managed action to control the waste increasing as shown in the graph below.

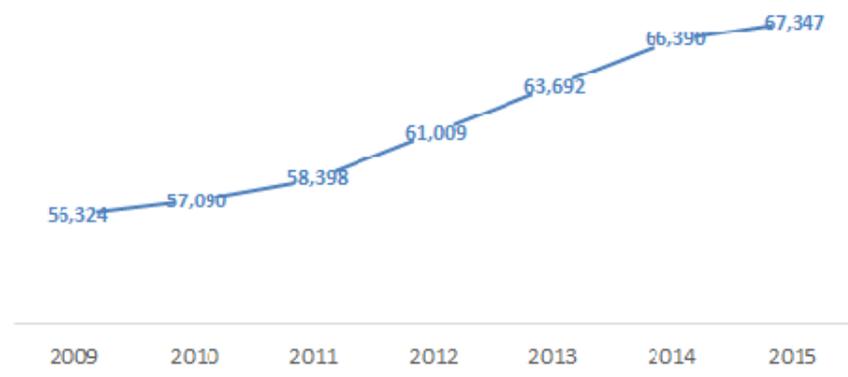


Figure 2. Waste Volume in Banda Aceh 2009-2015 (Source: BPS, 2016)

Based on a direct interview with DLHK3 Banda Aceh, it was explained that with the current volume of garbage transported from Banda Aceh to an average landfill of 160 tons per day, the current height of garbage in the Gampong Jawa landfill is 26 m above sea level while the maximum height is 30 m. The age of use of the Gampong Jawa TPA is calculated only until 2017 after that the Banda Aceh City garbage will be channeled to the Aceh Besar TPA in Blang Bintang. To overcome this problem, the Aceh Government is targeting to build 3R TPS in several areas, one of which is in Rukoh Village.

Rukoh is one of the densest villages in Banda Aceh with a population of 5,990 or averagely 55 people/Ha with 1,532 total households. Clearly, Rukoh Village has an area that produces significant household waste. The area also includes several village facilities such as markets, schools, campuses, shops and restaurants. The number of facilities influences the amount of garbage generation in Rukoh Village. The composition of waste from facilities is different from the composition of household waste so that it can affect the potential for reducing waste in Rukoh Village. The following is a breakdown of the number of facilities in Rukoh Village.

In this first step, identification of key variables that are related and contribute to the village waste management system is needed for the initial model conceptualization. The variables that are identified are variables related to the heavy flow of waste in accordance with Business as Usual (BAU) waste management contained in the study of Widyaningsih (2014). Based on the BAU, five main variables were chosen which were in accordance with the objectives of this study which are: population growth rate, number of people, total waste, amount of waste residue, and amount of transported waste to TPA.

2.2 Dynamic Hypothesis

In order to get the right conceptual model and can represent the real system, it requires an in-depth understanding of the system structure in a formal model such as CLD. The process was obtained from literature studies and evaluation directly by experts who understand the system to be built. In this study there are two environmental experts who play a role in improving the model built in accordance with the structure of the real model and experts also play a role in model validation. The Final CLD that was built is shown in the following figure.

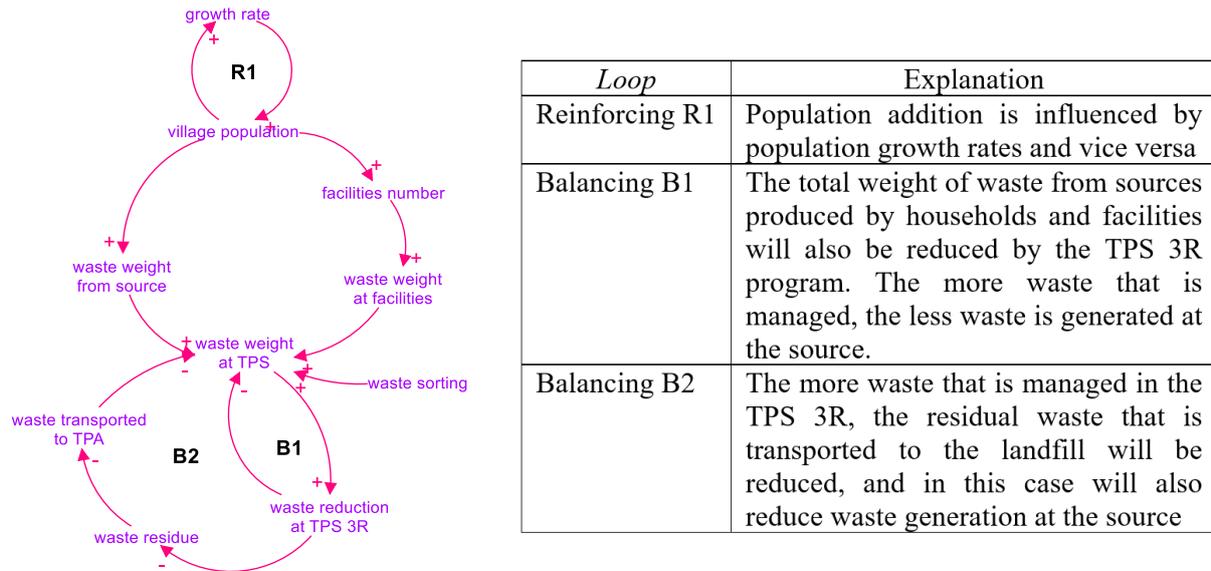


Figure 3. Final CLD and Feedback Loops Explanation

Based on the Final CLD, it can be seen that solid waste generation in an area is not only determined by household waste but also household-like waste generated by facilities in an area. Variables of waste segregation carried out by the community also determine the success or failure of the TPS 3R program in an area. If the waste is sorted properly, the percentage of waste processing also increases, and vice versa. The following is an explanation of the feedback loop in the Final CLD.

Table 1. Model Formulation references

Submodel	Structure	Formula	Data Input
Household Waste Composition	Agustia (2014)	Agustia (2014)	BPS
	Astuti (2014) Widyaningsih (2014)		Environmental Engineering of UIN Ar-Raniry
Facilities Waste Composition	Agustia (2014)	Agustia (2014)	BPS Agustia, dkk. (2014)
Total Waste in Rukoh	Mathematical Logic Surjandaridkk.	Mathematical Logic	-
TPS 3R Reduction	(2009) Escalante (2012)	Escalante (2012)	BPS TPS 3R Lambung
Waste Transportation	Mathematical Logic	Mathematical Logic	-

2.3 Model Formulation

The construction of the simulation model then began to form a stock and flow model, and it is based on CLD as well as previous studies that have the similar system domain which is the waste management system. The complete references of the stock and flow model is as follow:

Figure 4 is present to establish a clear view of the main model in subsystems.

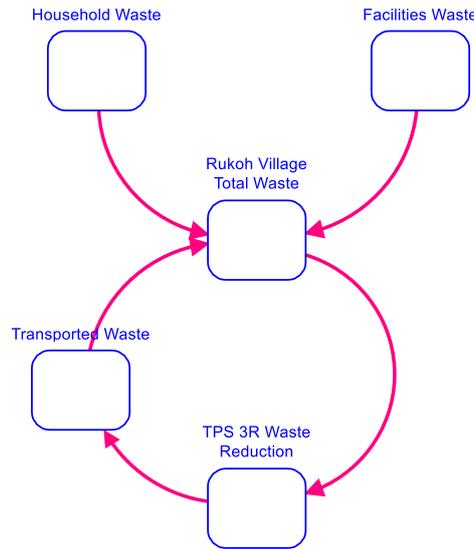


Figure 4. Stock and Flow Model in Macro View

2.3.1 Sub-model 1 Household Waste. This sub-model is built to show the relationship between population and total weight of waste and its waste composition (Figure 5).

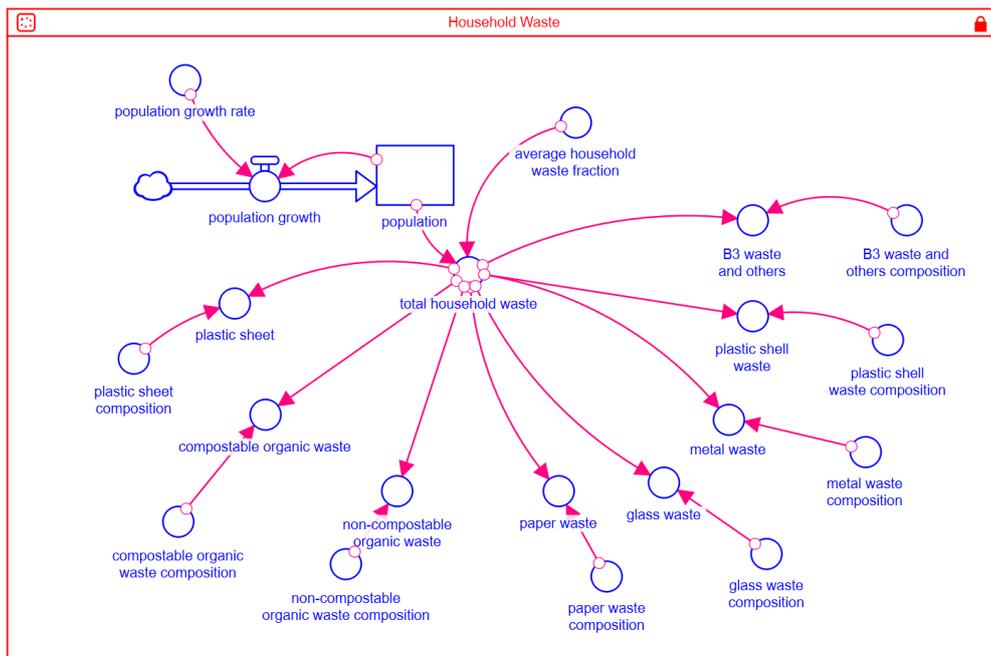


Figure 5. SFM Sub-model 1 Household Waste

The influential variables in this sub-model are population variables and household waste generation. The input data for the population variable is obtained from BPS while the waste generation variable and composition are obtained from the Environmental Engineering of U-Ar Arraniry.

2.3.2 Sub-model 2 Facilities Waste. This sub-model is made to show the weight of waste arising based on the number of facilities in a region. This sub-model can be seen in Figure 6.

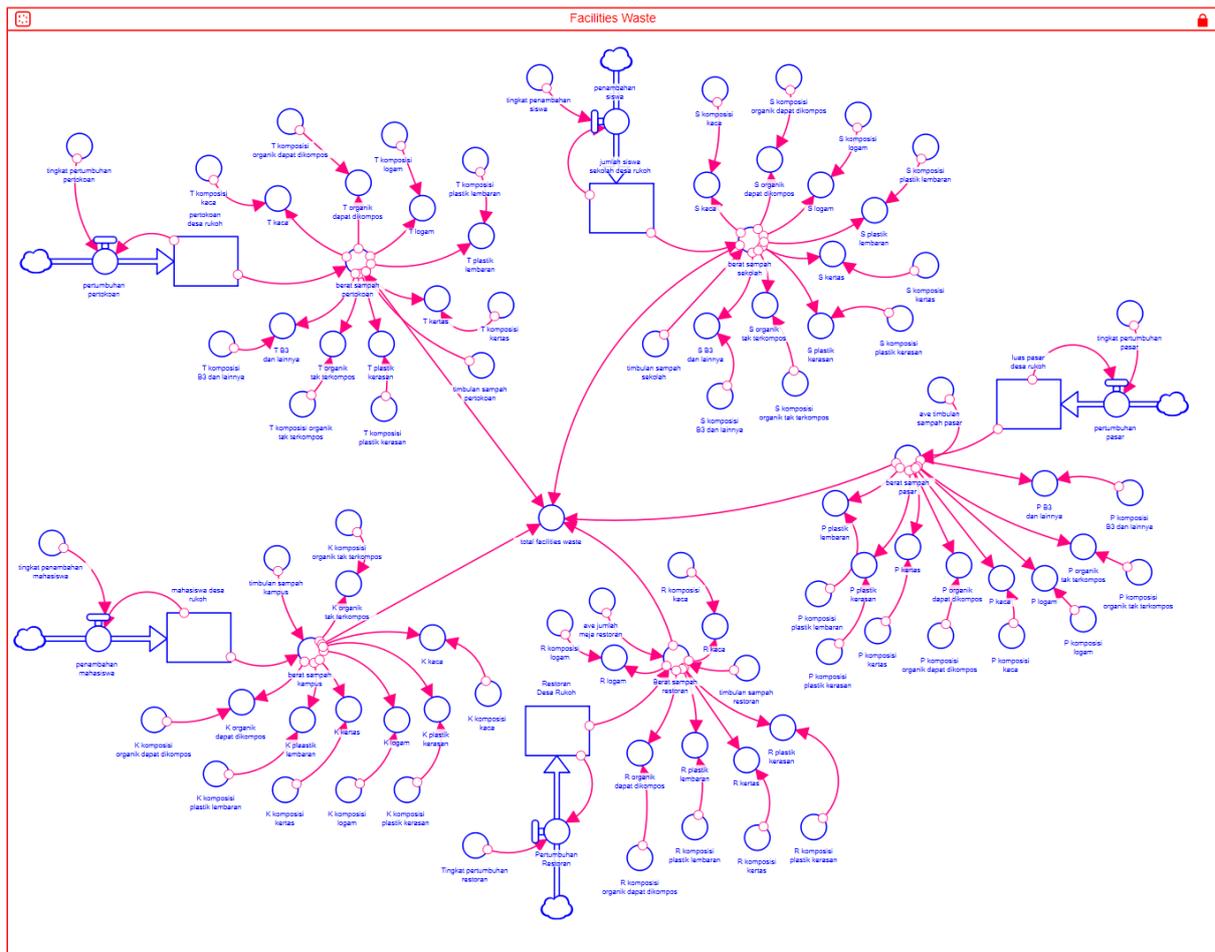


Figure 6. SFM Sub-model 2 Facilities Waste

Facilities that are calculated for weight of waste are schools, campuses, markets, shops, and restaurants. The total weight of the waste produced will depend on the increase in the number of facilities themselves. The input data for the variable number of facilities and facility growth are obtained from BPS and input data for generation variables and facility waste composition are obtained from Agustia's research (2014). Data from Agustia's research (2014) deserve to be used as a reference even though the research location is different because basically the activities contained in each facility tend to be the same even though they are in different locations.

2.3.3 Sub-model 3 TPS-3R. The sub-model of the TPS 3R reduction is constructed with variable and natar variables, obtained from observations on the 3R Stations TPS. This sub-model will run in the simulation of the TPS 3R intervention scenario. While in the existing condition there is no waste reduction by using TPS 3R so that in the existing condition simulation all variables in this submodel

are still not worth or value 0. This is intended to verify and validate the existing system model without involving intervention scenarios.

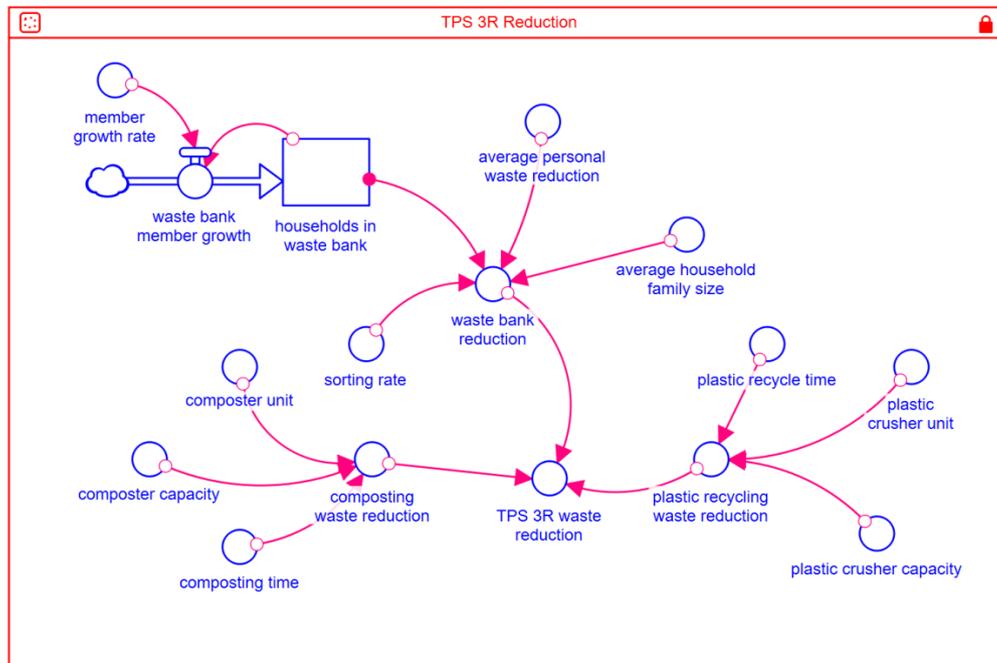


Figure 7. SFM Sub-model 3 TPS 3R

The reduction facility in this submodel follows the Lambung Village TPS 3R namely composting for organic waste, recycling plastic for plastic waste, and waste banks for waste other than organic and plastic. Reduction capability in each facility is assumed to be the same as the 3R Hull TPS. However, the variables that will change in value to be used as scenarios are the variables of the number of composter, the number of plastic enumerators, and the number of households. House

2.4 Model Testing

Based on the SFD model that has been built, a simulation is based on the existing conditions where the TPS 3R program has not been implemented and it is assumed that there is no reduction activity in Rukoh Village at this time. The following is the simulation results from existing conditions (Figure 8).

From the simulation results can be seen from the simulation results with the existing conditions have exponential growth behavior where the total weight of waste in the source continues to increase every year and all the waste is transported to the landfill without any reduction from the source. Thus, we can have the confidence that the model is valid.

The validation process in this model is also done by the structural validity test method. This is done because at the village level waste management system there is no historical data that can be used as actual data for the validation process with the behavior validity test method. As explained by Qudrat and Seong (2010), there are several tests in the structural validity test methods that require an in-depth understanding of the validation process. Therefore, in this study there are environmental experts in the waste treatment field to help model validation together the test from Stella software itself such as the dimensional consistency test. The result shows that the model is valid in which the units and formulas used are mathematically consistent. From the other tests too, such as extreme condition test, model parameter test, structure verification test, and boundary adequacy test, it was concluded that the model that had been built is valid which means it represents the real system.

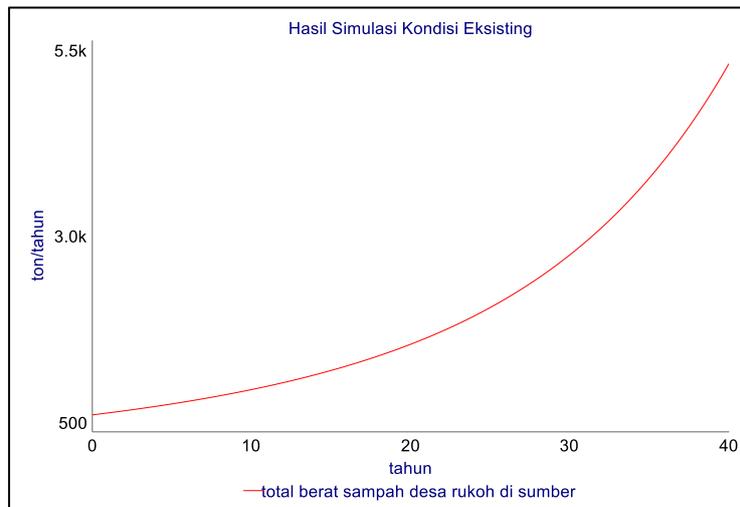


Figure 8. Simulation of Existing Condition

2.6 Policy Formulation (TPS-3R Intervention Simulation)

In order to achieve the waste reduction target of 30% by 2020 through TPS 3R, the intervention scenario is included in the model to achieve the target. There are several waste reduction parameters that can be selected according to the results of benchmarking with the TPS3 RL ambung Village, as follows:

- Additional composter unit
- Additional plastic crusher machine
- Growth in the number of households participating in the Waste Bank of TPS 3R

Table 4. Comparison of Scenario Simulation Results

Scenario	Composter (unit)	Plastic Crusher(unit)	Households Involved in Waste Bankby 2020	Waste residue (ton)	Reduction Percentage (%)
1	1	1	131	657,92	17,37
2	2	1	196	630,46	20,82
3	3	1	262	603,00	24,27
4	1	2	131	548,42	31,13
5	2	2	131	522,35	34,40
6	3	2	131	496,28	37,67

In determining the best scenario, it is necessary to have an understanding of the impacts that will arise from policies in terms of social, environmental and financial aspects. Based on the comparison of scenarios in Table 3.3, there are three scenarios that have a reduction percentage above 30% as well as a scenario that has a reduction percentage below 30%.

Based on the results of the three scenarios where the reduction percentage is below 30%, it can be concluded that the composter is unable to provide a percentage of waste reduction as much as 30% even though the number of participating families is increased because the ability to reduce waste in the composter is not as much as the ability to reduce plastic recycling. Meanwhile, based on the results of the three scenarios where the reduction percentage is above 30%, it can be concluded that a plastic unit of 2 units can provide a reduction percentage above 30% regardless of the number of composters and the number of households involved.

From the description of these considerations, the best scenario is scenario 4 with a reduction percentage of 31.13% in 2020, where the number of composters is 1-unit, plastic counting machines are 2 units, and the number of participating families is 131 households. This scenario was chosen because it is the most economical and realistic for the current situation. The simulation is run until 2020 which means that the Rukoh TPS 3R is likely not to be able to master the market from fertilizer products widely. So, it was concluded that by increasing the number of composter units by 1 unit, it would be more economical and realistic for now even though the amount of organic waste was more.

3. Conclusions

Based on the dynamic system modelling and simulation that has been done can use the TPS 3R intervention scenario in getting the best scenario for reducing Rukoh Village waste, here are some conclusions that can be drawn.

- The behavior of the waste management system in Rukoh Village which is displayed in the CLD model is influenced by several variables that are interconnected. There are three relations between variables in the form of loops in the waste reduction system model through this TPS 3R namely the population growth loop R1, Loop B1 TPS 3R waste reduction, and garbage B2 Loop transport.
- The behavior of waste generation generated in Rukoh Village through simulation results from the SFD model is exponential growth where the total weight of waste in the source continues to increase every year, where the waste comes from household waste and facility waste. In accordance with the simulation results, in 2020 waste generation generated in Rukoh Village is 796.27 tons/year or 2.18 tons/day.
- The best scenario in reducing waste is a combination of 1 composter unit, 2 plastic chopper machines, and 131 families participating in the TPS 3R. With this scenario, it can reduce waste as much as 31.13% in 2020 which is in line with the government target.

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