# Plastic Recycling from Household Waste

## Exploring the Policy space of the municipalities for improved Recycling rates

**TU Delft**
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# Management summary

In support to the European Union's move towards a circular economy, the Ministry of Infrastructure & Environment for The Netherlands has set up a national target to make the flow of primary materials into the system, completely circular by 2050. In context of plastic usage, this entails that all the plastic in the system should be completely renewable. To ensure this, the ministry has set up waste recycling target for municipalities in The Netherlands. In support to the target, this research is commissioned to study the emergent characteristics in Randstad area with respect to how recycling rate achievement of the municipalities can be improved. To collect insights on the emergence of behaviour based on interactions of municipalities and other actors considered, agent-based modelling method is used.

This study shows there are two policy levers to be considered by municipalities: with respect to households as waste producers, municipalities should increase their proactivity in improving perception and knowledge of households to separate recyclable plastic waste being generated. With respect to waste management firms, municipalities can consider shortening waste-processing contract duration with each firm to induce higher state of technological investment hence higher recycling productivity. Then, with respect to recycling rate achievement, the analysis shows that this contract duration policy by itself proves to be counter-productive given there are multiple municipalities considered. However, combination of both contract duration policy and higher proactivity by municipalities proves to be most optimal policy by municipalities to catch up with national government's rising recycling target over time, since implementation of both levers manages to improve waste separation rate at both households' and waste management firms' environment. This, however, comes with a trade-off: higher municipal expenditures over time compared to the base case, no-policy scenario.

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# Introduction

In support to the European Union's move towards a circular economy, the Ministry of Infrastructure & Environment for The Netherlands has set up a national target to make the flow of primary materials into the system, completely circular by 2050. In context of plastic usage, this entails that all the plastic in the system should be completely renewable (Netherlands, 2017). To ensure this, the ministry has set up 2 milestones; more than 50% recycled waste by 2030 and 100% by 2050. At the municipal level, there is a need for an acceleration in plastic reusability, as the current figures for recycling of household wastes in the Netherlands are around 36% (CBS, Trends in Netherlands, 2016). The municipalities are considering different incentives to improves the recycling rates of the plastics. Different studies are being commissioned on the "as-is" situation to explore the possible range of available measures which can be made available to ensure a smooth transition to circular economy.

One such study has been commissioned in the Randstad area, as being the financial nucleus of the Netherlands, the recycling rates are below national average. The Randstad area has a total of 140 municipalities across all 4 provinces i.e. North Holland, South Holland, Utrecht and Flevoland (Randstad, 2016). Municipalities in Randstad area will launch a pilot project to increase the plastic separation rate within their area and a TU Delft research team is handling the study the emergent characteristics of this socio-technical system.

# 1 Problem Formulation

## 1.1 Research Question

The focus of the project is to explore the potential measures available at the municipal level. In a socio-technical system with numerous interactions between different actors, each implemented measure can result in unprecedented outcomes. Hence, as an exploratory study, it is important to analyse the emergent impact of the interventions on the recycling rates and the extent of need of interventions.
Hence, the following research question can be formed:

*What are the trade-offs in the policy space of the municipalities to achieve the highest possible recycling rates?*

The policy space available with the municipalities will be influenced by certain factors and their influence on the system. Therefore, the following sub-questions are formulated to break down the research question:

1. *What are the factors that can influence the recycling rate objective of the municipalities?*
2. *To what extent can these factors be influenced by policy interventions?*

Experiments will be performed based on the system interactions to observe the degree of influence of the identified factors.

## 1.2 Methodology

In this research, agent-based modelling (ABM) is used as the main analysis method. ABM can inform emergence of system behaviour in long-term given how actors involved in the problem make decisions, act upon pursuing their objectives, and have interactions with other actors. The modelling and reporting structures are constructed based on formulation by (Nikolic, Dam, & Lukszo, Agent-based modelling of socio-technical systems, 2013), which can be systematically described in following order:

Step 1: Problem formulation and actor identification
Step 2: System identification and decomposition
Step 3: Concept formalisation
Step 4: Model formalisation
Step 5: Software implementation
Step 6: Model verification
Step 7: Experimentation
Step 8: Data analysis
Step 9: Model validation
Step 10: Model use

In the further steps, the problem is decomposed into smaller elements and the above sequence is applied to it. Based on the insights gained in the process, a attempt is made to answer the research questions.

# 2 Actor Identification

## 2.1 Actor Scan

In this section, a detailed Actor Scan is performed to highlight all the identified actors and their involvement is the problem. In the subsequent sections, the actors having high relevance to the problem will be clearly identified.

### 2.1.1 The Ministry of Infrastructure & Environment

Ministry of I&E has the mandate to act upon the circular economy objectives set by the Dutch Government. Hence in context of the problem, it is the context setter that is committed to set the Netherlands as an example for achievement of plastic waste recycling target to the Europe. To achieve the national recycling target, The Ministry provides guidelines to the regional administrative bodies, all the way to the municipalities, to work on plastic waste management within their own area. Their aim is to ensure that the that the municipalities have the administrative and legislative framework to achieve the national target to become completely circular (Netherlands, 2017)

### 2.1.2 Local Administration – Municipalities

Based on the directives provided by the ministry, the municipalities are one of the key players in the local arena, who are responsible to drive the system towards higher recycling rates. They provide the required infrastructure to ensure the collection and disposal of waste. The composition of the municipalities consists of domestic and commercial elements which are responsible to produce the waste. Each municipality must identify different mechanisms to deal with the total waste that is produced while ensuring that the maximum possible waste is recycled. The municipalities have the means to incentivize the local citizens as well as the waste processing firms to ensure the targets are achieved. However, they have limited financial budget to achieve this. These features make them important for further analysis.

### 2.1.3 Waste Producers – Households

The action of recycling plastic cannot be done by the municipality governments alone. Households have a role in determining how much amount of recyclable and non-recyclable plastic waste is there to be processed. Households consist of the citizens that are part of a municipalities. In the scope of the current problem, they are the primary waste producers. Based on their level of knowledge towards the impact of the waste on environment, households can identify recycling measures.

### 2.1.4 Waste Producers – Local Businesses

Another primary waste producing actor in the local economy are the commercial actors. These have been aggregated to include all the commercial activities that are carried out at the municipal level, including but not limited to Small Medium Enterprises (SMEs), service providers such as restaurants, tourism centres, museums, schools etc. The amount of waste produced by them is largely dependent on the nature and size of the commercial activity. This can be overcome by either creating representative population subsets from high waste producers or accounting for them individually. However, the current study being preliminary and exploratory in nature, and accounting for the dominant nature of households in waste production, this actor is left out of the scope of analysis.

### 2.1.5 Waste Processing Firms

The waste-processing firms are the ones that have the technological resources and processing capacity to process the incoming waste. The firms and municipalities have a contractual relationship with the incentives set up for the total recycling quantity. Based on the size of the firms and the mechanisms used by the municipality, there can be variations such as unit based pricing (UBP) or kerbside collection. Being private entities, one of the primary interest is maximizing their returns. This is facilitated through contract negotiations or adding additional services within their facilities, such as incineration and energy recovery. Additionally, the companies can sell products made of recycled plastic waste at given rate. However, the scope of the analysis is limited only to their recycling services.

# 3 System Identification & Decomposition

The goal of this section is to establish the boundaries of the model. Accordingly, the internal structure of waste management system will be identified based on how the selected agents interact among each other given their goals and resources within the environment in which they exist.

For problem scoping, the arena is set at the local governance level. This makes the Ministry of I& E as the context setter. The overall goals set by them are the abiding terms for the municipalities. This makes their role in the modelling work exogenous. Additionally, due to the diversity in the commercial waste producing actors and their relatively lower contribution to the overall waste production, they are left out of the scope of the analysis. Therefore, actors that will be modelled are;

- Municipalities
- Households
- Waste-Processing Firms

Based on the identified arena and the actors interacting in them, this section will elaborate on the actor scope and the states and behaviours of the actors within the scope. At the same time, the scope of the environment of the model in which agents interact will also be elaborated.

## 3.1 Actor Scope

### 3.1.1 Municipalities

The municipalities are the actors that create the infrastructure required to facilitate waste recycling within a fixed budget of their expenditure. Their prime role is to ensure the conformance to the recycling targets set by the ministry. This is achieved by releasing tenders to create contracts with the waste management firms and ensure competitive pricing of the recycling services. They can incentivize the recycling firms by offering unit base pricing (UBP) and levying a compensation if a certain amount of waste is not delivered. Hence, they have to ensure that a certain amount of waste is being collected from the households regularly. The municipalities also define the waste collection infrastructure, which can either be centralised or decentralised. A centralised collection infrastructure requires the residents to bring the wastes to a specific area for processing. Whereas, in a decentralized system, different local collection points are created where residents can deposit their wastes, such as in the case of Kerbside collection. At the same time, municipalities are capable to improve perception and knowledge of households regarding separation of waste. Refer to Section 3.1.2 for information regarding perception and knowledge of households.

The municipalities can be of different compositions, based on the following demographics; Less than 10000 inhabitants, between 10000 to 100000 inhabitants, above 100000 inhabitants; or based on percentage contribution to national GDP. For this analysis, we will consider only the demographics aspect of the municipalities, which is operationalized on number of households.

### 3.1.2 Households

Households existing in the municipality can be classified based on demographic basis, namely age and size. Each household based on its composition and motivation, produces different volumes of plastic waste per month. They may have different behaviour regarding separation of recyclable plastic waste based on their knowledge and perception. The action by households to separate recyclable plastic waste is called pre-separation. Knowledge is about whether the household has information on how to pre-separate the recyclable plastic waste from total plastic waste amount; perception is about whether household realizes the importance of doing separation of plastic waste from other base waste (Nikolic, SEN1211 Final practical, 2016). The pre-separation patterns of the households can also be influenced by the type of available infrastructure available in the municipality; centralized and decentralized system (Saphores, Ogunseitan, & Shapiro, 2012).

### 3.1.3 Companies

The waste-processing companies collect and process the household waste using their own plant technology. These companies commit waste processing based on contracts established with the municipalities. Therefore, the waste-processing companies will bid offers to the municipalities and set minimum waste recycling rate compliance, and the value of fines to be paid by municipalities in case the provided waste quantity is less than specified. If the contract is between both parties, waste-processing companies will start processing waste for the specified time span. The collection of waste can be committed either at household locations (decentralized) or at central point collection (centralized) with a pre-specified cost. Decentralized collection of waste leads to increasing cost of the companies due to transportation and fuel cost incurred in collecting waste in dispersed collection sites in the municipality.

Each waste processing firm has a fixed processing capacity, and technological processing efficiency. These facilities are used by firms to commit post-separation of the waste: which is separating recyclable plastic waste from the plastic waste in the collection sites that is not pre-separated by households. The higher capacity and efficiency are, then practically the higher amount of recyclable plastic waste can be post-separated. Firms will collect non-pre-separated plastic waste from the collection infrastructure and process the waste. The companies can invest in new technology and larger capacity implementation in case they cannot compete well with other companies in the bidding process. The profitability during the bid is always conserved. The investment fund will only be derived from their cash balances, as financial institutions are left out of scope.

Waste processing firms gain income by selling the recovered plastics, where the selling price is exogenously specified. Other than investments, the operation cost is another expenditure which affects the cash balance.

## 3.2 Environment Scope

The environment contains information external to the agents, which are relevant to decision making process and the mechanism of interactions among the agents. The environment considered in the model is basically waste management in the municipalities of Randstad area.

The prime factor external to the arena is the recycling rate target, which is defined centrally by the Ministry of Infrastructure & Environment. The Ministry instructs compliance of this target to the Municipality. Higher target can steer the direction of the municipalities significantly as they need to work harder to achieve it. Another external factor is the market selling price of the recovered plastics which is given based on Dutch market and is not determined by the system. Finally, availability of new waste-processing technology itself is exogenous, not to be determined by any agents involved in the model. The waste-processing companies can invest in implementing any existing technologies, but not in terms of R&D commissioning/investment. Additionally, the investment and technology and capacity are mutually exclusive and technological investments can be applicable to existing infrastructure by influencing only the efficiency of the process.

Given the description, environment inventory can be defined as follows:

- Target of recycling rate (Float; 0<=x <= 1)
- selling price of recovered plastic (Integer >=0)

# 4 Concept Formalisation

In this section, the identified agents and their behaviours are operationalized using computer primitives and their relationship with respect to each other is defined. Unified Modelling Language (UML) representations are used to coherently describe the relationship amongst them. Finally, the assumptions of model simplification and data sources are highlighted, and parallels are drawn to the available references used to make the assumptions.

## 4.1 Agent States and Behaviours

### 4.1.1 Municipalities

Municipalities have:

- Number of households; (Integer >=0)
- Cumulative expenditure due to paying contracts, fines and stimulating activities; (Integer >=0)
- Contracted firms; (integer >=0)
- Number of Stimulating activities to raise perception; (integer >=0)
- Number of Stimulating activities to raise knowledge; (integer >=0)
- Cost per perception-increasing Activity; (integer >=0)
- Cost per knowledge-increasing activity; (integer >=0)
- Total waste collected; (integer (kg/month) >=0
- Contract Duration; Integer >=1
- Percentage of separated waste by households; (Float, 0 <=x <= 1)
- Collection infrastructure; centralized vs decentralized;[1] (Float 0 <=x <= 1)
- Working contracts with firms; (lists)
- Fine cost; (integer >=0)
- Recycling percentage achieved; (Float 0 <=x <= 1)

Municipalities do:

- Request contract offer from firms;
- Select contract offers from the firms;
- Set contracts duration with Recycling firms
- Pay contracted costs
- Pay fines if not enough pre-separated waste is provided to firms
- Check if recycling percentage target is being achieved
- Commit knowledge-stimulating activities to raise knowledge for households
- Commit perception-stimulating activities to raise perception for households

### 4.1.2 Households

Households have:

- average waste produced per households per month; (integers (kg/month) >=0
- type of household; (String; Single, Couple, Old, Family)
- Production waste unit per household, depending on the type of household; (Float >=0)
- fraction of waste pre-separated by household; (float, 0<= x <=1)
- level of knowledge; (float, 0<= x <=1)
- level of perception; (float, 0<= x <=1)
- Factor how much perception/awareness of a household is affected by perception-stimulating activities; (float >= 0)
- Factor how much knowledge of a household is affected by knowledge-stimulating activities; (float >=0)

Households do:

- produce waste
- separate plastic waste out of the base waste produced
- pre-separate recyclable waste from the plastic waste

[1] This is aggregated in the setup (explained in later sections) and one municipality cannot change its infrastructure type during the model run.

- update knowledge upon stimulating activities
- update perception upon stimulating activities

### 4.1.3 Recycling firms

Companies have:

- working contracts with municipalities; (Links)
- Contract Duration; (Integer >=1)
- waste processing cost; (Float >=0)
- waste collection cost; (Float >=0)
- Income per sold recovered plastics; (Float >=0)
- cumulative cost; (Float >=0)
- cumulative Earning; (Float >=0)
- cash balance; (Float >= 0 or <=0)
- waste-processing technological efficiency; (Float 0 <= x <= 1)
- capacity of waste processing; (Integer (kg/month) >= 0)
- Factor of improvement of waste-processing capacity; (Integer >=0)
- Factor of improvement of waste-processing technological efficiency; (Float >=0)

Companies do:

- offer contract to municipality
- calculate income and expenditure
- update cash balance
- collect waste
- process waste
- sell recovered plastics
- receive fines from municipality
- Invest in technology
- Invest in capacity

## 4.2 UML Class Diagram

In this section, a UML class diagram is used to trace agent relationships in an object orientation. This helps is clearly observing hierarchies and shared objects among each class. In this case, the municipalities, households and Recycling firms are defined as class objects. The households are represented as a subclass of the municipalities with a strong association. This is due to the assumption that there is no change in composition of the municipalities in number of households during the runtime of 20 years. **Figure 1,** below shows the UML class diagram. Municipalities and Recycling Firms create the object contract between them which has its own set of attributes. At the same time households produce the object waste.

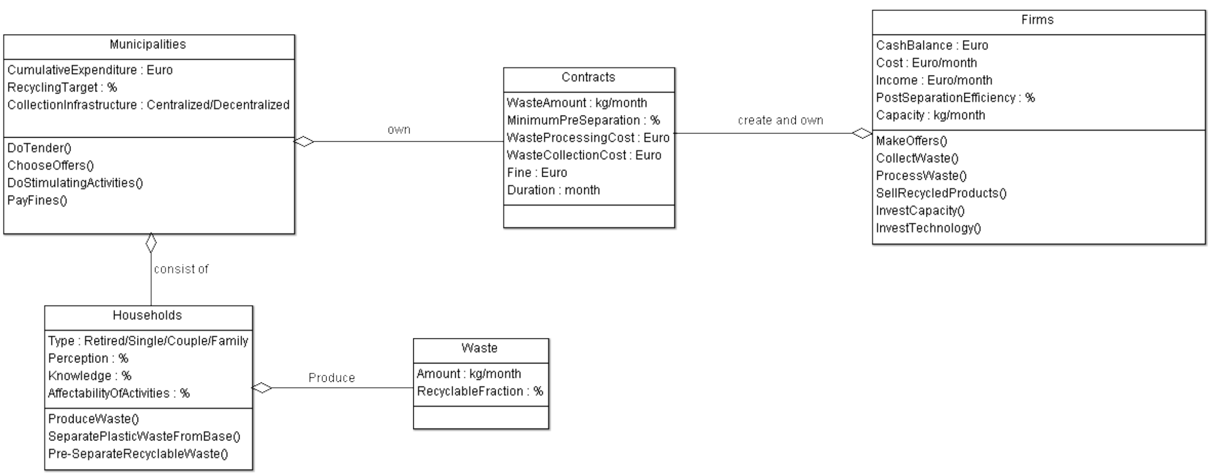


Figure 1 UML Class diagram of the problem

## 4.3 Assumptions

Based on the UML diagram, the following section elaborates on the assumptions made and their relation to the agent attributes. Due to the missing data from the problem, different available sources are considered with 2016 as reference year. The operationalisation of the assumptions is to be discussed in subsequent sections.

### 4.3.1 Households

- Percentage of Households distribution into the different demographic type is based on average distribution in municipalities of Randstad area (CBS, Population dynamics, 2016), and is fixed during the length of the run of the model
- Waste production formula for households is given as follows: base-waste(x) = 40 - 0.04*x – exp. (-0.01 * x) * sin (0.3 * x), where **x** is the year of the simulation time.
    - Therefore, a monthly base-waste function is derived by dividing the formula by 12, since the time in the model updates every month.
- Each household commits to separate plastic waste from base waste and pre-separate recyclable plastic waste based on an initial perception and knowledge value[2].
- There is no interaction among households which lead to change in perception and knowledge. This is ensured by using a random distribution function.
- Out of the total waste produced, the percentage amount of recyclable plastic waste is given as fixed.
- Higher awareness/perception translates to higher fraction of plastic waste from the base waste volume put. Higher knowledge means higher recyclable fraction in the household plastic waste
- The perception and knowledge for each household can be improved by stimulating activities of the municipalities.
- The waste produced is dependent on the type of household; old, single, couple or family.
- Decentralized waste collection infrastructure leads to more pre-separation of recyclable plastic waste by households compared to centralized infrastructure.
    - This is assumed since kerbside collection systems translate to less work for the people, and thus higher incentive to separate (Saphores, Ogunseitan, & Shapiro, 2012).

### 4.3.2 Waste-processing companies

- The base data for waste processing is benchmarked from the Attero company profile, as it has been discussed in the slides (Attero, 2016).
- The less waste being pre-separated, the more operating cost for a given company due to responsibility to post-separate the waste. Hence a minimum pre-separation rate of the plastics is promised by the municipalities.
- Waste collection cost rate is higher for decentralized rather than centralized infrastructure as it is assumed that the firms invest for more intricate collection mechanism.
- All firms have a positive cash balance at t = 0, since the model does not account for a loanable funds market.
- All recycled products are sold by recycling companies and that adds to their cash balance.
- Contracts are offered to municipalities due to municipalities' request for tenders.
- Each company can handle multiple municipalities, if it has sufficient capacity.
- Capacity investment will lead to more waste volume being handled and better post-separation efficiency, however, the efficiency increase is lower compared to a technological investment.
- Maximum capacity utilization will be 90% of total capacity before a firm decides to invest.
- Technological investment will lead to higher post-separation efficiency of the firms.
- A firm invests in technology when the offer recycling rate is lower than 10% excess to the target requested by municipalities.
- Capacity and technological investment will lead to higher operating cost per kg of waste, since companies maintain their profit margin.
- The increase in operating cost due to capacity increase is higher than increase in cost due to technological change.
- If companies' offer is not accepted by municipality it will invest in technological or capacity efficiency, based on the reason for non-acceptance.
- For contract procedure, the firms offer prices based on spare capacity to the municipalities.

[2] Knowledge and perception definitions are in line with the problem definition provided in the course (Nikolic, SEN1211 Final practical, 2016).

  - It is exogenously assumed that the firm has a buffer to store waste and will invest in capacity if collection is more than firm can handle at once. However, this rule is not applicable if the operating capacity is near 90% full capacity.
- Contracts will specify:
  - Maximum amount of waste sent to the companies by the municipality, since amount of household waste decreases over time.
  - Minimum percentage of waste pre-separation over the waste collected that must be complied by municipality.
  - Amount of fine that must be paid by municipality to the companies in case the minimum percentage of waste pre-separation is not complied.
  - Total amount of waste recycled by the firm (including pre-separated + post-separated amount).
  - Offer price, which is based on the operating and waste collection cost of the companies per month.
  - Time duration of the contract.

### 4.3.3 Municipalities

- Only if municipality needs waste processing, it will ask for contracts to be offered by companies. The contracts in turn are offered by companies.
- Municipalities expenditures over time will be studied and a minimum expenditure position while meeting the national target will be studied[3].
- Total amount of waste of each municipality is the sum of household waste in the corresponding area.
- Each municipality defines the achieved recycling rate as;

*Amount the amount of recyclable waste that is (going to be) recycled / Total recyclable plastic in a municipality*

- The amount of recyclable waste that is (going to be) recycled consists of plastic waste pre-separated by households and plastic waste post-separated by companies.
- The total recyclable plastic in a municipality is the total plastic that a municipality can recycle given that the citizens have perfect knowledge and perception of the issue[4].
- The municipality can only have one option of waste collection infrastructure that is fixed over time: either centralized or decentralized decided at the beginning of the run.
- Activities to increase perception and activities to increase knowledge are operationalized differently between each other.
- Educational activity by municipalities will cover all the households within their own area, where the level of effectiveness across all the households follows a normal distribution.
  - This has been operationalized assuming that different households have different retention level of similar activities.
- The municipality will commit and pay for activities to improve perception and knowledge, if:
  - Percentage of pre-separation by households is less than what is specified in the contract, and/or:
  - The Recycling rate of waste in a municipality is less than the exogenous target set by the Ministry.
- Municipality will pay fine to company if it cannot comply with the minimum percentage of waste pre-separation given in the contract.
- Municipalities have no interactions with each other in case of waste, information, or financial transfer.
- The fines paid by municipality due to contract foul is a fixed value, and does not depend on amount of waste processed or collected.
- Municipalities select the cheapest offer of waste-processing from the companies, firstly based on the capacity, and later based on efficiency.
- If no firm has spare capacity, the contract is created with firm having highest efficiency on the assumption of fast moving inventory and stock buffer at the end of firms.

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[3] The reason to make this assumption is that municipalities are in position to run budget deficits and any deficit in the budget can be compensated through taxation and additional fund allocation from a national level in the consecutive year. This implies that municipalities have practically a non-exhaustive budget.

[4] This additional complexity has been added in the model as efficiency, in its general form is conformance to the most ideal case. This adds a rigor to the model.

## 4.4 Parametrisation

This section highlights the variables, either global or agent parameters, that will be defined externally in the model. These variables have been based on assumptions or literature, wherever found relevant.

### 4.4.1 Global variables

**Initial Government recycling target:** The recycling target is external to the model and has been set to **75%**. This is indicative of the Dutch government vision till 2020 (Rijksoverheid, 2017). The current levels are at **50%** and this will be used as base for 2016. However, in the model, this target will update in steps with the passage of time.

**Yearly target improvement:** It is considered that the national recycling target are not included in large steps, rather in yearly percentage increments from the model base value. This gives time for the municipalities to take policy actions.

**Percentage recyclable waste:** The ratio of possible recyclable waste to the total waste collected. The Dutch recycling target is 75%, however, in theory, up to 80% of the waste can be recycled (Central, 2017). In the model, this is fixed at **80%** to account for long run.

### 4.4.2 Setup Variables

The setup variables are the ones that will help in populating the model once the Setup button is pressed and define the fixed part of the model. There is a possibility to change these structural parameters either by slider or by accessing the code. However, for consistency of experiments, we will not change them. The option is provided as a slider to test the structural effects on the model function.

#### *4.4.2.1 Household variables*

**Base Waste Quantity:** The per capita plastic waste produced is given by a yearly base waste function[5] (Nikolic, SEN1211 Final practical, 2016). This translates to a monthly waste of **3.55** kg/person for a household of single person[6]. Different types of households produce different waste quantities (Nikolic, SEN1211 Final practical, 2016). Hence, a multiplication factor for each type is defined to calculate exact values. The is defined as;

- Old; **0.75**
- Singles; **1**
- Couple; **2**
- Family; **3**

**Household distribution:** The Household Distribution of the Randstad region, based on the household type is set per municipality (CBS, Population dynamics, 2016). However, there is a slider possibility to change the distributions;

- Old; **8 %**
- Singles; **32 %**
- Couple; **31 %**
- Family; **29 %**

**Perception to recycle:** In the global variables, it has been mentioned that the total base waste has 80% of recyclable plastic. However, due to lack of perception, different households put plastic recycling at varying importance level. This results in collection of lesser volumes of recyclable plastic. In the model, it is assumed that initially all households give **40%** importance to plastic recycling with a standard deviation of **15%**. Hence only 40% of recyclable plastic is drawn out from the total base waste. This perception can be increased through awareness programs.

**Infrastructure Effect:** The motivation to pre-separate the waste is also driven by whether the municipality has a Kerb Collection system (Decentralized), or a centralized deposit depot. For the model, we assume a factor of multiplication over the pre-separation rate at the setup of model. The factor is set to **1.0** if it is a Centralized system, and **1.1** if it is decentralized system.

[5] Since the base waste function is yearly, and the time step in the model is one month, we have converted the base waste function as waste(x) = (40 - 0.04*x - exp. (-0.01* x) * sin (0.3*x))/12. This is a simplification made at the expense of mathematical accuracy.

[6] For further calculations in municipality and firm's parametrisation, this value will be used as reference.

**Pre-separation Percentage:** In the Netherlands, the average pre-separation rate at source is 31% (Wageningen, 2016). As different households have a different affinity towards separation, a standard deviation of **5%** is applied to the rate in the model. The effect of the knowledge increase program will increase the pre-separation percentage.

#### *4.4.2.2 Municipality Variables*

**Number of municipalities:** The Randstad area has a total of 140 municipalities across all 4 provinces i.e. North Holland, South Holland, Utrecht and Flevoland (Randstad, 2016). The population in the Randstad Region is **8.1 Million** (CBS, Population dynamics, 2016) and the Number of private households in Randstad is **3.74 Million** (CBS, Population dynamics, 2016). As the demographics differences across municipalities are left out of scope, it is important to calculate the average households per municipality.

*Average number of households per municipality = Number of private households in the Randstad/Number of municipalities*

Therefore, an average Randstad municipality is considered to have **26300** households. As the scope of the analysis is limited to Attero, which processes the waste for 20% of Dutch Population (Attero, 2016), we will calculate the number of municipalities that fit this criterion and assume that all the waste is picked up from Randstad. Therefore, Attero collect waste for;

0.2 * 7720787 = 1.54 Million *households*

With the average number of households as 26300,

*Number of Municipalities = Households served / average number of households per municipality*

Using the above formula, it is calculated that Attero serves **59** municipalities. Therefore, the number of municipalities in the model is limited to **60**. However, for efficient running and due to computational time for the model, the testing is done at significantly lower number of municipalities.

**Average Households per Municipality:** As calculated in the previous section, the average number of households is 26300 (CBS, Population dynamics, 2016). Therefore, for simplicity, the number of households has been rounded off to **26000**[7] per municipality as the mean with a standard deviation of **2000** household.

**Household Education Program:** To strive for the targets set by the ministry, the municipalities organise education programs for the households. There are 2 types of program based on the area of focus of the municipality;

Table 1 types of education programs

| Type of Education Program | Effect on Households |
|---|---|
| Awareness program | Raises the perception to recycle |
| Knowledge programs | Raises the pre-separation rate |

**Cost of Household Education Programs:** The promotion of circular economy target and raising awareness of the people comes at a cost. Each program, with marketing, media, workshop and follow-up is assumed to cost **15 Euro/Household/program**.

**Effectiveness of Knowledge Programs:** One knowledge program is assumed to increase the effect of pre-separation by **8%** at 100% effectiveness. As different people behave differently to training and awareness programs, the retention of the training to increase the awareness is more widely spread. By assumption, **50%** of all the training will be retained by the households with a spread of **25%.**

*Actual Effectiveness = Effectiveness at 100% * retention level*

Hence at 60% retention, as mentioned above, the actual effectiveness is 0.08 * 0.6, i.e. **4 %** with a standard deviation of **2%**.

[7] In the model 1 agent is considered as 1000 households. This is also done to reduce the computational time of the model.

**Effectiveness of Awareness Programs:** Similarly, awareness is assumed to increase the effect of their respective variable by **8%** as well at 100% effectiveness. However, experimentation can be done by varying the percentage.

**Percentage Centralized Infrastructure:** Out of the considered sample of municipalities, a certain percentage are allotted Centralized infrastructure. This is done by using a **0-100%** input, where **0%** means all municipalities having **decentralised** and a **100%** translates to all having **centralized** infrastructure.

**Pro-activeness towards recycling:** The municipality in the model frequently check if the national targets are being conformed to and act to strive towards it. To do so, 2 parameters are introduced to define the pro-activeness of the municipality as shown in the Table **2** below;

Table 2 Proactiveness metrics

| Pro-activeness Parameter | Meaning |
|---|---|
| Frequency to review target | How frequently does the municipality review the target to see if an action is needed towards awareness and knowledge increase activities.<br>- The value can be from **1 – 12 months**. |
| Likeliness to take initiative | If an action is required, how likely (probability) that the municipality will act on the initiative.<br>- The value can be from **0 – 100 %**. |

The pro-activeness in a municipality can be hypothesized to affect the recycling rate. This parameter has been added to make the initiative procedure more realistic.

#### *4.4.2.3 Contract Variables*

**Minimum Recycling Target:** The key requirement for a contract to be formed is the minimum recycling target requested by the municipality on the processed waste. This will be considered the same as the government target of **50%** for 2016, and will be updated in steps as the time passes.

**Contract Duration:** The standard duration of contract is set to **36 months** as given in the problem description (Nikolic, SEN1211 Final practical, 2016). However, this can be altered in the model.

**Minimum pre-separation percentage:** To make profit out from the waste collected, the firms need a minimum guaranteed percentage of pre-separated plastic to reduce the processing cost on the collected plastic. Therefore, a pre-separation percentage of **25%** is stipulated in the contract which can be altered for experimentation.

**Fine Value:** The municipality is liable to a fine value if it is not able to deliver the minimum pre-separation promised. The fine defined for the same is **500000 Euro**

#### *4.4.2.4 Recycling Firms variables*

**Number of Factories:** As the recycling benchmark is based on the information provided in the Attero presentation and website (Attero, 2016), the number of separation & recycling factories is assumed to be **4**. This entails that each of the plant is responsible initially for **15** municipalities.

**Capacity per Factory:** As mentioned earlier, the monthly recyclable waste possible a household can produce is **3.55 kg** for a household of single person. However, in terms of recyclable waste, the maximum possible is 0.8 * 3.55, i.e. **2.84 kg/person**[8]. However, at the beginning, the model is set to a perception of **40%** toward recycling. Since the capacity of companies is represented of the current recycling of the municipalities, the capacity of company is calculated based on current waste production;

*Current waste production = Base-waste production * perception to recycle*

This gives us a waste value of **1.42 kg/person**. The average household size in the Randstad area is **2.2** people (CBS, Population dynamics, 2016) which is calculated;

*Average household size = Population of the Randstad / Number of private households in the Randstad*

[8] **3.55 * 0.8** kg

Therefore, the capacity for each unit should be minimum to process waste of 15 municipalities worth of households; 1218 tonnes of waste per month.

*Capacity per unit = 1.42 (kg/person) * 2.2 (persons/household) * 26000 (households/municipality) * 15 (municipalities)*

If **15%** of company capacity is spare for future projects, the Capacity per factory is assigned as **1450** tonnes/month with standard deviation of **10%**[9].

**<u>Post separation Efficiency</u>:** At the current moment, based on the input from Attero Slides (Goosens, 2016), the post separation efficiency at the beginning of the project is considered as **25%** with standard deviation of **2%**.

**<u>Operation Cost</u>:** After referring multiple sources, a clear estimate of operating cost was not found. This is related to the fact that standard operating cost is company specific and related to the technological and sunk cost. Therefore, a mean operating cost of **0.35 Euro/kg** with a standard deviation of **0.05 Euro** will be assigned randomly to the firms. This is done to enhance the competition effect

**<u>Collection Cost</u>:** The collection cost of the waste is the cost that the recycling firms incur through logistics elements of the process. The transport fee is generally calculated at Cost per tonne per km (Nedvang, 2016). Since the spatial complexity of the problem is left out of scope, the waste collection cost for centralized is considered as **0.1 Euro/kg** and for decentralized as **0.15 Euro/kg.**

**<u>Selling price of Plastics</u>:** Since the post-separating operation adds to cost, the selling price of pre-separated and post-separated plastics is significantly different. The selling price of pre-separated plastics is **0.43 Euro/kg**, and for post-separated plastics as **0.87 Euro/kg** (Nedvang, 2016).

**<u>Innovation Cost</u>:** The cost for innovation is decided under the assumption that the improvement of efficiency is achieved without increasing the physical capacity of the system. Due to the aggregation of innovation, the cost is set at **200000 Euro**.

**<u>Efficiency Increase</u>:** From the provided information on evolution of processing efficiency over time (Goosens, 2016), the average increase is 7.5% over the cited periods. To maintain consistency and account for future improvements, the increase in efficiency is set at **6%** per investment. An increase in efficiency increases the operating cost by **2%**

**<u>Capacity Increase Cost</u>:** In general, the cost for capacity increase is highly variable and depends on multiple factors such as size, scale, location, etc. Since the scope for increase in our model specifies a one-year period for capacity, increase, only small-scale capacity increase by adding equipment is considered. Therefor the cost of capacity increase is set to **1 million Euro**.

**<u>Capacity Increase</u>:** Capacity increase will be considered when the operating capacity is at 90% of full capacity. The **increase in capacity of 10%** is assumed for small scale investment t. As the new capacity will be installed with state-of-the-art machinery, there will be an **efficiency increase of 4%** as well. An increase in capacity **increases the operating cost by 5%**.

**<u>Cash Balance</u>:** Due to the absence of a loanable funds market, the firms need a certain fixed capital amount to account for initial expenditures in the model run beginning. This is handled by providing a cash balance of **10 Million Euro** to each firm as a buffer for operating cost and investment scope.

[9] It is important to note that this has been considered for 60 municipalities. In the model, if the number of municipalities are reduced, this value can be adjusted as well to add realistic computation.

# 5 Model Formalisation

## 5.1 Model narrative

This section covers description of the behaviour of all agents considered in the model. The behaviour narrative consists of "which agent does what to whom and when" (Nikolic, Dam, & Lukszo, Agent-based modelling of socio-technical systems, 2013), therefore interactions among the agents will be considered. The narrative is given based on what happens in every tick. Figure **2** below gives a breakdown of the recycling rate calculation used for firms and municipalities. The firms calculate the recycling rates based on the waste received by them, pre-separated and post-separated. Whereas, municipality compares the total recycled waste per month with the possible recycling rate if the households had perfect perception and knowledge.

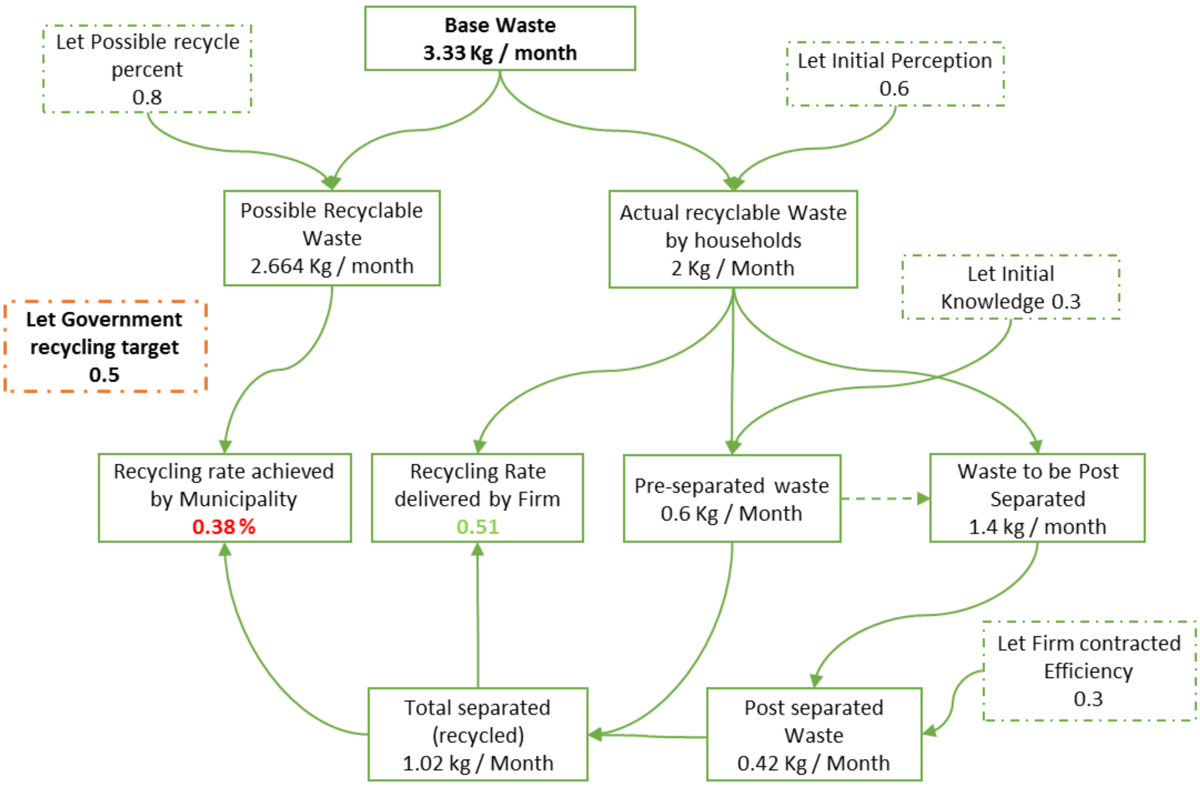


Figure 2 Recycling rate calculation metric for Municipalities and Firms

In every tick, households will produce certain amount of waste. Households will check: their degree of perception and knowledge, and the type of collection infrastructure in their municipality. In the municipality with decentralized waste collection, the households will require less effort to separate the recyclable plastic waste compared to municipality with centralized infrastructure. Degree of perception and knowledge of the households will determine to what extent they will commit separation of plastic waste out of total base waste produced and pre-separation of the recyclable plastic waste out of total plastic waste, respectively.

The plastic waste not pre-separated by households makes up total amount of waste in need to be post-separated by firms to improve recycling rate of the municipalities. Therefore, based on the amount of waste in need to be processed, the municipalities will check whether they have ongoing contracts necessary to cover all the waste processing. In case of the lack of contracts, the municipalities will demand for contracts offered by waste-processing companies by tender mechanism. Municipalities will firstly set the tender based on waste-handling capacity. Based on this, the municipalities will choose contracts that has highest overall recycling rate and lowest monthly price offer. If no companies can comply with the necessary capacity, the municipality will look for companies with highest efficiency and give the contract to them. This assumes that the companies have a stock buffer mechanism at their end to store the access waste. This has been left out of scope. Total recycling rate for the municipality is calculated as sum of recyclable plastic waste pre-separated by households and waste post-separated by companies. After contract is agreed, municipalities will check if: percentage of pre-separated waste of households is lower than what is specified in the contract, and whether total recycling rate is lower than the Ministry target; on either/both ways, they will commit perception and knowledge-stimulating activities. Therefore, other than the plausible fine mechanism, municipalities will incur cost based on: the price of offer agreed in the contracts which they must pay to companies processing waste, and commission of activities increasing perception and knowledge. Since the fine is pre-specified highly, municipalities will do their best to avoid paying the fine to these companies.

Companies will check whether they have the sufficient budget to cover all operational cost necessary for the whole contract period; in that case they will apply for the tender. Waste-processing companies winning the tender will handle the operational process of waste-processing. Companies will collect waste from the collection infrastructures and incur collection cost accordingly. For waste already pre-separated by households, companies will just collect the pre-separated recyclable waste. For waste not pre-separated, companies will have to collect the combined the whole municipal plastic waste and post-separate them. All the recyclable waste collected will be processed by companies and eventually be sold based on pre-specified price.

Regarding pre-separation rate set in the contract agreed, waste-processing companies will be paid a fine by municipalities unable to achieve the rate. Waste-processing companies will start investing in technological efficiency if their contract offers are not chosen by municipalities due to recycling rate requirement. If the companies cannot comply with the level of capacity which could be fulfilled by other companies in the tender, then it will invest in capacity. All capacity and technological investments require 1 year of development. Therefore, other than investments, the companies will incur cost from operational cost based on amount of waste processed and collected, which in turn will be reimbursed by municipalities based on the contract agreed.

## 5.2 Pseudo Code

In this section, the agent attributes are defined, as used in the pseudo-code and later in the code implementation. Based on the definitions, a pseudocode is created that provides the base for implementation on the software.

### 5.2.1 Agent Attributes

For creating the model, it is important to clearly define agent attributes. To operationalize the agent behaviours, different attributes have been defined and used first to create the pseudocode and later for the code. An extensive list of these can be found in **Appendix I**.

### 5.2.2 Setup Function

In this section we will present the pseudocode for the setup function for the agents and the environment[10].

#### *5.2.2.1 Model Preparation*

- Clear outputs
- Reset the tick counter to the beginning of the model

#### *5.2.2.2 Global Variables*

- Set recycle-percent-target = initial-recycle-percent-target; value (**Slider**)
- Set Target-update-counter = 0
- Set tick-counter = 0
- Set initiative-tick = 0

#### *5.2.2.3 Household Variables*

- Create-households = Mean (26 * total-municipalities) SD[11] (Value)
- Based on the percentage distribution defined in the global screen;
    - Set household-type = string; one of → {old, single, couple, family}
    - Set waste-factor = value {from household-type}
- Assign municipality-belong to one-of the municipalities
- Set base-waste-function = (40 - 0.04* **tick** - exp.(-0.01***tick**) * sin(0.3*x))/12)
- Set base-waste = 0

[10] Refer section Parametrization for the values
[11] SD = Standard Deviation

- Set is-awareness-training? = False
- Set perception-to-recycle = mean (init-perception-to-recycle) SD (Value)
- Set awareness-effectiveness = mean (init-awareness-effectiveness) SD (Value)
- Set recyclable-waste = 0
- Set is-knowledge-training = False
- Set pre-separate-percent = mean (init-pre-separate-percent) SD (Value)
- Set knowledge-effectiveness = mean (init-knowledge-effectiveness) SD (Value)
- Set pre-separated-waste = 0

#### *5.2.2.4 Municipality variables*

- Create-municipalities = total-municipalities
- Set total-base-waste = 0
- Set possible-recyclable-waste = 0
- Set actual-recyclable-waste = 0
- Set total-pre-separated-waste = 0
- Set contracted-waste = 0
- Set non-contracted-waste = 0
- Set awareness-program = 0 (value)
- Set awareness-cost = 0
- Set knowledge-program = 0 (value)
- Set knowledge-cost = 0
- Set fine? = False
- Set municipal-fine = 0
- Set municipal-fines-total = 0
- Set total-fines = 0
- Set education-program-cost = value
- Set education-cost = 0
- Set total-recycled-waste-municipality = 0; sum of all recycled-waste-municipality
- Set recycling-rate-achieved = 0
- Set municipal-expenditure = 0
- Based on the percent-centralized-infra;
    - Set collection-infra = “Centralised” or “Decentralised”

#### *5.2.2.5 Recycling firm Variables*

- Create-firms
- Set capacity = mean (init-capacity) SD (Value)
- Set efficiency = mean (init-efficiency) SD (Value)
- Set operate-cost = mean (value) with SD (value)
- Set tech-effect-operate-cost = value
- Set sell-price-pre = value
- Set sell-price-post = value
- Set fine-earnings = 0
- Set waste-collect-cost = value x (Centralised) or value y (Decentralized); y > x
- Set total-sell-earning = 0
- Set total-operating-cost = 0
- Set total-collect-cost = 0
- Set offer-non-contracted-received = 0
- Set offer-cost = 0
- Set offer-recycled = 0
- Set offer-recycle-percent = 0
- Set investment-capacity = value
- Set can-bid? = True
- Set investment-tech = value
- Set total-pre-separated-received = 0
- Set total-waste-received-firm = 0
- Set total-waste-post-separated = 0
- Set total-waste-recycled-firm = 0
- Set tech-improve? = False
- Set capacity-improve? = False

- Set capacity-effect-tech = value
- Set capacity-effect-operate-cost = value
- Set factory-cash-balance = value
- Set capacity-improve-time = counting capacity improve time
- Set tech-improve-time = counting tech improve time
- Set capacity-utilized = 0

### 5.2.3 Go Function

In this section, the sequence of the program along with main procedure will be shown, all happening within a tick. The pseudo-code is shown in basic form. During implementation, certain parts will be defined differently and called as procedures within Netlogo.

#### *5.2.3.1 Update Global Variables*

- If target-update-counter < 11
  - Set target-update-counter = target-update-counter + 1
- Else
  - Set target-update-counter = 0
  - Set recycle-percent-target = recycle-percent-target + (Percent-increase-target * recycle-percent-target)
- If tick < 240
  - tick
- Else
  - Model Stop.
- Set initiative-tick = initiative-tick + 1
- Plot the selected functions[12]

#### *5.2.3.2 Update Household*

- Update perception-to-recycle
  - If is-awareness-training? = True
    - Update awareness-effectiveness = Mean (init-awareness-effectiveness) SD (value)
    - Update perception-to-recycle = perception-to-recycle + awareness-effectiveness * perception-to-recycle
    - Set is-awareness-training? = False
  - Else do nothing
- Update pre-separate-percent
  - If is-knowledge-training? = True
    - Update knowledge-effectiveness = Mean (init-knowledge-effectiveness) SD (value)
    - Update pre-separate-percent = pre-separate-percent + knowledge-effectiveness * pre-separate-percent
    - Set is-knowledge-training? = False
  - Else do nothing
- Check the Collection-infra of the municipality-belong
  - Set infrastructure-effect = value x (Centralised) or value y (Decentralized); y > x
- Calculate base-waste-function = (40 - (0.04 * tick-counter - (e ^ (-0.01 * tick-counter)) * sin (0.3 * tick-counter))) / 12
- Calculate base-waste = waste factor * base-waste-function * 1000[13]
- Calculate recyclable-waste = base-waste * perception-to-recycle
- Calculate pre-separated-waste = recyclable-waste * pre-separate-percent * infrastructure-effect

[12] This is excluded from pseudocode and implemented directly in the software.
[13] Each household agent is 1000 households

#### 5.2.3.3 Update-Municipality

- Check **Running Contracts**
- Calculate total-base-waste = Sum of all the household base-waste with municipality-belong = self
- Calculate possible-recyclable-waste = total-base-waste * possible-recycle-percent
- Calculate actual-recyclable-waste = Sum of all the household recyclable-waste with municipality-belong = self
- Calculate total-pre-separated-waste = Sum of all the household pre-separated-waste with municipality-belong = self
- Check
  - If actual-recyclable-waste > contracted-waste
    - Set non-contracted-waste = actual-recyclable -waste - contracted waste
    - Enter **request-bid**[14]
    - Set contracted-waste = sum of all contracted-waste-agreed of my-contracts
  - Else do nothing
- Set municipal-expenditure = municipal-expenditure + sum of contract-price of my-contracts
- Check my-fines = sum of all fine-request
- Check
  - If my-contracts > 0
    - Ask my-contracts
      - Check if contract-value-difference = (total-pre-separated-waste of myself) - ((actual-recyclable-waste of myself) * pre-separated-promised)
  - Check
    - If contract-value-difference < 0
      - Set fine? = True
      - Set municipal-fine = fine-of-contract
      - Set municipal-fines-total = municipal-fines-total + municipal-fine
      - Set municipal-expenditure = municipal-expenditure + municipal-fine
      - Set total-fines = total-fines + 1
      - Set factory-cash-balance of contract-neighbors = factory-cash-balance + municipal-fine of myself
      - Set fine-earnings = fine-earnings + municipal-fine of myself
    - Else do Nothing
  - Else do Nothing
- Set total-efficiency-received = sum of contract-efficiency of my-contracts
- Set running-contracts = count my-contracts
- Let actual-efficiency-received = (total-efficiency-received / (running-contracts))
- Set total-recycled-waste-municipality = (((actual-recyclable-waste - total-pre-separated-waste) * (actual-efficiency-received)) + total-pre-separated-waste)
- Set recycling-rate-achieved = (total-recycled-waste-municipality / possible-recyclable-waste)
- Check
  - If municipal-initiative-frequency <= initiative-tick
    - If recycling-rate-achieved < recycle-percent-target
      - Set initiative-tick = 0
      - Check the pro-activeness towards recycling
      - Set is-awareness-training? = True
      - Set is-knowledge-training? = True
      - Set awareness-cost = (education-program-cost * households with municipality-belong = myself * 1000)

[14] Separately defined function in subsequent section of the report.

            - Set awareness-program = awareness-program + 1
            - Set knowledge-cost = (education-program-cost * households with municipality-belong = myself * 1000)
            - Set knowledge-program = knowledge-program + 1
            - Update education-cost = knowledge-cost + awareness-cost
        - Else Do Nothing
    - Else do Nothing
- Check
    - If fine? = True
        - Set is-knowledge-training? = True
        - Set knowledge-cost = (education-program-cost * households with municipality-belong = myself * 1000)
        - Set knowledge-program = knowledge-program + 1
        - Update education-cost = knowledge-cost + awareness-cost
        - Set fine? = False
    - Else do nothing
- Set municipal-expenditure = municipal-expenditure + education-cost

#### *5.2.3.4 Update-Firms*

- Check
    - If capacity-improve? = True
        - Check if capacity-improve-time <= 12
            - Set capacity-improve-time = capacity-improve-time + 1
        - Else
            - capacity-improve-time = 0
            - Set capacity = capacity + (capacity-improve-percent * capacity)
            - Set efficiency = efficiency + (capacity-effect-tech * efficiency)
            - Set capacity-improve? = False
    - Else
        - Do nothing
- Check
    - if tech-improve? = True
        - Check if tech-improve-time < 12
            - Set tech-improve-time = tech-improve-time + 1
        - Else
            - tech-improve-time = 0
            - Set efficiency = efficiency + (tech-improve-percent * efficiency)
            - Set tech-improve? = False
    - Else
        - Do nothing
- Enter **submit-offers**
- Set capacity-utilized = sum of contracted-waste-agreed of my-contracts
- Enter **firm-offer**
- Set total-waste-received-firm = (total-waste-received-central + total-waste-received-decentral)
- Set total-pre-separated-received = (total-waste-received-firm * (mean [pre-separate-percent] of households))
- Set total-waste-post-separated = ((total-waste-received-firm - total-pre-separated-received) * efficiency)
- Set total-waste-recycled-firm = (total-waste-post-separated + total-pre-separated-received)
- Set total-operating-cost = ((total-waste-received-firm - total-pre-separated-received) * operate-cost)
- Set total-collect-cost = ((total-waste-received-central * waste-collect-cost) + (total-waste-received-decentral * waste-collect-cost * 1.01))
- Set total-sell-earning = ((sell-price-pre * total-pre-separated-received) + (sell-price-post * total-waste-post-separated))

- Set factory-cash-balance = (factory-cash-balance + total-sell-earning - total-operating-cost + total-collect-cost)

##### *5.2.3.5 Contract Making*

- Procedure **Running Contracts**
    - Check
        - If-else contract-time-running < contract-period
            - Set contract-time-running = contract-time-running + 1
        - Else
            - Ask to Die
    - Set municipal procedure = add-municipality-tenders contracted-waste sum of contracted-waste-agreed
        - Enter **request-bid**
    - Check
        - If municipalities my-contracts = 0
            - set contracted-waste = 0
            - Enter **request-bid**
        - Else do nothing
    - Enter **firm-offers**
- Procedure **request-bid**
    - Ask firms to **submit-offer**
    - Procedure **submit-offer**
        - Set offer-non-contracted-received
        - Set offer-cost = ((offer-non-contracted-received * waste-collect-cost) + (offer-non-contracted-received - (offer-non-contracted-received * pre-separate-percent-req)) * operate-cost
        - Set offer-recycled-post ((offer-non-contracted-received - (offer-non-contracted-received * pre-separate-percent-req)) * efficiency)
        - Set offer-recycled (offer-recycled-post + ((offer-non-contracted-received * pre-separate-percent-req)))
        - Set offer-recycle-percent (offer-recycled / offer-non-contracted-received)
        - Enter **firm-offers**
    - Check
        - If firms with can-bid? = True > 0
            - create-contract-with firms having lowest offer-cost
            - Set contract-period = init-contract-period
            - Set contracted-waste-agreed = non-contracted-volume
            - Set recycle-percentage-agreed = offer-recycle-percent of firm
            - Set fine-cost = 500000
            - Set contract-price = offer-cost of firm
            - Set contract-time-running = 1
            - Set present-post-separation-rate = offer-recycled-post of firm
        - Else
            - create-contract-with firms having highest efficiency
            - Set contract settings as above
- Procedure **firm-offers**
    - If offer-recycle-percent > 0.9 * recycle-percent-target
        - If capacity-utilized < 0.9 * capacity
            - If factory-cash-balance > 0
                - Set can-bid? = True
            - Else do nothing
        - Else
            - Set can-bid? = False
            - If factory-cash-balance > 0
                - If capacity-improve? = False
                    - Set capacity-improve? = True

            - Set factory-cash-balance = factory-cash-balance - investment-capacity
            - Set operate-cost = operate-cost + (capacity-effect-operate-cost * operate-cost)
            - Set capacity-improve-time = 1
         - Else do nothing
      - Else do-nothing
- Else
   - Set can-bid? = False
   - If factory-cash-balance > 0
      - If tech-improve? = False
         - Set tech-improve? = True
         - Set factory-cash-balance = factory-cash-balance - investment-tech
         - Set operate-cost = operate-cost + (tech-effect-operate-cost * operate-cost)
         - Set tech-improve-time = 1
      - Else do nothing
   - Else do-nothing

# 6 Software Implementation

The section elaborates on the use of pseudo-code developed in the previous section to develop a model in Netlogo environment. The initial pseudo-code created was not translated one to one into the environment due to limited experience with the environment. The syntax of the environment required some changes to be made in the logic of the pseudo-code, which lead to rethinking of the pseudo-code more than once.

## 6.1 Program Development

The model in Netlogo was created using iterative approach. Since the names of the parameters and variables were pre-defined before moving to the programming phase, the programming part was split and worked on individually. The shared environment of Google drive was used to create versions of code and clear versioning was used to keep track of the most recent versions to avoid overwriting and maintain clarity of progress.

For the plotting functions, the existing models in the Netlogo library were referred to speed up the visualisation code process. The final model "Waste recycling Plastic_final.nlogo" has been attached with the report. The program has been commented extensively for ease of readability and updating for future. The names of the parameters and variables have been clearly defined so that they are relatable to the problem definition.

# 7 Model Verification

In this section, the model is tested for intended functionality. The purpose here is to see if the model conforms to the behaviour that was perceived while implementing the code. In verification phase, the framework of (Nikolic, Dam, & Lukszo, Agent-based modelling of socio-technical systems, 2013) is used. The verification is done by putting the model for single agent testing, minimal model testing, followed by Multi-agent testing. If the model confirms to an attribute of the test, **confirmed** is used to give an affirmative, otherwise, **error** is used for a bug, along with the fix that was incorporated.

Figure **3a** below shows the model view once the setup button is pressed. The municipalities are represented by the large buildings on the Left with different shades of violet. The firms are represented by the factory icons on the top of the screen with shades of brown. The middle part of the world environment is filled with the households, with each type of household represented by a different colour; Yellow – family, Green – couple, Blue – old, Red – single.

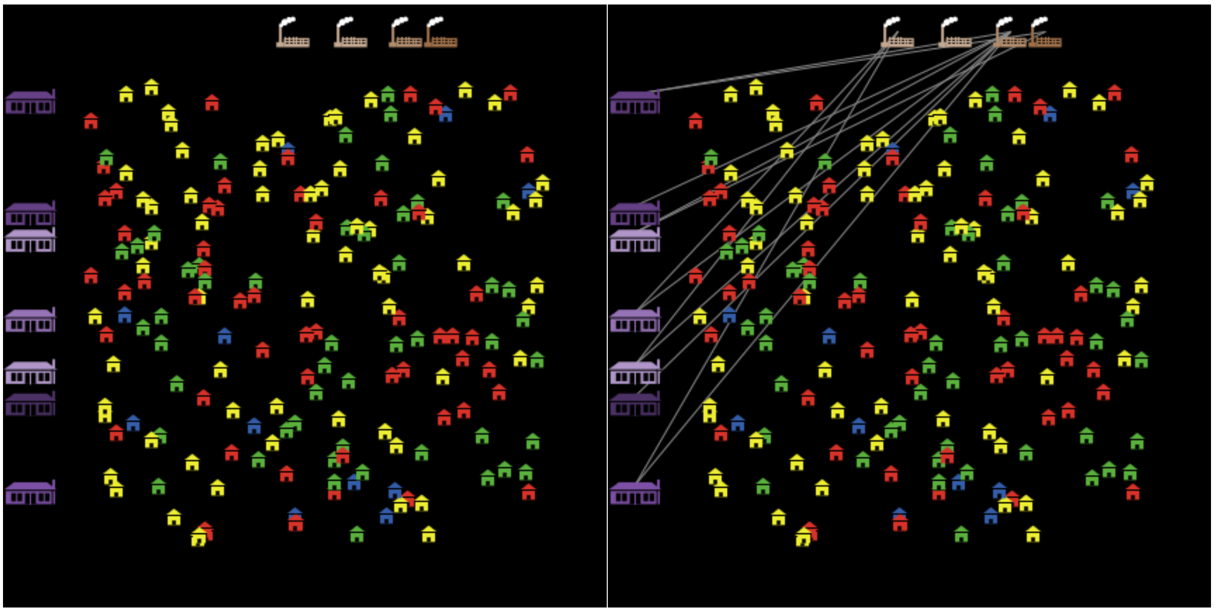

Figure 3 a) Model under "Setup" mode b) Model under "Go" mode

Figure **3b** shows the model under "Go" condition. The lines between municipalities and the firms represent the contracts. These are established in the form of links and are visible for the entire duration. Once the duration of the contract period is over, the links die and the contracts procedure leads to formation of new links.

## 7.1 Single agent Testing

In this verification method, acknowledging the complexity of the model, actual behaviour of individual agent is verified against the expected behaviour.

Table 3 Verification of Attributes for Single Agent Testing

| Verification Attribute | Result |
|---|---|
| The base waste produced by household is equal to expected value based on household demographic type | Confirmed |
| Each household has a unique municipality | Confirmed |
| The pre-separation value of waste depends on the knowledge of the household | Confirmed |
| The percentage waste recycled is based on the perception of the household | Confirmed |
| The waste value of a household with Decentralised infrastructure is more than Centralised infrastructure, all else being the same | Confirmed |
| The number of municipalities created is equal of number set in global | Confirmed |
| Each municipality has a collection infrastructure type | Confirmed |
| The value of total waste for each municipality matches the theoretical value | Confirmed |

| | |
|---|---|
| Municipalities register non-contracted waste and create additional contracts | Confirmed |
| Municipalities check their recycling achieved based on pro-activeness | Confirmed |
| Municipalities pay the firms for the contracted waste | Confirmed |
| Municipality expenditure value updates with each additional expenditure | Confirmed |
| Firms have a capacity and an efficiency value as defined | Confirmed |
| Firms create offers if they can bid | Confirmed |
| Each firm has an initial cash balance | Confirmed |
| Firms update efficiency and/or capacity if they can't bid; given they have funds | Confirmed |
| Firms process the waste based on the efficiency | Confirmed |
| Firms don't invest if they have excess capacity and efficiency | Confirmed |
| Contracts update the recycling targets as the companies invest | Confirmed |
| Contracts stores the offer cost, pre-separation promised and offer quantity | Confirmed |

## 7.2 Minimal-model Testing

In this verification method, the model attributes are verified with minimum number of agents required to run the model. i.e. One municipality consisting of one household with one firm operation;

Table 4 Verification of attributes for Minimal Model testing

| Verification Attribute | Result |
|---|---|
| Household belongs to the municipality and increases their perception and knowledge if municipality engages in knowledge programs | Confirmed |
| The change of knowledge and perception is different for each program due to the given standard deviation | Confirmed |
| The municipality gets the same amount of waste as the household | Confirmed |
| All the waste recycling increase is done through knowledge programs as firms do not innovate | Confirmed |
| Municipality does education programs (awareness and knowledge) if recycling targets are not met | Confirmed |
| Municipality keeps spending on knowledge programs even if the effectiveness is set to zero | Confirmed |
| The firm closely follows the municipal target and does not innovate due to no competition | Confirmed |
| Firms invest in efficiency if the effectiveness of the knowledge programs is set to zero | Confirmed |
| The contracts are repeated with the same firm due to no competition | Confirmed |
| The model stops after 20 years | Confirmed |

## 7.3 Multi agent Testing

In Multi-agent testing the model as a whole is tested under normal and extreme conditions to see if the

Table 5 Verification of attributes for multi agent testing

| Verification Attribute | Result |
|---|---|
| The number of households for each municipality is different due to the normal spread | Confirmed |
| The municipalities perform differently in recycling targets with leading and lagging municipalities | Confirmed |
| Multiple contracts are created with multiple firms from the same municipality based on the current price | Confirmed |
| Due to clear leading and lagging municipalities the firms compete with each other and have cyclical cash balances | Confirmed |
| Higher increase of recycling target requires municipalities to be proactive to reach the recycling targets | Confirmed |
| All municipalities have contracts at all times | Error; non-contracted waste not updated after each contract; **Fixed** |
| Model is under operation if the global parameters are set at extreme conditions; individually and in combination | Confirmed |

# 8 Experimentation

In this section, experimentation setup of the model is given. The idea is to obtain insights regarding how uncertain factors and policies can influence the system being modelled. This experimentation part is particularly aimed to answer the research question 'What are the trade-offs in the policy space of the municipalities to achieve the highest possible recycling rates?'.

To facilitate process of answering the research question, some independent and dependent variables will be determined. Independent variables work as policy levers of municipalities, whereas dependent variables are KPIs (**Key Performance Indicators**) of the experiment. Independent variables are operationalized into parametric values, where the effect on the KPIs are tested across scenario space, where for each combination the model is run for 30 replications. The number of replications is chosen to acquire significance of the experimentation result.

To understand how much recycling rate of the municipalities are achieved, then **average recycling rate** of all municipalities will be used as first key performance indicator (KPI). Then, in order to acquire insights on the possible financial trade-off, **average of municipalities' expenditures** is taken as second indicator. Therefore, the policies will be tested based on their effects on these indicators given scenarios provided.

The experiments are run for five municipalities and four firms; these not-too-high numbers of agents are chosen in order to provide more insights on dynamic of interactions among multiple municipalities and firms while ensuring quick run of the experiments. The Netlogo experimentation is committed with 10 replications; motivation of the choice is to balance between the need to take into account random iteration order for each run, and not giving too much computational burden on the data analysis.

## 8.1 Scenario Space

In this section, explanation about scenario space is provided. As opposed to traditional scenario measures, scenario space approach is chosen due to non-limiting nature of exploration across possible combined parameter values. Therefore, scenario space will identify the scope of parametric uncertainties of the model (Nikolic, SEN1211 Final practical, 2016), where the model will be run repeatedly according to the parameter settings.

In order to determine the parameter for experiment, firstly variables with uncertain values will be picked from Parametrization section. It is to note that parameters taken here are meant to give insights regarding influence of notable uncertain factors in terms of achieving high recycling rate of municipalities given its expenditure trade-off. To put more detail, motivation for each parameter is given as follows:

- operating cost uncertainty can affect cost of municipalities since they have to reimburse operational cost of firms processing the waste.
- Effectiveness of awareness- and knowledge-stimulating activities will directly be related to how much the municipalities' stimulation to households can influence the households' perception and knowledge towards tendency of pre-separation.
- The more municipalities with decentralized infrastructure, the easier it will be for households to commit pre-separation of plastic waste; which could add to recycling rate improvement. However, it can also add into collection cost of firms which has to be reimbursed by the corresponding municipalities, which will eventually come into their expenditures. It is to note that collection infrastructure in municipalities are deemed specific (Nikolic, SEN1211 Final practical, 2016) for municipality across the time steps, therefore the collection infrastructure type is not deemed a policy option.

Therefore, the experimentation will be highlighting these uncertainties which are supposedly not modelled using, for instance, random distribution in Netlogo code. Knowing the parameters, the range of values for each parameter will be determined on discrete basis with three subset of values: low, medium, and high values. For some parameters with predetermined mean and standard deviation, the values will be varied accordingly. It is to note that other uncertainties which are not considered in the scenario space are modelled using random distribution in Netlogo code; one benefit of this approach is larger time efficiency of committing model analysis in scenario space.

All in all, the scenario space is shown in Table **6**:

Table 6 Scenario Space

| Parameter | Low value | Medium value | High value |
|---|---|---|---|
| Operating cost (Euro/kg) | 0.3 | 0.35 | 0.4 |
| Effectiveness of awareness stimulations | 0.04 | 0.08 | 0.13 |
| Effectiveness of knowledge stimulations | 0.03 | 0.05 | 0.1 |
| Fraction of municipalities with centralized collection infrastructure | 0 | 0.5 | 1 |

## 8.2 Policy Space

In this section the policy space of municipalities is given. Policy space is based on plausible measures which can be implemented by municipalities to improve recycling rate.

With respect to household-level intervention, there are two possible policy measures: intensifying frequency to review recycling rate target to see whether stimulation is needed, and commissioning the stimulation activities with higher likelihood. Since they have different operationalization in terms of how they can affect households' behaviour towards pre-separation, combination of the policy parameters will be explored to see their effects on the key performance indicators.

With respect to firm-level intervention, it is possible for municipalities to change the contract duration with waste-processing firms. The motivation is as follows. If municipalities manage to shorten contract duration with participating firms, then it means municipalities have to open tender more often. Consequently, this will lead to more competition among the firms to win the tenders given the model time span. Since the firms losing in tender will improve their technology state, this condition of more tenders will force the firms to innovate more frequently.

In reality, this reduction of contract duration from the initial 36 months may be implemented through negotiations with the waste-processing firms. In any case, shorter contract duration can be taken as possible policy measure by municipalities. For this experimentation, 3 months is taken as contract duration lever option.

In short, policy space implementation in the experimentations is given in Table **7**:

Table 7 Policy Space implementation

| Parameter | Low value | Medium value | High value |
|---|---|---|---|
| Likelihood to act towards achieving recycling target | 0 | 0.5 | 1 |
| Frequency of reviewing target (month) | 1 | 6 | 12 |
| Contract duration (month) | 3 | - | 36 |

## 8.3 Hypothesis

In this section, hypotheses on how the policy space implementation can lead to recycling rate achievement with its plausible trade-offs will be described.

Firstly, it can be hypothesized that within household-level policy domain, higher likelihood to take initiatives combined with intensified frequency to review target should best improve recycling rate, since the combination indicates very high proactivity of municipalities towards achieving the target. Since these actions should be committed from municipality's budget, they will therefore come at the expense of municipality's increasing expenditures. Therefore, the hypothesis can be formulated as follows:

*Hypothesis 1: With respect to household-based policy context, combination of high likelihood in taking stimulation initiatives and high frequency to review target will best improve average recycling rate of municipalities, at the expense of higher expenditure, compared to the base case condition.*

With respect to contract duration, it has been explained how shorter contract duration could lead to higher investment of innovation by firms due to more frequent competition among them. This investment action could be reflected in the level of capacity and efficiency improvement of the firms. With this contract measure, therefore it is expected that with the technological improvement leading to higher post-separation rate will be improved, hence improvement of the recycling rate.

Therefore, second hypothesis can be formulated as follows:
*Hypothesis 2: shorter contract duration will lead to more innovation by firms.*

Suppose that municipalities want to leverage on this possibility and be efficient on their expenditures, it can be argued to be hardly possible for municipalities to just focus on contract duration without commissioning any stimulation activities. This is because recycling rate performance also consists of pre-separation improvement; the fact that stimulation activities could reach all households within the municipality implies significantly important effect to improve recycling rate on pre-separation basis compared to the effect of post-separation improvement due to innovation by itself, since percentage of capacity and efficiency improvement for each investment is not high (refer to Parametrization for motivation of this point).

However, combination of both shorter contract duration lever and higher proactivity of municipalities to stimulate knowledge and awareness could be hypothesized to best improve recycling rate compared to all other possible combination of levers. Since post-separation rate is hypothesized to improve given the lever, municipalities have to provide more reimbursement and this causes corresponding increase of municipal expenditures on average.

Therefore, third hypothesis can be formulated as follows:
*Hypothesis 3: combination of both shorter contract duration lever and higher proactivity of municipalities will best improve average recycling rate of municipalities compared to all other possible combination of levers, with corresponding increase of municipal expenditures.*

# 9 Data Analysis

In this section, the analysis of data obtained from Netlogo behaviour space experimentation will be provided. This section will mainly be used to prove the hypotheses formulated at the previous section.

## 9.1 Open Exploration

Firstly, the visualization of the uncertainties is provided in the Figure **4**. Visualizations are given for the two key performance indicators defined: average recycling rate and average expenditure of municipalities.

It can be shown that without policy levers being implemented, recycling rate improvement already occurs at low rate. This happens due to self-mechanism of firms competing with each other in order to win waste-processing tenders by the municipalities. Because of the competition, firms start investing in technology; which all in all leads to better post-separation rate. However, since pre-separation awareness and knowledge of households is not improved, the post-separation effect on recycling rate is not significant.

Secondly, in the expenditure graph it is shown that the average expenditure of municipalities increases despite no policies implemented. This shows how municipalities interact with firms: under the contract mechanism, municipalities are providing reimbursement to firms working in their area based on firms' operating cost.

All in all, the open exploration shows that the mechanism of interactions among agents as to improve recycling rate of municipalities is actually ongoing. However, under the influence of uncertainties the rate of improvement is rather low, i.e. still way below 50% initial target. Therefore, this implies the need to implement policy levers of municipalities and observe their effects.

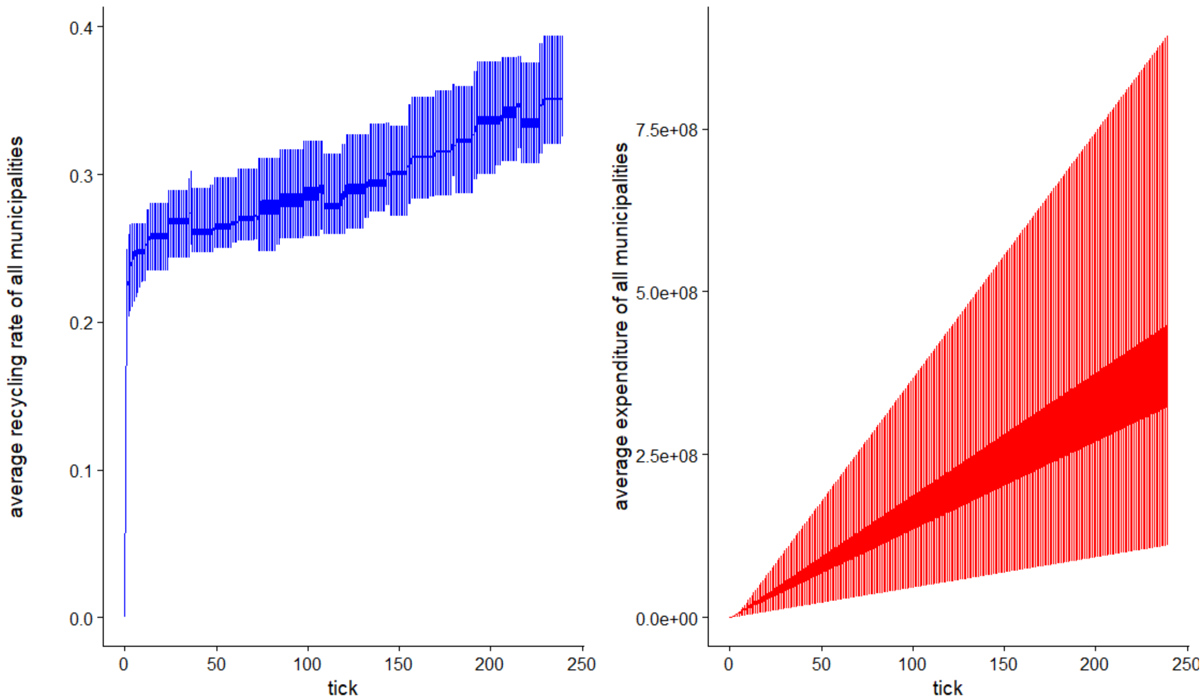


Figure 4 Uncertainty analysis on 2 KPIs: average recycling rate (left) and expenditure (right) of municipalities

## 9.2 Hypothesis Testing

In order to prove hypothesis 1, effect of plausible combination of proactivity policies on the KPIs will be provided in the Figure **5** and Figure **6**.

Figure **5** shows that combination of high likelihood in commissioning stimulation activities and high frequency in reviewing target leads to better recycling rate performance compared to other proactivity policy combinations. Meanwhile, Figure **6** shows that particular combination does not lead to higher expenditure of municipalities. As shown in the boxplot, average expenditure is higher across the low taking-initiatives likelihood factor compared to the others. This gives insights on the fine mechanism which is ongoing: due to low awareness- and knowledge-stimulating activities, pre-separation rates in municipalities are low, therefore fines having to be paid are higher and this is reflected in the higher expenditure of municipalities.

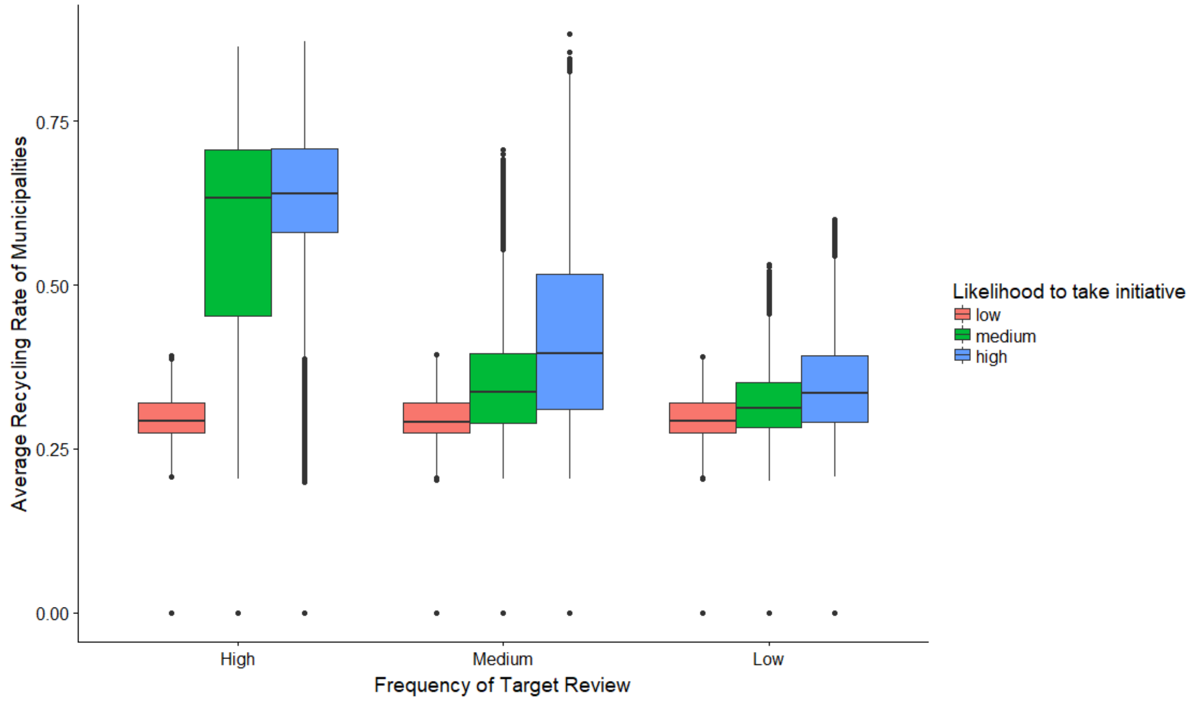


Figure 5 Effect of combinations of household-level interventions towards average recycling rate of municipalities

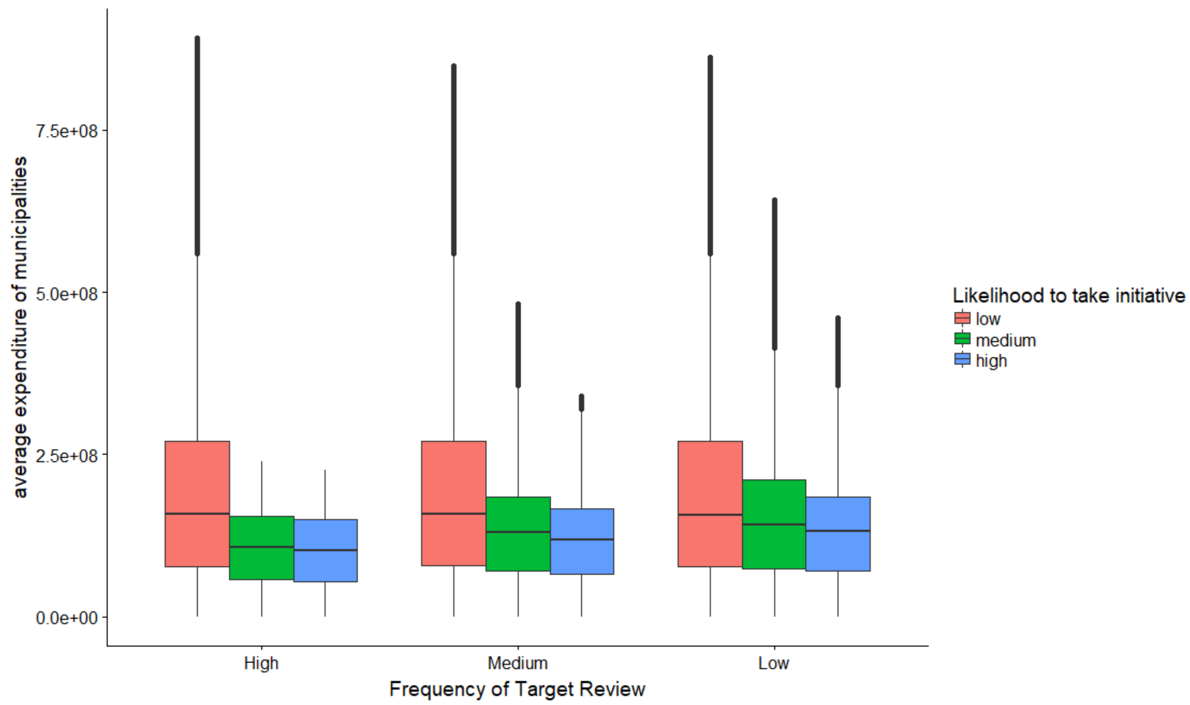


Figure 6 Effect of combinations of household-level interventions towards average expenditure of municipalities

Therefore, **hypothesis 1 is proven to be not entirely correct**: With respect to household-based policy context, combination of high likelihood in taking stimulation initiatives and high frequency to review target will best improve recycling rate of municipalities compared to base case condition. However, this improvement does not come at the expense of higher expenditure due to avoidance of fine payment as specified in the contracts.

To prove hypothesis 2, Figure **7** and **8** are shown. Figure **7** shows that capacity improvement is higher given the innovation by firms compared to the base case condition. Meanwhile, Figure **8** shows that average innovation state of firms; however, it shows quite a striking result: less efficiency improvement compared to base case scenario.

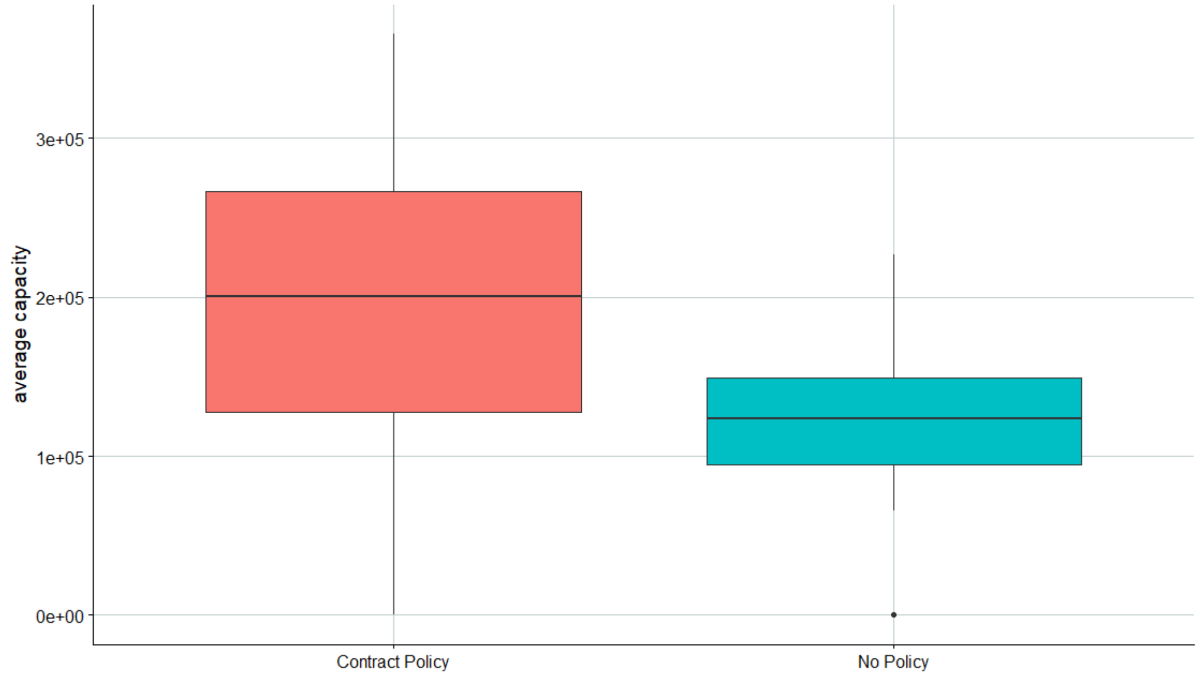


Figure 7 The effect of contract duration policy on average capacity of firms

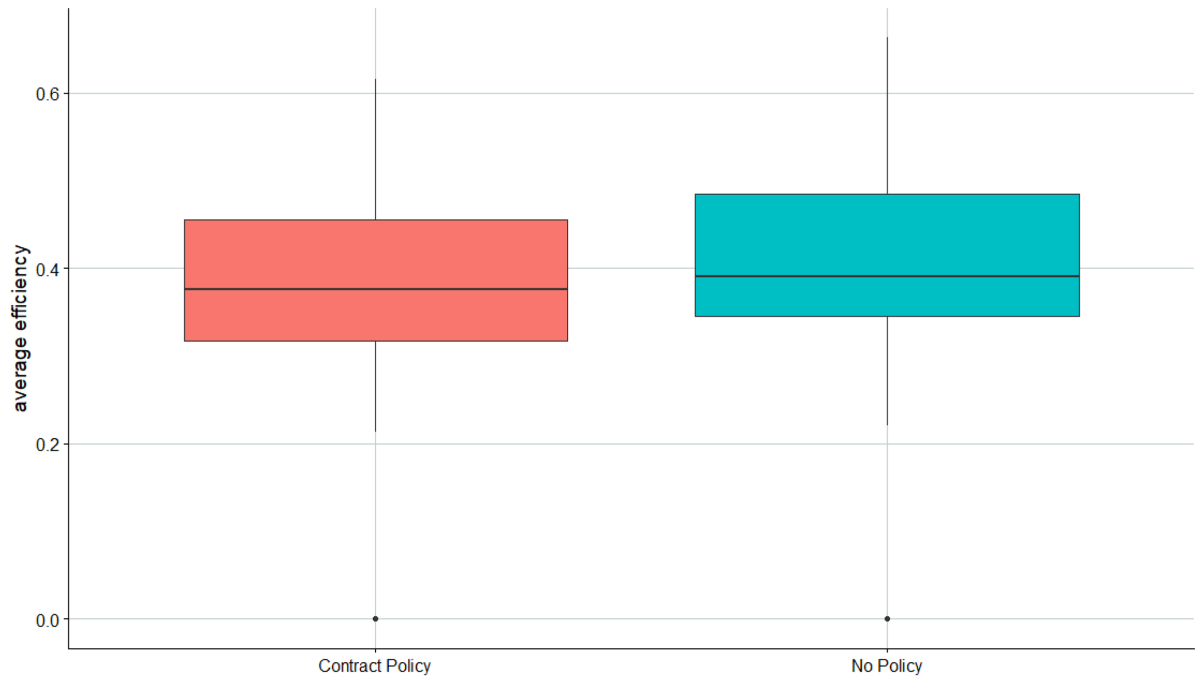


Figure 8 The effect of contract duration policy on average efficiency of firms

Explanation of the phenomenon is given as follows: Shorter contract duration leads to more innovation by firms due to more fierce competition among them. However, the effect differs for capacity and technological efficiency of firms. Given shorter contract duration, average capacity of firms will significantly increase compared to the base case scenario. This means that despite achieving efficiency requirement already, the firms which do not have sufficient capacity to process waste will nevertheless invest in capacity.

However, the effect on efficiency is the opposite: average efficiency of firms is lower compared to base case. This is because given multiple number of municipalities and firms, each municipality will not let waste accumulating in its area without being processed. Therefore, despite no firms having sufficient efficiency to achieve recycling target, municipalities will select firms based on the highest efficiency available (i.e. best among the worst). All in all, existence of multiple municipalities creates imperfect competition for the firms where current state of the achievement of cost reduction and efficiency target is not well-reflected in the contract selection mechanism. Putting it another way, there is also slight competition among municipalities to pick the best-performing firms and this manages to reduce the incentives for firms to invest in technological efficiency.

To add slightly more insights into its effect on the KPI, Figure **9** shows the effect of shorter contract duration policy on recycling rate on average. It shows that just shortening contract duration proves to be counter-productive for municipalities themselves; since efficiency increase is low, then the amount of waste being post-separated by firms will not be increased.

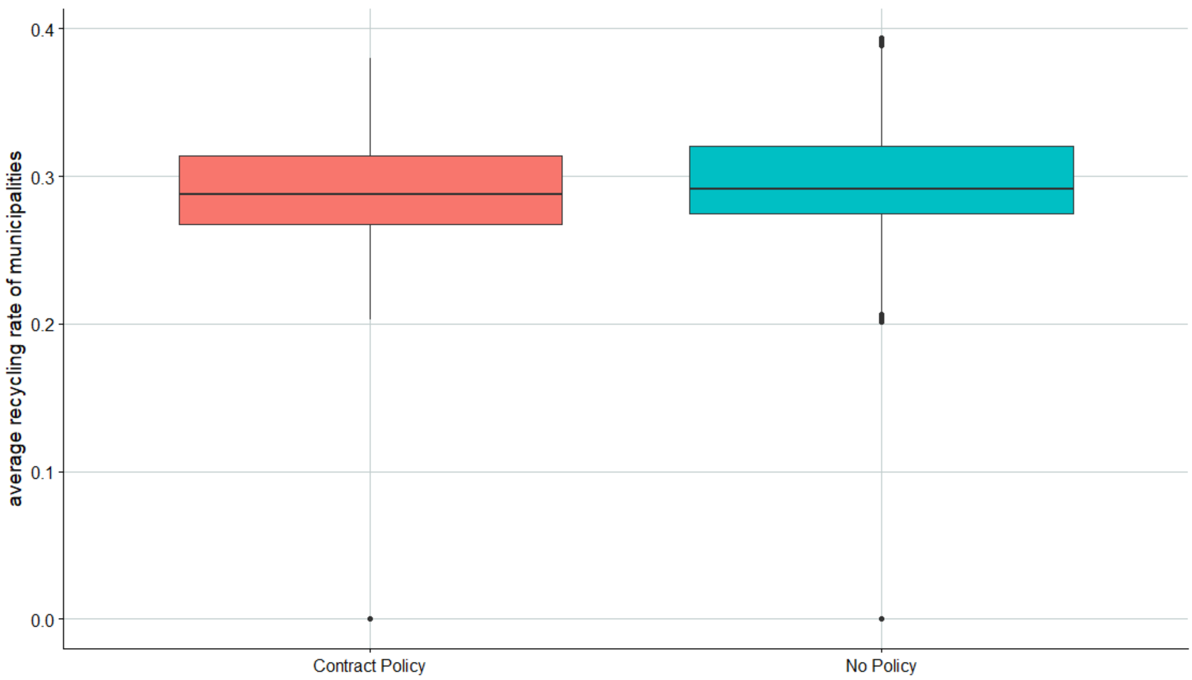


Figure 9 Effect of combined contract duration policy on average recycling rate of municipalities

Finally, to prove hypothesis 3, Figure **10** and **11** is provided. Figure **10** shows that combination of shorter contract duration and high proactivity levers can lead to slightly higher average recycling rate compared to sole proactivity policy. This hypothesis is proven to be true even though rate of efficiency increase is lower given shorter contract duration policy as argued in Hypothesis 2, with no proactivity policy considered. This implies that combination of proactivity and contract duration is important to improve the recycling rate, since contract duration measure only could be counter-productive. This shows that only by combining both levers, both pre-separation rate of households and post-separation of firms can be increased. This phenomenon reflects insightful emergence of pattern in the modelled system.

All in all, this gives clear insight to municipalities that given the scenario space, high proactivity and shorter contract duration could provide optimal achievement toward recycling rate target. Figure **11** also shows how trade-off occurs: average expenditures of municipalities over time is increasing correspondingly with respect to sole proactivity policy (Note: the display in Figure 11 seems less apparent since the exponential number in the y-scale is huge, however closer examination will visually prove the thesis). This is caused by higher reimbursement which should be provided to firms given higher waste being processed in post-separation mode, thanks to higher capacity and efficiency due to implementation of both levers. The cost of reimbursement having to be paid now exceeds the benefit of avoiding fine payment.

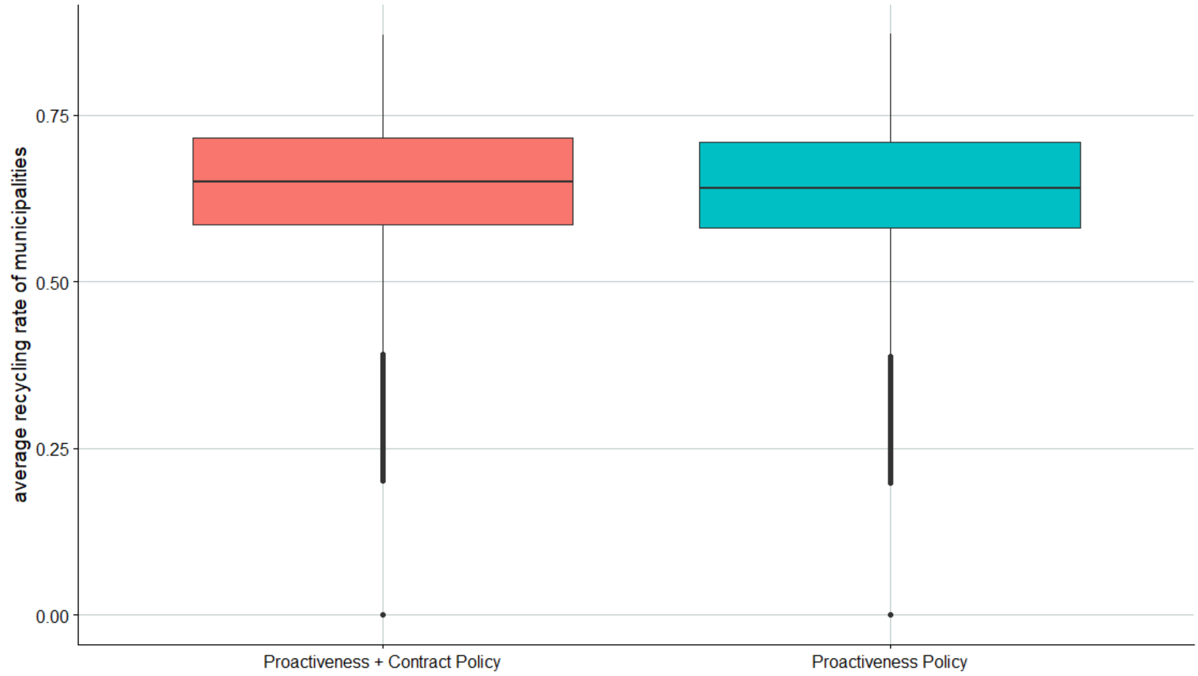


Figure 10 Effect of combined contract duration and proactivity policies on average recycling rate of municipalities

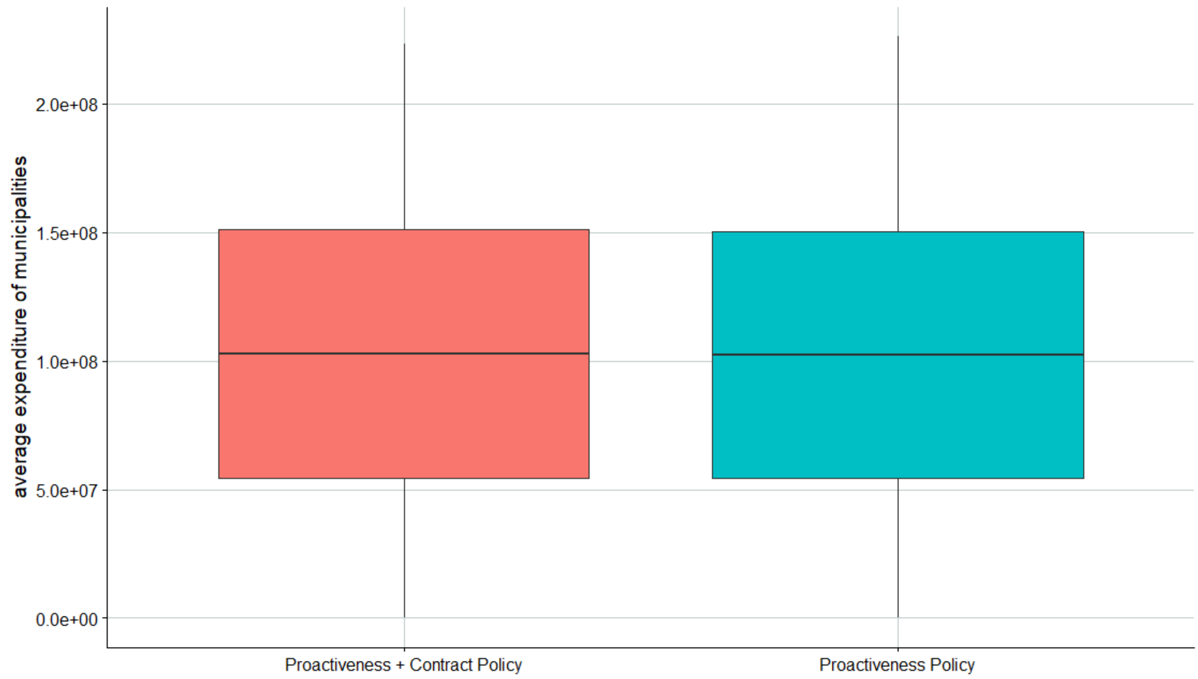


Figure 11. Effect of combined contract duration and proactivity policies on expenditure of municipalities

The summary of given hypotheses and their corresponding validity are provided below:

- *Hypothesis 1: With respect to household-based policy context, combination of high likelihood in taking stimulation initiatives and high frequency to review target will best improve average recycling rate of municipalities, at the expense of higher expenditure, compared to the base case condition.*

  **False**: With respect to household-based policy context, combination of high likelihood in taking stimulation initiatives and high frequency to review target will best improve recycling rate of municipalities compared to base case condition. However, the policy-induced improvement does not come at the expense of higher expenditure due to avoidance of high fine payment

- *Hypothesis 2: shorter contract duration will lead to more innovation by firms.*
  **False**. Higher technological progress compared to base case scenario is represented in average capacity improvement, but not on the technological efficiency. The effect on efficiency in this hypothesis test is also reflected in the effect on recycling rate.

- *Hypothesis 3: combination of both shorter contract duration lever and higher proactivity of municipalities will best improve average recycling rate of municipalities compared to all other possible combination of levers, with corresponding increase of municipal expenditures.* **True**

# 10 Model Validation

"*Essentially, all models are wrong, but some are useful.*" (Box & Draper, 1987, p. 424) , As all models are simplifications of reality, this model is no exception. In this section we compare the model with real world and highlight the limitations. Since no real case study has been performed to validate the findings of the model, this section will discuss its limitations. It is important to highlight here that, wherever lack of data, attempts have been made to make realistic assumptions that are motivated using relevant available literature and case studies. However, by no means is the model an exhaustive replication of the real process.

Therefore the use of the model is largely exploratory and only to understand the aggregate policy alternatives available at the disposal of the client. The subsequent section will discuss on the use of model.

## 10.1 Limitations

Based on the discussion presented in the previous subsection, it is important to highlight the key limitations of the model with respect to the real world. Although the limitations are implicitly highlighted through the assumptions made, it is important to specify them explicitly, although not exhaustively;

### 10.1.1 Households

- The households themselves do not change over the time period, i.e. a single does not become a couple or visa-versa
- No initiative is given to the households with respect to the awareness and knowledge increase and the role is merely responsive with regards to the programs run by the municipality.
- There is no exchange of information between the households themselves to update their understanding

### 10.1.2 Municipalities

- The number of households within the model is fixed during the run and does not include population dynamics and migration
- The size of the municipalities in terms of number of households is similar with no scope for large, medium and small municipalities
- The municipalities cannot exchange information between themselves for collaborative purposes
- Other waste producing elements of within a municipality such as small and medium commercial businesses, hotels etc. are not considered within the model
- The municipalities cannot update their collection infrastructures over time
- Municipalities create contracts only on the lowest price and does not consider other factors such as the trade-offs between cost, recycling rate, fines and the commitment of firms to innovations

### 10.1.3 Firms

- The number of firms in the model is fixed and they have access to unlimited financial resources
- The scope for return of investment and profitability aspect of investments is not part of the model
- The effect of sudden technological breakthroughs and cost reduction technologies has not been considered within the model
- The firms do not proactively innovate and are forced to do so only if the contracts are not formed.

# 11 Model Use

In this section, conclusion of the work is presented. This section argues the model design and analysis can provide answer to the research question. Therefore, this section consists of two parts: firstly, conclusion of how the research question is answered will be described. Secondly, recommendation for future scope will be presented.

## 11.1 Answering Research Question

As presented at section 1, the research question in this report is: *What are the trade-offs in the policy space of the municipalities to achieve the highest possible recycling rates?* To answer this research question, this section will cover the two given sub-questions to provide more detailed insight.

### 11.1.1 What are the factors that can influence the recycling rate objective of the municipalities?

Answer to this sub-question is developed in a systematic approach. Firstly, key performance indicators that can potentially lead to trade-off for municipalities are defined. Two indicators set in the model are: average recycling rate of the municipalities, and average expenditure of the municipalities. Again, while cash balance of municipalities is considered limitless, it is natural for municipalities to have intention on incurring lowest cost possible while reaching highest possible recycling rate in their area.

Secondly, factors whose uncertainties are highly relevant in influencing achievement of these objectives are defined. Highlighting these factors is a crucial step since they are to be analysed in greater detail on model analysis. To summarize, these factors are:

- Waste-processing operation cost of the firms. Uncertainty of this element can affect expenditure of municipalities since they have to reimburse operational cost of firms processing their waste.
- Effectiveness of awareness- and knowledge-stimulating activities perceived by households. The higher the value of effectiveness, the more effectively municipalities' stimulation to households can influence the households' perception and knowledge towards tendency of pre-separation. This mechanism is useful for municipalities not only to improve recycling rate, but also to avoid fine.
- The number of municipalities with centralized collection infrastructure as per total municipalities being modelled. The more municipalities with decentralized infrastructure, the easier it will be for households to commit pre-separation of plastic waste; which could add to recycling rate improvement. However, it can also add into collection cost of firms which has to be reimbursed by the corresponding municipalities, which will eventually come into their expenditures.

### 11.1.2 To what extent can these factors be influenced by policy interventions?

The answer to this sub-question builds on the first sub-question. The idea is to observe how the tailored policies can affect the KPIs of municipalities considering the uncertainty of model factors. Netlogo behaviour space function has been utilized to commit scenario space analysis which takes into account plausible combination of uncertain factors and policy measures. Description in this section will therefore be classified based on policy levers being considered.

#### *11.1.2.1 Proactivity of municipality*

The extent to which municipalities are considered proactive is based on two parameters: Likelihood to act towards achieving recycling target, and Frequency of reviewing recycling target being set. These levers will eventually affect behaviour of households committing pre-separation since these activities can increase their perception and knowledge. The analysis shows that within the context of household-based measure, combination of high likelihood in taking stimulation initiatives and high frequency to review target will best improve recycling rate of municipalities compared to base case condition. However, the levers' implementation does not come at the expense of higher expenditure compared to the base case (no policy) condition. This is because in base case, municipalities must pay high amount of fine to the contracted firms due to low pre-separation rate in the area. The high proactivity manages to avoid requirement in paying high fines, hence not increasing the total average expenditure covered.

#### *11.1.2.2 Contract duration (and combination with the proactivity of municipality)*

This section provides two insights: firstly, regarding effect of contract duration change only; and secondly, the effect of combination of contract duration and proactivity policy.

Contract duration measure only is shown to have two-sided effect on innovation state of firms: increasing average capacity of firms but reducing average efficiency as well. As has been explained in data analysis section, this shows that existence of multiple municipalities and firms in the model creates unique imperfect competition dynamics, where current state of the achievement of cost reduction and efficiency target is not well-reflected in the contract selection mechanism. With respect to recycling rate KPI, this measure only is proven to be counter-productive.

However, combination of shorter contract duration and high proactivity of municipalities creates different dynamics. Given the policy boundaries, the combination of proactivity and contract duration is highly important to improve the recycling rate, since they both increase pre-separation and post-separation rate productively with respect to improving recycling rate achievement. This achievement, though, comes at the expense of correspondingly higher municipal expenditure; which is a different condition compared to implementation of high proactivity policy only. This is caused by higher reimbursement which should be provided to firms by municipalities, given higher waste being processed in post-separation mode. The cost of reimbursement having to be paid now exceeds the benefit of avoiding fine payment.

## 11.2 Reflection & Future Scope

This report shows the usefulness of agent-based modelling to approach waste recycling problem in Randstad area. With respect to the policy analysis, the model and data analyses manage to show comparable insights based on different policy measures being implemented.

Nevertheless, some scope of improvement, which might be useful for generating more insights in the model, is currently excluded due to time and resource limitation[15]. One important limitation, with respect to Randstad area being observed, is that only five municipalities and four firms are considered in the model analysis due to resource limitation in running the model analysis. This condition does not entirely reflect actual condition of Randstad area. Nevertheless, the model analysis still managed to generate insightful findings regarding interactions between multiple number of municipalities and firms; for example, on the idea of (im)perfect competition.

This scope is presented below for future research commission:

- The model can include depreciation value of asset, to account for more realistic approach on how productive capacity of firms could change over time.
- The model experimentation can be run for less limited range of values (to consider wider range of uncertainties) and relevant number of municipalities in the area, when resource limitation is non-existent.
- The model can be extended by adding some incentive mechanism like unit based pricing given to firms to encourage higher innovation levels
- The model can also include possible competitive advantage (e.g. operating cost reduction, more recycled products sold) gained from more experience in waste processing activities.
- The contract mechanism can be more accommodative towards trade-offs of recycling rates, innovation commitment, price and fines.

[15] For additional model extension possibilities refer info tab of the Netlogo Model.

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# Appendix I. Attribute List

The section represents the operationalisation of the agent attributes based on the assumptions. **Table 1** below shows a list of different agent behaviours and the computer primitive used to define it.

Table 8 Agent Attribute List

| Agent | Attribute | Description |
|---|---|---|
| **Households (turtle)** | base-waste-function | base waste function as per the formula given in the problem description |
| | household-type | assigning household types |
| | waste-factor | multiplication factor per household type |
| | base-waste | Ideal Base waste value given the households collect all the possible plastic |
| | is-awareness-training? | proxy for awareness training |
| | infrastructure-effect | Multiplication factor to account for motivation based on centralized and decentralized infrastructure. |
| | perception-to-recycle | stores the current perception value towards recycling |
| | awareness-effectiveness | stores the awareness training effectiveness value |
| | recyclable-waste | the recyclable waste produced based on the perception value |
| | is-knowledge-training? | proxy for knowledge training |
| | pre-separate-percent | stores the current post separation percent value |
| | knowledge-effectiveness | stores the knowledge training effectiveness value |
| | pre-separated-waste | the pre-separated waste per households |
| | municipality-belong | proxy to assign municipality to each household |
| **Municipalities (turtle)** | collection-infra | the type of collection infrastructure of a municipality |
| | total-base-waste | total base waste collected |
| | possible-recyclable-waste | the maximum amount of waste that can be recycled under perfect conditions |
| | actual-recyclable-waste | actual waste collected |
| | total-pre-separated-waste | actual pre-separated waste |
| | contracted-waste | waste under contracts |
| | non-contracted-waste | waste not under contracts |
| | awareness-program | counter for number of awareness programs |
| | awareness-cost | total cost of awareness program |
| | knowledge-program | counter for number of knowledge programs |
| | fine? | proxy to see applicability of fine |
| | municipal-fine | value of fine |
| | municipal-fines-total | total value of fines |
| | total-fines | counter for number of fines |
| | knowledge-cost | total cost of knowledge program |
| | education-program-cost | cost for combined knowledge and awareness programs |
| | education-cost | cost per education activity |
| | total-recycled-waste-municipality | total waste recycled |
| | recycling-rate-achieved | recycling rate actually achieved |
| | municipal-expenditure | municipal expenditure |
| | municipality-singles-belong | household of singles per municipality |
| | municipality-old-belong | household of old per municipality |
| | municipality-couples-belong | household of couples per municipality |
| | municipality-family-belong | household of families per municipality |

| | | |
|---|---|---|
| | municipality-population | total municipal population |
| | running-contracts | running contracts |
| | total-efficiency-received | total efficiency of the running contract firms, used as a proxy to calculate municipal recycling rates |
| **Waste Management Firms (turtle)** | offer-recycled-post | offer value of recycled post-separated |
| | capacity | current capacity of firms |
| | efficiency | current efficiency of firms |
| | operate-cost | current cost of operations of firms |
| | tech-improve-time | counter to check the efficiency improvement |
| | capacity-improve-time | counter to check capacity improvements |
| | capacity-utilized | total utilized capacity of firms |
| | waste-collect-cost | collection cost for waste |
| | can-bid? | proxy to check bidding ability of firms |
| | tech-improve? | proxy to check need for efficiency improvement |
| | factory-cash-balance | total cash balance of firms |
| | capacity-improve? | proxy to check need for capacity improvement |
| | capacity-effect-operate-cost | effect of capacity improvement on operating cost |
| | capacity-effect-tech | effect of capacity improvement on efficiency improvement |
| | total-waste-post-separated | total waste post separated by firms |
| | total-waste-received-firm | total waste received by firms |
| | total-waste-recycled-firm | total waste recycled by firms |
| | tech-effect-operate-cost | effect of efficiency improvement on operating cost |
| | sell-price-pre | selling price of pre-separated plastic |
| | sell-price-post | selling price of post-separated plastics |
| | fine-earnings | earnings from fines |
| | total-sell-earning | earnings from selling plastic |
| | total-collect-cost | total collection costs |
| | total-operating-cost | total operating costs |
| | offer-non-contracted-received | offer quantity of plastic received |
| | offer-cost | offer cost submitted |
| | offer-recycled | offer for recycled quantity submitted |
| | offer-recycle-percent | offer recycle percentage quoted |
| | investment-capacity | cost for a capacity investment |
| | investment-tech | cost for efficiency investment |
| | total-pre-separated-received | total pre-separated plastic received |
| **Contracts (link)** | fine-cost | fines cost agreed in contracts |
| | recycle-percentage-agreed | recycle percentage agreed in negotiations |
| | contracted-waste-agreed | waste quantity agreed |
| | contract-period | contract period |
| | contract-time-running | proxy to check contract running time |
| | contract-price | price of the contract based on offer price |
| | present-post-separation-rate | post separation rate agreed |
| | contract-efficiency | efficiency value of the firm |