Delft University of Technology

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Agent Based Model on Waste Collection In Municipality Delft

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Contents

1 Introduction

Nowadays humanity faces several important challenges. One of these challenges is to transition from a linear to a circular economy. Defined as the traditional economic model, a linear economy follows a take-make-waste pattern. The absence of feedback means that goods are produced, consumed, and eventually thrown away. In our consumerist society, waste is present at all levels (individuals, groups, organizations, municipalities, etc.) and across the entire life cycle of a product (design, resource extraction, manufacturing, consumption and end-of-life). Unfortunately, this huge amount of waste produced by an ever-growing economic throughput is either disposed in landfills, incinerated, or reaches nature (soil, waterways, oceans, etc.).

For the past decade, fierce criticism against the linear economy arose from several sectors of society. Politicians, academicians, researchers and citizens mainly blame the numerous environmental damages caused by the conventional system. Extraction of natural resources causes massive and often irreversible destruction or profound alteration of Planet Earth's natural capital. Running an entire modern economy also takes a toll on the environment because of the current dependence on fossil fuels as a primary source of energy. In addition, plastics are prevalent in mass consumer culture. For example, the marketability of fast-moving consumer goods and the need for packaging materials have continuously increased the demand for plastics. According to the plastic soup foundation the amounts of plastic produced increased from 2 million ton in 1950 to 368 million ton in 2019 [3]. Their prevalence has resulted in a phenomenon called plastic pollution and the persistency of microplastics in the environment.

As opposed to the conventional linear economic paradigm, a circular economy follows the 3R approach: reduce, reuse and recycle. Resource use is minimized (reduce). Reuse of products and parts is maximized (reuse). And last but not least, raw materials are recycled to a high standard. By extending the material life cycle, recycling as well as reusing, minimise resource extraction and waste generation. Thus, according to the McArthur Foundation the circualr economy is a concept for "gradually decoupling economic activity from the consumption of finite resources and designing waste out of the system". It is based on three principles: design out waste and pollution; keep products and materials in use; regenerate natural systems.

In line with these principles, the Dutch Government aims to transition the national economy to a fully circular system by 2050 [1]. Next to other substances, bold efforts will be required to reduce plastic production from raw materials and prevent it to be discarded. With more than 1.900 kiloton of plastics marketed in the country in 2017, recycling must play an important role to succeed with this transformation challenge. Therefore this project aims to explore the trade-offs in the policy space of municipalities to maximise their recycling rate. The research project focuses at the the municipal governance level because it is responsible for organising and monitoring the waste collection and recycling for their area. The Municipality of Delft was chosen as the case study for this research project, to guide the authors of this report to build a model upon realistic numbers

Agent Based Modelling is the tool box used to investigate the potential impact of policy measures on the recycling rate of the Municipality of Delft. Therefore, this report is organised according to the modelling cycle that has been applied to build the model. In section 2, the Agent Based Modelling methodology is introduced. Then, section 3 describes all the modelling steps undertaken to build the model and deliver output. Section 4 engages in a discussion regarding the choices made to build the model and the outcome of this modelling exercise. Finally, section 5 provides recommendations according to the results of the model before concluding the report.

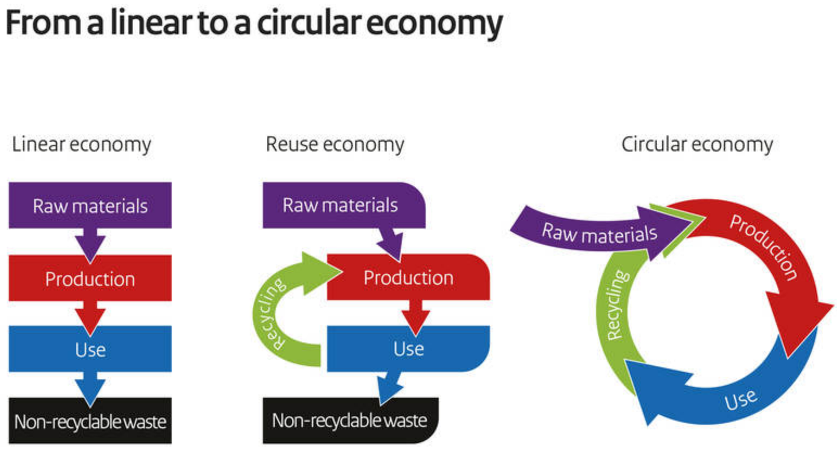

Figure 1: From a linear to a circular economy [1].

2 Methodology

As presented in the introduction, Agent-Based Modelling is the methodology used to model the complex adaptive system of waste recycling in the Dutch municipality of Delft. An agent-based model is a computational representation of the real world. Such model consists of individual 'agents' interacting according to a set of rules, wherefore the effect (i.e., behaviours) of these rules can be examined. For the purpose of this research project, an agent-based model is well equipped to simulate and understand the potential effects of policy changes on society and plastic recycling rate. With this approach, the authors aim to discover the trade-offs and synergies related to policy measures and try to deliver recommendations to policy makers accordingly.

To deliver a comprehensive agent-based model, the modelling cycle has been applied as follow. First, the conceptual model is defined. This stage starts with the definition of the model's goal and the research questions derived from this goal. The approaches to address the research questions are specified in parallel. The conceptual phase also includes the definition of process, concepts, features, agents, agent-environment interactions, and the visualisation of the model. Second, the conceptual model is translated into a formal model to explain how the research case is modelled. This phase takes place right before implementing the code. Working on a formal model requires to develop variables and functions from the concepts and relationships defined in the conceptual model. Once the formal model is complete, it can be implemented into a code. To write the code, this project uses the Mesa framework available with Python programming language. Third, the modelling cycle covers the experimental runs of the model. These experiments aim to verify and validate the behaviour of the model before interpreting the model's output. Finally, the modelling cycle ends with simulations and data analysis. During this last stage, insights are derived from the model output.

In the next section "Modelling cycle", the report will walk you through each step of the cycle to explain the development of the model from the research objectives to the output analysis.

3 Modelling Cycle

3.1 Conceptual model

As stated in the "Methodology" section, the conceptual model introduces the research objective, research questions and the model definition.

3.1.1 Research objective

The goal of this academic project is to apply the concept of Agent Based Modelling and system thinking to explore the trade-offs in the policy space of the municipality to optimize the plastic recycling rate. To do this, two research approaches will be employed. An exploratory model approach and a hypothesis-driven approach to respectively address the first and second research question presented below.

3.1.2 Research questions

The first question this research aims to answer is:
What is the behaviour of the model under various parameters, and how does it relate to the reality of plastics recycling?
This question is addressed in the Modeling Cycle part (section 3) of the report where the model is built and tested under different conditions.
With the second research question, the effect of proposed policies on the system will be examined and answered in the recommendation section of the report (section 4):
What is the influence of policy changes on the efficiency of plastic waste recycling.
This question investigates the effect of four hypothetical policies on the system:

- Increasing the number of waste collection points (i.e., underground containers) on the territory of the municipality;
- Deploying an annual billboard communication campaign;
- Deploying an annual digital communication campaign;
- Organising educative events towards the population to boost;

The purpose of the first measure is to ease waste disposal by improving the accessibility of waste collection facilities. The objective is to verify whether improved accessibility of waste collection points has a positive impact on the quantity of waste and plastic gathered. The three following measures are suggested to boost citizens' perception, importance and knowledge about plastic recycling and so encouraging them to adopt behaviours that foster plastic recycling. To determine the effect of these different policies, three different scenarios are modelled. A good, middle and bad scenario, where the policies respectively have a strong, moderate and weak impact on the model.

3.1.3 Model diagrams

To define the model, two diagrams are depicted in this section. First, the use-case diagram. Second, the class diagram.

Figure 2 is a use-case diagram to illustrate how waste gets collected by the municipality from households. The process starts with the households. Trash is produced and sorted at home before either being brought to centralized collection spots or collected at home by the recycling company contracted by the municipality. Households may also not follow the sorting rules, and not separate waste. Therefore the use-case "Separate waste" is an extend of "Deposit waste".

The second entity is the municipality. Their use-case is to transfer the waste from the containers or homes to the recycling company. In order to transfer waste, waste must be disposed in containers or gathered in front of houses for pick-up. Thus, "Deposit waste" must be included by the "Transfer waste" use-case. The municipality also buys activities to educate the households on recycling and increase the overall recycling rate therefore "Observe activities" from the household is included by "Buy activities" from the municipality. The municipality also must accept contracts offered by the recycling companies therefore "Accept contracts" must include "Offer contracts" from the recycling company.

The third entity is the Recycling company. Their use case is to offer contracts and to process the waste (collect it from either at home or the centralized spot).

After having explained the recycling process, the next class diagram is presented.

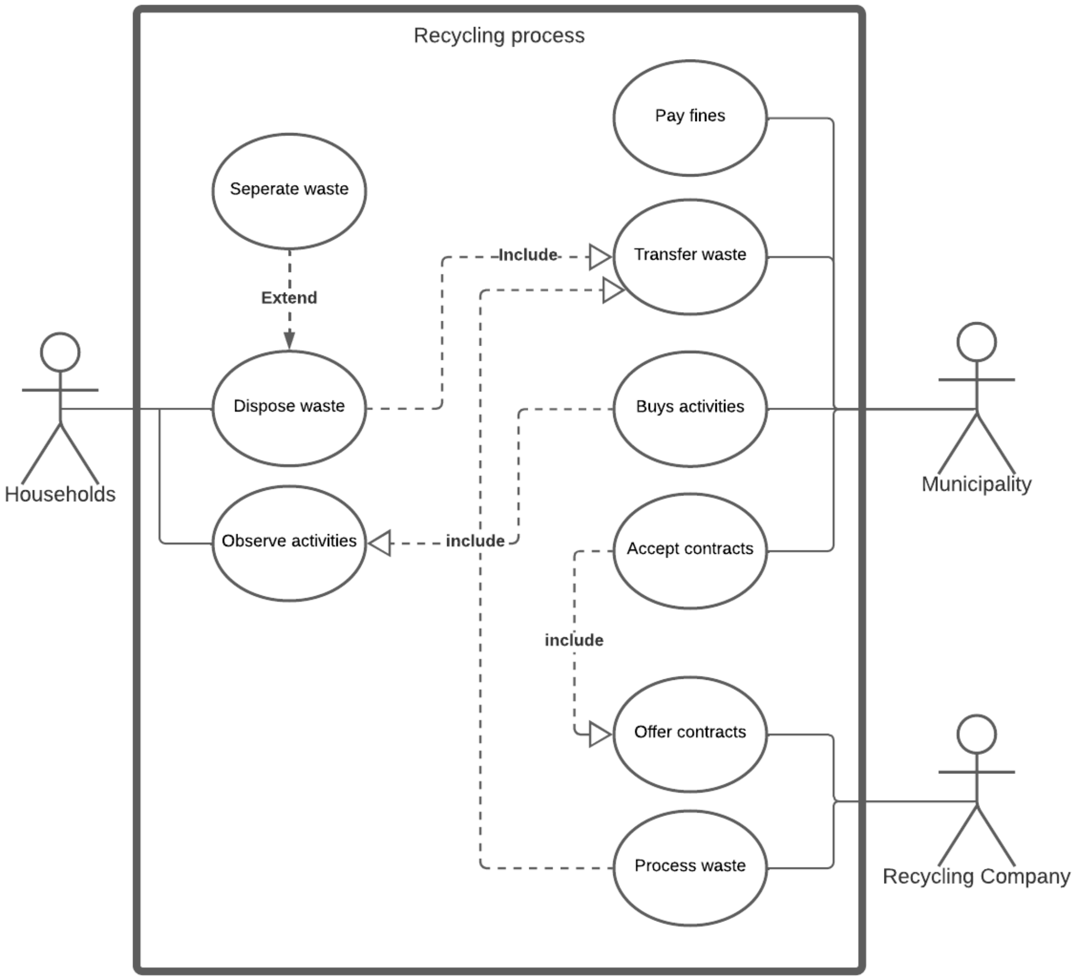

Figure 2: Use Case Diagram for waste recycling in municipality

Figure 3 provides an overview of the classes modelled for this research project. First, there is the agent classes. These classes includes the actual agents of the system and they are characterised by attributes (upper box) and actions or methods (lower box). An attribute is a variable value of the class. A method is an action the class can perform or undergo. Households consist of single, couple, elderly and Families. All share the same attributes and methods although values may differ. Their attributes define households' distance to a centralized waste disposal, plastic production as well as their understanding, perception and importance in respect with recycling activities. Household agents are also able to perform actions: generating, separating and throwing out trash as well as being part of a policy activity.

The municipality also includes several attributes and methods. The municipality buys activities, has several waste contracts, recycling targets, budget, several attributes related to demographic information. The municipality's methods include choosing contracts, buying activities and paying fines.

The final agent is the recycling company. The attributes consist of active contracts, collected fines and technology. The recycling company is responsible for offering contracts, collecting waste and fining the municipality if the agreed amount of waste is not met.

Besides the agents, there are so-called 'non-agents'. These objects are: waste, contract, offer and activity. Waste consists of the attribute Household data to track where the waste comes from. Waste can be generated and then transferred from households to the municipality. Contracts include more specifications such as the cost, the duration and how much plastics or waste is being collected. These contracts specify the quantity of plastic collected and the plastic recycling rate.

An offer is made of attributes such as the amount of trash, the potential fine, the target and the base waste foreseen in the contract.

The final class is the Activity. Activities can be implemented by the municipality to trigger change in the perception, knowledge and importance factor of the households or improve accessibility of collection points. The attributes of the activities combine the cost, effect per step, efficiency of the activity on the targeted variables, and the duration of the activity.

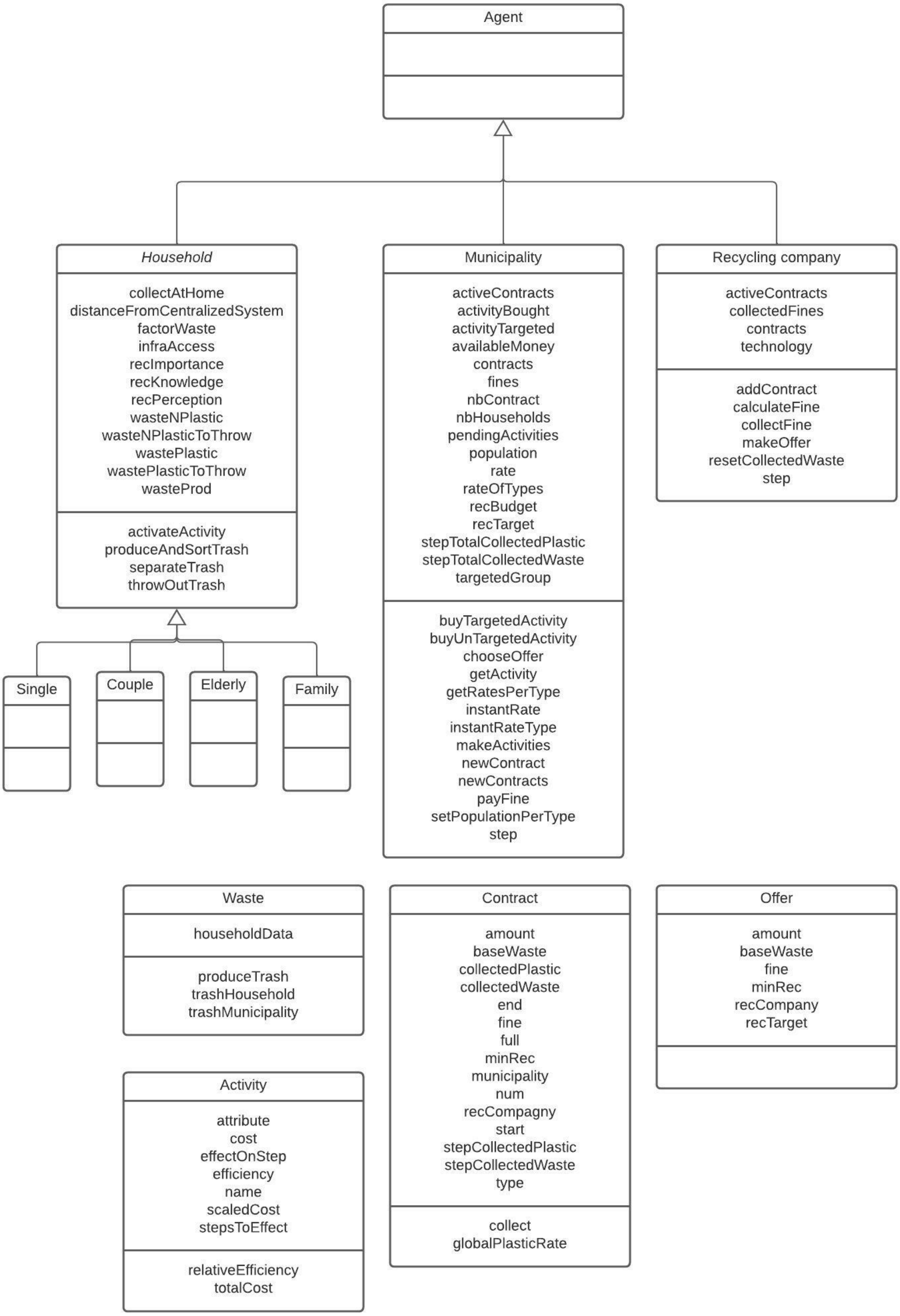

Figure 3: Class Diagram in the model

3.2 Formal model and implementation

In this subsection we will discuss the Formal model and its implementation in Python. The model was built using the mesa [2] framework in Python. The base Model class was extended to create the **RecyclingModel.py** class. This is the main model of the simulation and contains many agents extended from the Agent class from the mesa framework. These agents are of three different types: Municipality, Household or Recycling company. There are also classes for Contracts, Offers (of the contract), Activity and Waste. The model uses a slightly modified (local) version of the randomActivation Schedule. The model also has many data collectors which track many attributes during the execution of the code to give us our outputs.

Upon the creation of the agents, we use a normal distribution (defined by mean and standard deviation) to obtain the values of their attributes. In this sense we are able to create a large variety of agents that all have different values but who's values and the spread of these values is realistic.

Each Class contains many functions which we will not go in detail about as they are quite heavily commented and mostly self explanatory however the most important function is the step() function. This function is called every time a "time step" takes place in the code and launches a sequence of events which makes the model function and "live". We will now go in depth into this sequence of events and what happens in the code execution.

3.2.1 The step() function

In this subsection we will discuss what each agent does at each step function.

The Municipality will do these things at each step:

- Archive ended contracts
- Buy new contracts if needed
- Check the rate of recycling, if rate too low and end of year -> buy activity

To buy an activity the municipality will:

- Check the rate of recycling for each type of household
- If the households recycle about the same –> buy most efficient activity for whole municipality
- Otherwise buy targeted activity for lowest performing type of household

The Household will do these things at each step:

- Produce the trash
- Determine using its individual perception, knowledge and importance towards recycling how much of its plastic waste it will recycle
- Separate the trash based upon the above
- Throw out the trash in this manner either with at home collection or at a centralized collection spot
- Check for new activities
- If new activity available from municipality then do it

Finally the recycling company at each step will:

- Reset the trash it collected at the previous step
- Collect the trash
- If the contract is over Make offer for a new contract

As can be seen above, the main functionality of the model is very simple but of course there is a lot more complexity that goes into it which can be seen from simply running the code in the debug function to go through an entire step.

3.2.2 config.json file

The **config.json** file contains all the main variables for the model. Using such a file permitted us to avoid having dozens of hard coded variables spread all over the code and enabled a centralized file where all these variables were present. The **config.json** file is present below with a quick explanation of the purpose of each variable.

```
{
  "households": {
    "family": {                         # object containing the values for the family household type
      "demographic" : 0.07,             # the % of households of this type in municipality
      "rateFactor" : 2.5,               # waste production as a factor of base
      "recPerception": {                # the perception towards recycling as a normal distribution
        "Mean": 0.5,
        "Var": 0.025
      },
      "recImportance": {                # the importance towards recycling as a normal distribution
        "Mean": 0.5,
        "Var": 0.075
      },
      "recKnowledge": {                 # the knowledge towards recycling as a normal distribution
        "Mean": 0.5,
        "Var": 0.025
      }
    }

    ... similar object as above for retired, couple, single ...

  },
  "lengthContract" : 3,                 # length of contract in years
  "nBContract": 5,                      # maximum amount of contracts extisting at once
  "moneyDispoPerHousehold": 1100,       # budget of municipality for each household for 20 years
  "recyclingTarget": 0.5,               # starting recycling target (50%)
  "pricePerTon": 30,                    # price of collecting 1 ton of waste in euros
  "plasticRateInWaste" : 0.195,         # Rate of plastic in waste (19.5% of waste is plastic)
  "distanceToCenter" : {                # How far a household is to collection spot (norm dist)
    "Min" : 30,
    "Mean" : 150,
    "Var" : 50,
    "Max" : 300
  },
  "fineFactor" : {                      # Variables used to determine how much a fine is
    "factor" : 0.1,
    "delta" : 0.1
  },
  "partAtHome" : {                      # Uniform distribution of households having at home collection
    "Min" : 0.55,
    "Max" : 0.65
  },
  "contractTargetDelta" : 0.03,         # Variance in contract making on target
  "contractPriceDelta": 0.03,           # Variance in contract making on price
  "accessProportion" : {                # Uniform distribution of household access to infrastructure
    "Min" : 0.90,
    "Max" : 0.981
  },
  "numberOfHouseholds" : 1000,          # Total number of households in municipality
  "numberOfRecComps" : 10               # Total number of recycling companies in municipality
}
```

3.3 Verification and Validation

After having introduced the formal model and explained its implementation in Mesa, this section describes the tests conducted to observe how the model behaves under various conditions ans so answering the first research question. With these verification runs, attributes' values are eventually validated to define a final model that delivers stable and acceptable results. For each run and the three scenarios, five indicators are analysed: (1) type and number of activities bought, (2) budget consumed, (3) waste and (4) plastic collected as well ass (5) plastic recycling rate. Based on observations, attributes' values are adapted to refine the model's output.

3.3.1 Run 1 - Initial conditions:

For the first verification run, figure 4 shows that the only activities bought are digital and billboard campaigns. New collection points are not built, either because the efficiency does not justify the construction cost (10.000€/collection point) or because the network of collection points has reached saturation. Saturation means here that adding new collection points does not improve the quantity of waste collected nor the recycling rate. Educative events foreseen by the municipality are not implemented either mainly because this activity does not sufficiently boost the perception, importance and knowledge of households regarding plastic recycling.

Step	Activity Bought	activityTargeted	targetedGroup
12	Billboard campaign on recycling importance	False	None
24	Billboard campaign on recycling importance	False	None
36	Billboard campaign on recycling importance	False	None
48	Billboard campaign on recycling importance	False	None
60	Billboard campaign on recycling importance	False	None
72	Digital campaign on recycling importance	True	Couple
84	Billboard campaign on recycling importance	False	None
96	Digital campaign on recycling importance	True	Couple
108	Billboard campaign on recycling importance	False	None
120	Digital campaign on recycling importance	True	Couple
132	Digital campaign on recycling importance	True	Couple
144	Billboard campaign on recycling importance	False	None
156	Digital campaign on recycling importance	True	Couple
168	Digital campaign on recycling importance	True	Couple
180	Billboard campaign on recycling importance	False	None
192	Digital campaign on recycling importance	True	Couple
204	Billboard campaign on recycling importance	True	Retired
216	Billboard campaign on recycling importance	False	None

Activities Bought bad

Step	Activity Bought	activityTargeted	targetedGroup
12	Billboard campaign on recycling importance	False	None
24	Billboard campaign on recycling importance	False	None
36	Billboard campaign on recycling importance	False	None
48	Billboard campaign on recycling importance	False	None
60	Billboard campaign on recycling importance	False	None
72	Digital campaign on recycling importance	True	Single
84	Digital campaign on recycling importance	True	Couple
96	Billboard campaign on recycling importance	False	None
108	Digital campaign on recycling importance	True	Couple
120	Digital campaign on recycling importance	True	Couple
132	Billboard campaign on recycling importance	False	None
144	Digital campaign on recycling importance	True	Single
156	Billboard campaign on recycling importance	True	Retired
180	Billboard campaign on recycling importance	False	None

Activities Bought middle

Step	Activity Bought	activityTargeted	targetedGroup
12	Billboard campaign on recycling importance	False	None
24	Billboard campaign on recycling importance	False	None
36	Billboard campaign on recycling importance	False	None
48	Billboard campaign on recycling importance	False	None
60	Digital campaign on recycling importance	True	Single
72	Billboard campaign on recycling importance	False	None
84	Digital campaign on recycling importance	True	Single
96	Billboard campaign on recycling importance	False	None
108	Billboard campaign on recycling importance	False	None
240	Digital campaign on recycling importance	True	Single

Activities Bought good

Figure 4: Run 1: Activities bought for the bad, middle and good scenarios

As we can see in figure 5, budget consumed in the three scenarios is almost the same. In addition no scenario uses a significant share of the budget available for plastic recycling although the bad scenario implements many more activities to reach the recycling target rate. The explanation can be found in the cost to run the activity. The activity cost is set per step and household. However, the budget per household for each activity has been estimated for the actual number of households in the municipality (48 177). However, the model runs with only 1000 households to speed the execution of the code. Therefore, the cost of activities should be multiplied by 50 to be aligned with the municipality's global budget.

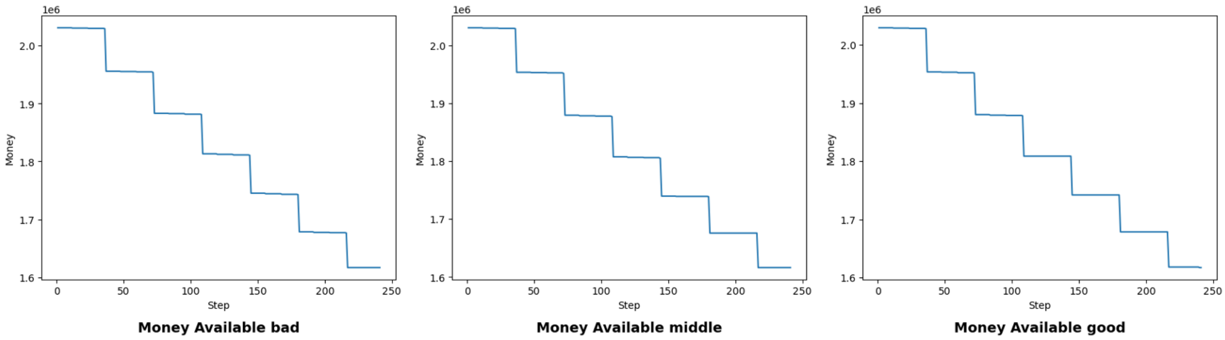

Figure 5: Run 1: Budget consumed for each scenario

Figures 6 and 7 show that the quantity of waste and plastic collected experiences several drops with different magnitude for each scenario. These collection drops take place at the end of contracts with recycling companies. The issue in the model comes from the fact that households have the possibility to dispose trash in nearby municipal collection containers even if they can benefit from "at home" collection service. When the distance from home and the containers is smaller than 300m, households discard waste in containers rather than waiting for collection. This means that stock capacity in containers can be exceeded. Thus, the recycling company cannot cope with the quantity of waste gathered at collection points while little is being collected at home. Then, when a new contract starts, the newly appointed organisation must deal with a large amount of untreated waste. This is demonstrated in the graphs by the peaks in waste and plastic collected. This instability in the model must be addressed by defining stricter rules on the collection methods assigned to households.

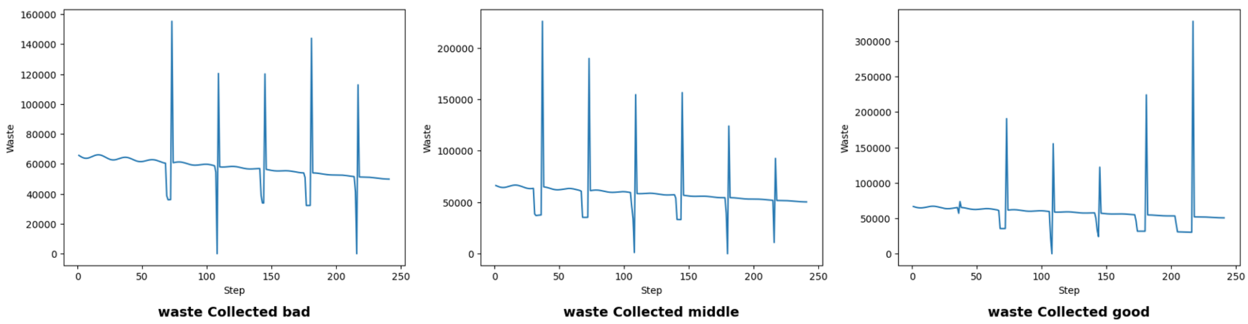

Figure 6: Run 1: Waste collected over time for each scenario

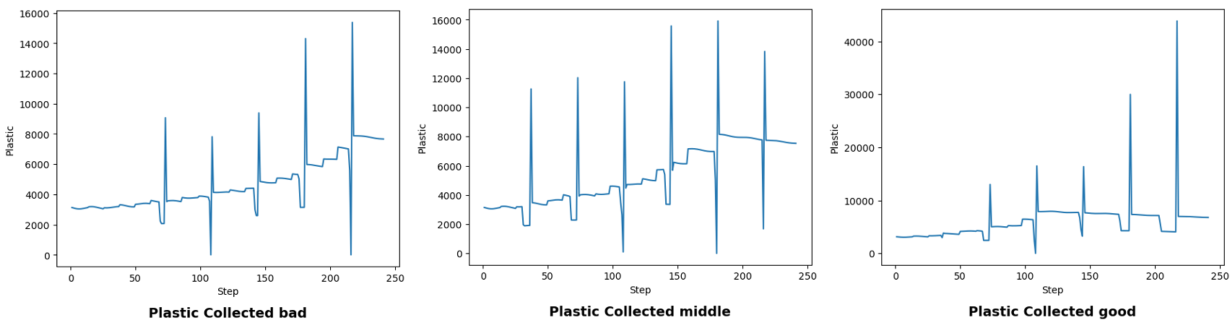

Figure 7: Run 1: Plastic collected over time for each scenario

Surprisingly, the recycling rate at the end of the 20-year period is higher for the bad and middle scenarios although they are expected to deliver weaker results. In addition, drops in the recycling rate (figure 8) observed for all scenarios remind us the drops seen in waste and plastic collection (figures 6 and 7). Addressing the drops in the collection of waste and plastic shall probably stabilise the recycling rate for all scenarios too.

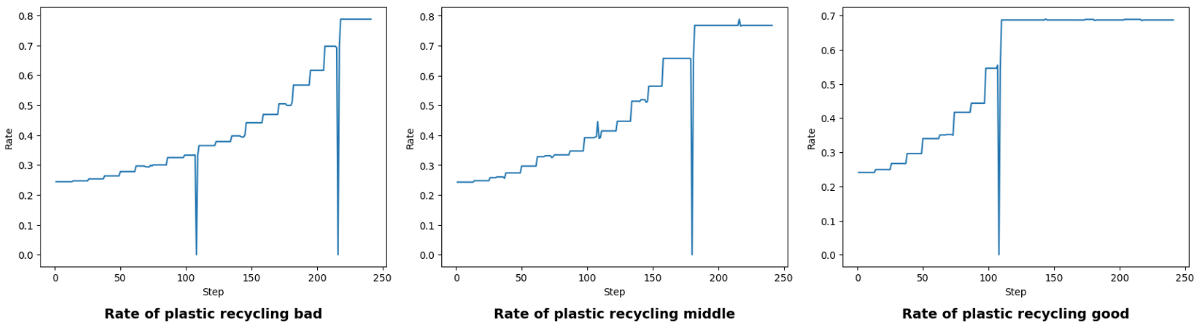

Figure 8: Run 1: recycling rate for each scenario

3.3.2 Run 2 and 3 - New activity costs:

We saw in the first verification run that budget available was underused. As explained, this issue came from the misalignment between the estimated activity cost per step and household and the number of households created in the model. To align the activity cost with the municipality's budget, the activity cost was first multiplied by 50. As we can see in figure 9, the budget is more extensively consumed. Over the 2 million euros available, around 1 million is used for each scenario. In addition, the same figure shows that budget is not only consumed for staring new contracts but also for deploying billboard and digital campaigns neither as educative events nor new collection points are selected by the model. For the third, run, the activity cost was multiplied by 100 compared to the initial values. In addition, the cost of building new collection points was divided by two while keeping the same impact on the recycling rate. However, types of activities bought remained limited to billboard and digital campaigns. The budget graphs are not shared in this report because they demonstrate the same patterns as in figure 9. The only difference is that the remaining budget at the end of the 20-year time frame for recycling activities drops to 0,4, 0,7 and 0,9 million euros respectively for the bad, middle and good scenario. Therefore, the initial budget of 2100€ foreseen per household for recycling activities over 20 years is too ambitious for the activities suggested in this model.

3.3.3 Run 4 and 5 - rationalising the model :

The fourth run consisted of reducing the budget per household dedicated to recycling activities from 2100 to 1100. Suggesting additional and bolder measures could have been an alternative to budget reduction. Due to time constraints, these model improvements could not be delivered. As explained in the next section "Simulation and data analysis", the main consequence is that budget is almost completely used after 20 years and the municipality may even run out of budget for some scenarios.

The final verification run was then launched to solve inconsistent waste and plastic collection scores as well as the related recycling rate as we observed in the first run. The model was stabilised by applying stricter rules on households' options for disposing trash. The method used is to set a fixed share of households that benefit from "at home" collection to dispose their waste in containers. This share ranges between 55 and 65 percent of the population. Consequently, collection points in neighbourhoods do not get overloaded and all trash disposed can be treated by the municipality. The outcomes of this modification in the model is more extensively presented in the last step of the modelling cycle: simulation and data analysis.

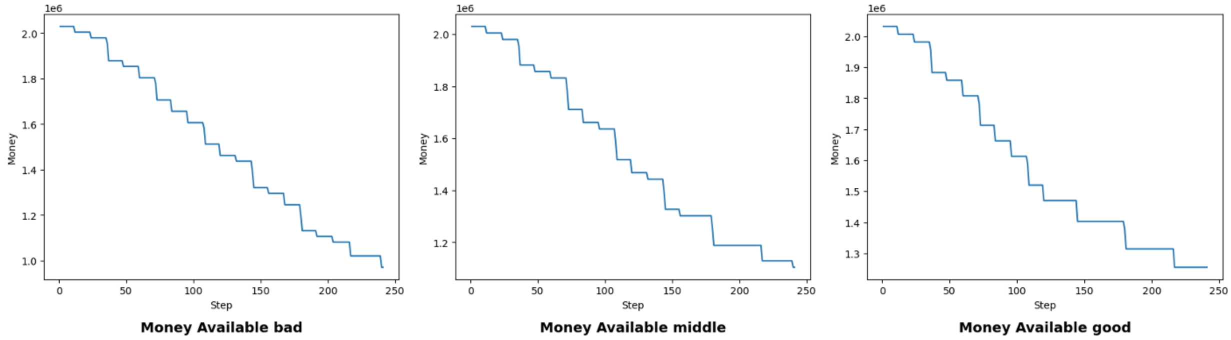

Figure 9: Run 2: Budget consumed for each scenario

To conclude this section and summarise our answer to the first research question, we observed that the choice and frequency of activities implemented are not strongly sensitive to changes in cost. The number of policies launched over 20 years remained stable across the five verification runs. However, the budget available for policy measures is naturally affect by these changes in cost. Another key finding is that preventing households benefiting from "at home collection" to dispose trash in containers, allows the municipality to better control the waste flows and so better manage collection. The next section of the modelling cycle describes the simulation settings of the final model and the analysis of its output.

3.4 Simulation and Data Analysis

The simulation and data analysis section is the last piece of the modelling cycle. This part presents the results of the final model that must support the municipality's future decisions to boost the plastic recycling rate in its area. The model's output are analysed according the five key indicators listed in the previous section.

3.4.1 Activities

The first indicator to be analysed is the types of activities bought by the municipality.

Figure 10 shows that an activity is bought every year. In the middle scenario the municipality bought yearly activities for 15 years (up to step 180). In the good scenario, the municipality launched yearly activities for 10 years (up to step 120) and then implemented an additional activity for the 15th year (from 180 to step 191 included) of the model. The reason for this becomes clear when analysing results from the following subsections. In principle, the municipality stops buying activities when the recycling target are met. The recycling target starts in year one with the objective to increase by 5 percent every four years. In the bad scenario, activities bought never achieve the reach the recycling target. In the middle scenario, the target seems to be met after 15 years (step 180). Then the municipality stops buying activities from this moment onward. In the good scenario the target is met during the 10th year of the model. However, the municipality starts a new campaign in year 15 to maintain the recycling rate after a five-year period without buying activities.

Besides the amount of activities bought, some of the activities are targeted at a specific group. First the model analysis if there is a specific group which has an outlying recycling rate. If this is the case, an activity is bought which has the most impact on that group. We observe that campaigns are either targeted to all household types or to elderly people. This is caused by the fact that digital campaigns focus on all demographic groups except elderly since those people are less affected by those types of campaigns. After a implementing a digital campaign, the perception, knowledge and importance of recycling are improved with billboard campaigns. This phenomena can be seen in all three scenarios.

Step	Activity Bought	activityTargeted	targetedGroup
12	Digital campaign on recycling importance	False	None
24	Digital campaign on recycling importance	False	None
36	Digital campaign on recycling importance	False	None
48	Digital campaign on recycling importance	False	None
60	educative events on recycling importance	True	Family
72	Billboard campaign on recycling importance	True	Retired
84	Billboard campaign on recycling importance	True	Retired
96	Billboard campaign on recycling importance	True	Retired
108	Digital campaign on recycling importance	False	None
120	Billboard campaign on recycling importance	True	Retired
132	Billboard campaign on recycling importance	True	Retired
144	Digital campaign on recycling importance	False	None
156	Billboard campaign on recycling importance	True	Retired
168	Billboard campaign on recycling importance	True	Retired
180	Digital campaign on recycling importance	False	None
192	Billboard campaign on recycling importance	True	Retired
204	Billboard campaign on recycling importance	True	Retired
216	Digital campaign on recycling importance	False	None
228	Billboard campaign on recycling importance	True	Retired
240	Billboard campaign on recycling importance	True	Retired

Bad Scenario Activities Bought

Step	Activity Bought	activityTargeted	targetedGroup
12	Digital campaign on recycling importance	False	None
24	Digital campaign on recycling importance	False	None
36	Digital campaign on recycling importance	False	None
48	Billboard campaign on recycling importance	True	Retired
60	Billboard campaign on recycling importance	True	Retired
72	Billboard campaign on recycling importance	True	Retired
84	Billboard campaign on recycling importance	True	Retired
96	Billboard campaign on recycling importance	True	Retired
108	Digital campaign on recycling importance	True	Single
120	Billboard campaign on recycling importance	True	Retired
132	Billboard campaign on recycling importance	True	Retired
144	Digital campaign on recycling importance	True	Single
156	Billboard campaign on recycling importance	True	Retired
168	Digital campaign on recycling importance	True	Single
180	Billboard campaign on recycling importance	True	Retired

Middle Scenario Activities Bought

Step	Activity Bought	activityTargeted	targetedGroup
12	Digital campaign on recycling importance	False	None
24	Digital campaign on recycling importance	False	None
36	Digital campaign on recycling importance	False	None
48	Billboard campaign on recycling importance	True	Retired
60	Billboard campaign on recycling importance	True	Retired
72	Billboard campaign on recycling importance	True	Retired
84	Billboard campaign on recycling importance	True	Retired
96	Billboard campaign on recycling importance	True	Retired
108	Billboard campaign on recycling importance	True	Retired
120	Digital campaign on recycling importance	True	Couple
180	Billboard campaign on recycling importance	True	Retired

Good Scenario Activities Bought

Figure 10: Lists of bought activities for the three scenarios

3.4.2 Budget

The second indicator tracks hows the budget is consumed through the years by buying activities and new contracts with recycling companies.

The municipality starts with a budget of 1100 euro per household for the next 20 years. The total budget for 1000 households reaches 1.1 million euros. To start of with the bad scenario, in the first graph of figure 11 there can be observed that the budget moves down in a pattern. First there are 3 little jumps down, followed by a bigger step. This pattern repeats until the budget gets close to 0. Every year there can be one activity bought, and once every 3 years the municipality buys a contract. In the bad scenario, an activity is bought every year (see figure 10). This explains the repeating pattern in this scenario. The pattern found in the bad scenario was also visible in the middle and good scenario, but stops respectively after step 15 (step 180) and 10 years (120). As explained above, this is due to the municipality stopping to regularly launch new activities. Consequently, the municipality run out of budget only in the bad scenario.

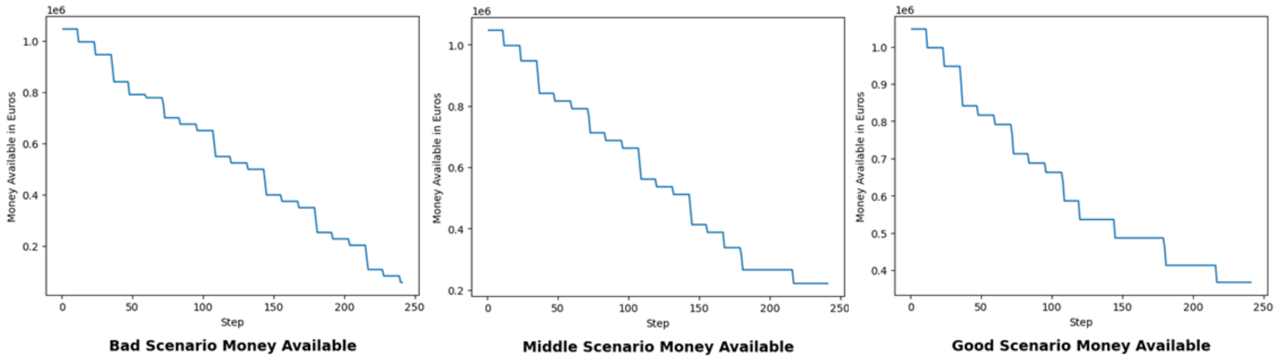

Figure 11: Budget consumed for the three scenarios

3.4.3 Waste collected

In this subsection the third indicator is analysed: amount of collected waste.

From figure 12 it can be concluded that the amount of waste collected stays approximately the same over the 3 different scenarios. The periodically fluctuations are caused by the waste production function given in the assignment. The middle scenario however shows a slight decrease in the amount of waste collected from the start. This indicates that the amount of waste produced is slightly lower in the scenario.

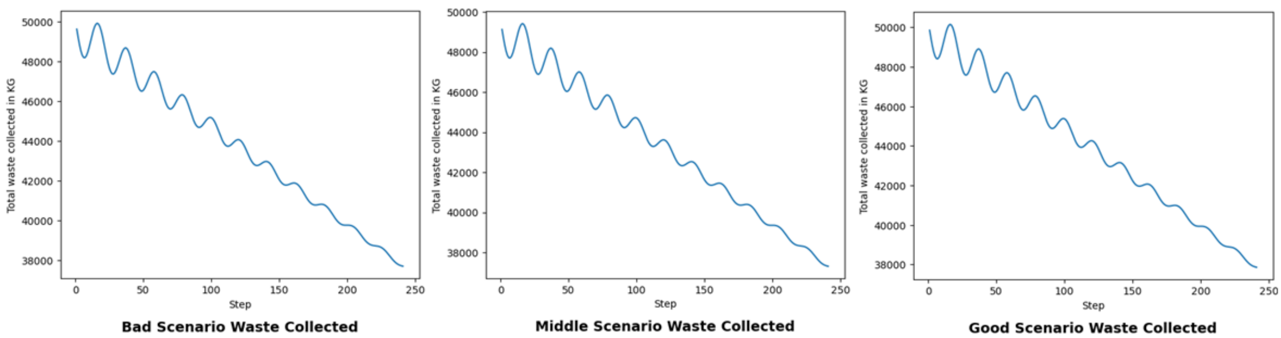

Figure 12

3.4.4 Plastic collected

The fourth indicator analysed here focuses on the quantity of plastic collected.

The graphs in figure 13 show the that amount of plastic collected increases over time. In the bad, middle and good scenarios the maximum amount of plastic collected respectively exceeds 5000kg, 6000kg and 6100kg. When looking back at figure 10, we observe that the bad scenario needs activities every year. In addition we observe in 11 that the budget is running out. These observations combined explain why in the bad scenario the total amount of plastic recycled is lower than in the middle scenario. In the middle scenario the peak is at step 180, where according to figure 10 the last activity was bought. From this point, the graph continuously follows the waste production function provided in the assignment. In the good scenario, the first peak occurs at step 120, where the periodically activities stops. The final peak is at step 180, where the final activity is bought. These observations show the role played by activities increasing and maintaining the quantity of plastic collected for entering the recycling process.

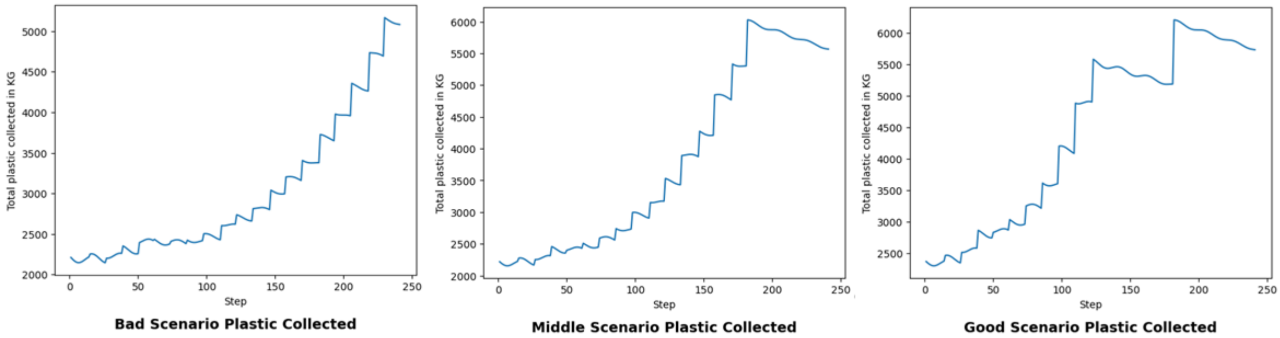

Figure 13

3.4.5 Recycling rate

Finally, the analysis parts concludes with the plastic recycling rate obtained from the model.
In figure 14 the recycling rate of the 3 scenarios are displayed. The goal of the model is to reach a recycling percentage of 50%, increased by 5% every 5 years. In the bad scenario this goal is never met. The recycling rate of plastic never reaches the intermediary steps and caps below the 70% after 20 years. This explains the results from figure 10 which shows that in the bad scenario the activities are bought every year, trying to catch up to the goal. In the middle scenario, figure 14 shows that the goal is met at step 180. This explains why the municipality stops buying activities at step 180, where the recycling rate peaks. Then, no additional activities must be launched because the recycling rate remains above target. In the good scenario, the goal is first met at step 120, where the goal was to have a recycling rate of 60%. When suddenly after step 180 the goal increases to 65%, it needs to buy another activity to increase its recycling rate. This explains why in figure 10 the purchases of activities stops at step 120, and it explains why at step 180 another activity is bought. This also explains the 2 peaks in figure 13, where at step 120 and 180 peaks are visible.

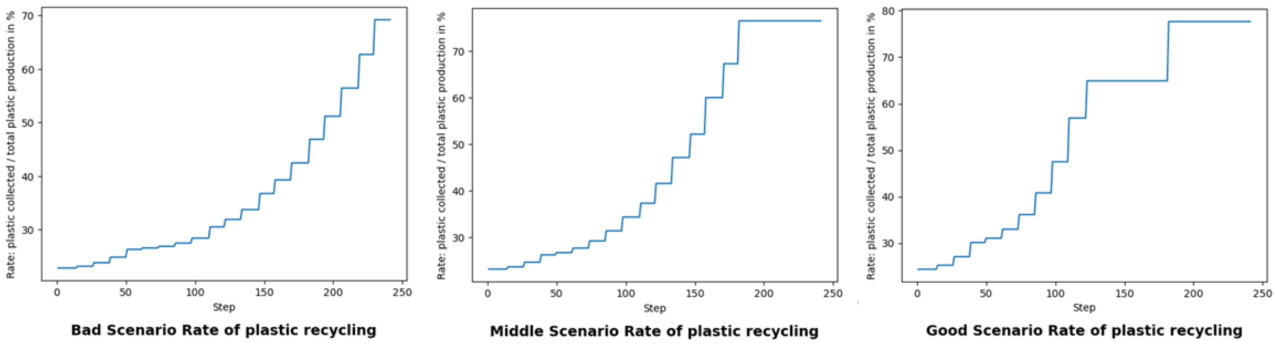

Figure 14

4 Discussion

The previous section highlighted the main outcomes of the developed model. The analysis enabled to appreciate how the five indicators evolved over time under the municipality's intervention. In this section, the model's limitations are acknowledged and discussed in order to identify opportunities for improvements.

First, the model analysis showed that the digital campaign is very effective for all different demographic groups, except for elderly. Elderly are rarely tech-savvy, but they are more sensitive to physical activities like billboards. During a year when budget is dedicated to digital campaign, all groups increase their perception, importance and knowledge score in favour of recycling, except elderly people. The next year, a billboard campaign is launched since elderly household's recycling score highly differs from the other groups. The reliability of a model relying on only two types of measures to reach recycling target can be questioned. Only using 2 types of campaigns would lead to a very monotonic campaign policy. Instead variety of innovative policies should be stimulated to improve the relevance of such model. In the same vein, some could argue that the desired effect of the measures could fade away due to their redundancy. As people get used to the same approach being repeated, their attention and responsiveness would certainly decrease.

Second, when a certain plastic recycling rate increase due to the activities of the municipality, the rate remains stable even if no activity is performed. In a realistic world the rate would decrease when there is less or even no effort from the municipality to promote behaviours in favour of plastic recycling. Therefore, the recycling rate of the municipality should go down when there is a period without activity. //
Third, the current model launches only one campaign possible per year. In reality, several activities could be combined to trigger synergies. For instance, a communication campaign associated with a tax program and infrastructure plan would have a stronger impact on the recycling rate.

Finally, the last limitations discussed here concern the effect caused by the measures undertaken by the municipalities. All activities in the model only have a positive impact on the recycling rate. In reality, policies could be unpopular and generate resistance among the population.

5 Recommendations

In this chapter the recommendations following from the model will be elaborated.

5.1 Recommendations on refining the model

As described in the the discussion there are multiple flaws which could be implemented in a more realistic version of the model. First the knowledge, perception and importance of the households should go down when there is no activity performed by the municipality. This could be implemented by introducing a function to the knowledge, perception and importance scores of the households, which results in a decrease when there is no activity. Secondly the effect of similar activities should decrease over time, and be reset when the activity has not been used for one year. This could be implemented by introducing a if statement to check if the former activity was similar to the new activity. If that is the case, the effect of the activity can be reduced by a factor. Thirdly the municipality should be able to buy multiple activities. This can be done by making multiple activities in which the current activities are combined. This would lead to a variety of combinations. However, it should also calculate that when there is an overkill of activities combined for a longer period of time that the effect will decrease.

5.2 Recommendations on policy

Since the model has quite some logical flaws, it would be quite hard to give some actual policy advise on what policy to use. To make this model a model which can be used to derive some actual recommendations with, the next things are needed. The first thing is to update the model with the above described recommendations on refining the model. The second advise for the municipality would be to set up an extensive research on the effect of different campaigns. The thing to keep in mind here, is that it is extremely hard to quantify the effect of hypothetical campaigns on the households. Several ways of doing this, is by performing literature research, putting out surveys under the citizens, and look to empirical data where data from past campaigns can be analysed. Finally it is also very important to make a very accurate zero measurement on how well the different demographic groups recycle in the municipality. This can be done by interviewing or surveys. By doing this, combined with an accurate as possible quantification of the activities, the model can be as accurate as possible. Final thing to mention, even if the model gets the upgrades mentioned in the recommendation section, it still is very hard to give a certain picture of the future. There are a lot of unforeseen things that could happen that disrupts the system, causing the model to be wrong.

6 Conclusion

To increase society's chances to fully transition from a linear to a circular economy, every actor in society must embrace the concepts of this new paradigm that designs out waste from socio-economic systems. In the Netherlands, municipalities play a crucial role in steering this transition for citizens. Therefore, this project aims to investigate the trade-offs in the policy space to achieve the highest possible plastic recycling rate. Agent Based Modeling is the approach used for this research project to address the aforementioned challenge. Thus, a full modelling cycle was applied in order to build a model that simulates the behaviour of agents involved in the municipal waste recycling activities. The model was defined, developed, tested and eventually validated. Then, model's outcomes were analysed to derive relevant advises to support the local government of the municipality of Delft to undertake promising actions that could boost the recycling rate of plastic. The model shows insightful results regarding the evolution of the recycling rate in respect with waste and plastic collection. In addition, the measures modelled proved to have a clear impact on plastic recycling. However, the report identified several limitations that are opportunities to further improve the model's usefulness in guiding civil servants in their mission of phasing out waste from households.

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