Plastic fantastic

An Agent-Based modelling study on the plastic recycling system

SEN1211: Agent-based Modelling

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TU Delft

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by

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Project Duration:	Q2 2021/2022

Cover Image: TU Delft

Summary

The consumption of plastic has large consequences for human health and environment. Although a great percentage of plastic is recyclable, the actual percentage of plastic that is recycled is lagging behind. In this research, it is tried to capture the human behaviour that underlies the recycling process. This is done by the construction of an ABM model that simulates recycling behaviour on a municipal level. In the research, several policies are implemented targeting on either the perception and knowledge of households concerning plastic recycling or on subsidizing recycling companies.

It became clear that the policies targeting the behaviour of households had the largest impact. Enacting a policy that offers subsidies to recycling companies only lead to a minor increase in the percentage of recycled plastic. Furthermore, it can be stated that the outcomes for different are relatively similar, despite their differences in demographics. Further research should look into the the perception and knowledge of households, competition between recycling companies and the effectiveness of legal instruments.

Contents

1

Introduction

1.1. Problem description

The exorbitant consumption of plastic has large consequences for human health and environment (Heidbreder et al., 2019). An increasing percentage of plastic ends up in the ocean and there are third world countries that are rapidly developing into a plastic waste dump (Monbiot, 2018). Plastic offers many advantages in its usage; it is easy to shape and it corrodes hardily (Shen & Worrell, 2014). The entire replacement of plastic by other materials is therefore unlikely, but plastic recycling could provide a solution to the environmental problems raised by the usage of plastic. However, although a large percentage of plastic is recyclable, the actual percentage of plastic that is recycled is relatively low (Shen & Worrell, 2014). The problem is complex since it is attributable to erratic human behaviour. In this research it is tried to capture this complexity by developing an ABM model that simulates the interaction between consumers, policy makers and plastic recycling companies. The results could provide insight into the policies that might be effective for increasing the percentage of plastic that is recycled in municipalities with different characteristics.

1.2. Research question

The question that is addressed in this report, is the following:

> *"What are the trade-offs in the policy space of the municipalities if they wish to achieve the highest possible recycling rates?"*

1.3. Modelling setup

An agent-based model is constructed in this project to get insight into plastic recycling in the Netherlands. The behaviour of this model will be tested under various parametrizations to gain insight into real worlds mechanisms of city-level plastic recycling. In this model several policy instruments will be included. These instruments will be analysed on their effectiveness.

The agent-based model is created in the Python programming language with use of the Mesa package. The Mesa package is a modular framework for creating and analyzing agent-based models.

1.4. Report structure

In the next chapter, a demarcation of the system will be illustrated and explained in the conceptual design. During the formalisation in chapter 3, the implementation of the conceptual model in Mesa is covered. Afterwards, the verification and validation is shown in chapter 4. In chapter 5, the analysis is performed. Afterwards, in chapter six, the conclusion and further recommendations are presented.

2

Conceptual Design

2.1. Model Overview

The conceptual model that can be seen in 2.1 shows the representation and demarcation of the system. The households produce garbage and separate a certain fraction of plastics in that waste. Recycling companies pick up the plastic from the households of the municipality that they are in contract with. The recycling company puts all the plastics in a machine that will separate the recyclable plastics from the non-recyclable plastics. The recyclable plastics will be sold, the non-recyclable will be burned. The municipality can affect the system by introducing policies that either target the households or the recycling companies.

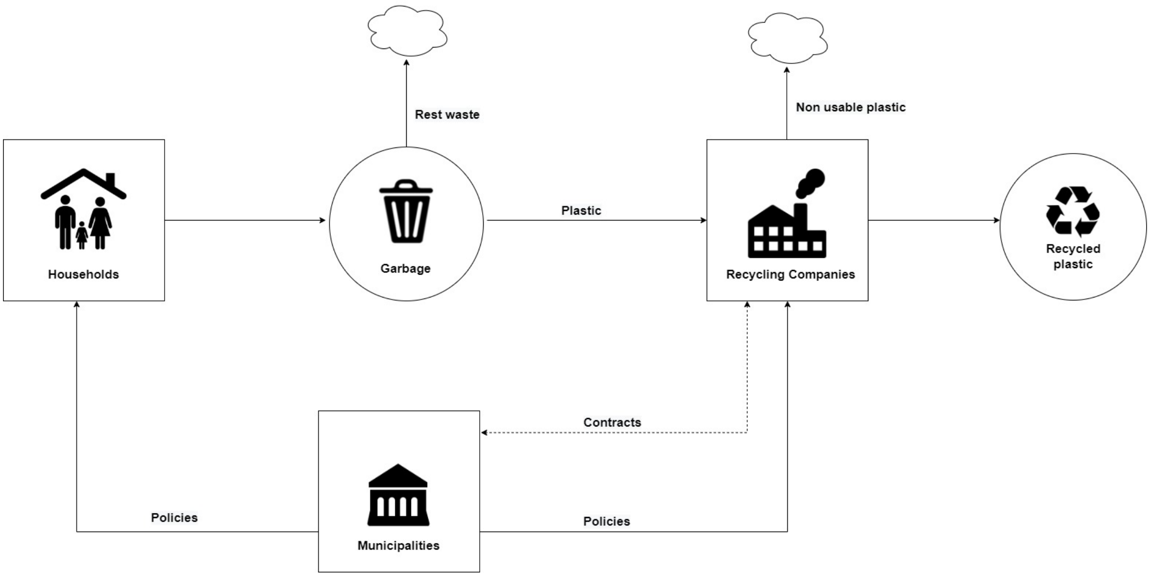


Figure 2.1: Model overview of the recycling process

2.2. Agents

Three different agent are present in the system: Household, Municipality and Recycling Company. Besides the three agents there are two objects: Technology and Contract. A Technology object belongs to a Recycling Company, the attributes throughput and percentage are adjusted whenever the corresponding recycling company decide to upgrade the technology. A contract is an agreement between a municipality and a recycling company. As attributes, it contains the municipality and recycling company that it belongs to. The full overview of all the agents, with their attributes and functions can be seen in Table 2.1.

Table 2.1: Overview of agents and objects

Entity	Has	Does
	Agents	
Household	Type: Single, Couple, Family, Retired Couple, Retired Single. Perception: View on recycling and how much effort they put in to recycle. Knowledge: How well a household knows which plastic is actually recyclable. Municipality: In which the household lives.	Produce Waste. Separate waste based on knowledge and perception. Get influenced by policies.
Municipality	Households: Number and distribution of household type. Contract: Shared contract with a Recycling company.	Look for new contracts. Implement policies.
Recycling Company	Technology: see Technology. Contract: Shared contract with a Municipality. Budget: To buy upgrades for the Technology and is increased by the profit made for selling recyclable plastic.	Collect plastic from households in the contract Municipality. Last form of plastic separation. Sell the recycled plastics to increase budget. Buy upgrades for their technology.
	Objects	
Technology	Throughput: How much waste it can handle. Percentage: Extra separation factor. Version: Version which relate to throughput and percentage and can be upgraded.	
Contract	Municipality and Recycling Company: Links the two of them together for a period of three years	

2.3. Policies

The policies that are implemented in the model can be divided into two categories. In the first category, three policies are present that are targeted on the behaviour of the households in the model. In the first policy, the municipality tries to increase perception of households by running a campaigning. It is expected that by running this campaign regularly, the perception of the households will increase by a percentage. This percentage is to a certain extent random, and differs for the types of households since we expect that not every household is susceptible for the campaign. The second policy is targeted on increasing the knowledge of people, by giving workshops or handing out flyers. The increase in knowledge is also partly random but does not differ per type of household. In the third policy, both the perception policy and the knowledge policy are introduced. In the second category of policy measures the recycling companies are targeted instead of the households. In this policy, the municipality provides subsidies for recycling companies to update their technology.

2.4. Time

For the run of the model a time span of 20 years is chosen, this is to capture every possible event at least once. The event with the longest time span is the upgrading of the technology which has to be done at least once every 10 years, since that is set as the lifespan of the technology. All the big events with their timespan can be found in Table 2.2.

Table 2.2

Event	Time period	Ticks
Households dump their waste	Every month	1
Contracts are renewed	Every 3 years	36
Technology lifespan	10 years	120
Run of the model	20 years	240

2.5. KPI's

To measure the performance of the system, there are KPI's defined. For the three different municipality, those include the average percentage of the waste that turns into recycled plastic for all households. The percentage is chosen to make it easy to compare the performance of the different cities and policies with each other.

2.6. Assumptions

The model is considered to be a simplification of reality. As stated by Box (1979), all models are wrong and this is also applicable to this model. Therefore, the aim is to create a model that is fit for purpose, which comprise drawing conclusions about the impact of different recycling policies on the recycling system. An overview of important assumptions in our model can be found in Table 2.3.

Table 2.3: List of Assumptions

	Assumption
Waste	The amount of waste producing members of a household is assumed to be: • (Retired) Single: 1 • (Retired) Couple: 2 • Family: 4 The waste is assumed to be linearly dependent on the amount of members in the household.
Perception	The perception is basically the view of households on recycling and how likely there are to separated their waste. This does depend on type: • It is assumed that a retired type is more likely to find it not that important, resulting in a lower perception range. • It is also assumed that in a couple people will have a strong influence on each other, making it more likely to have a higher perception. • Families are assumed to behave like a couple in relation to the perception.
Knowledge	The knowledge is how well households know what plastic is actually recyclable. This does again depend on their type: • It is assumed that a retired type is in general less likely to have the required knowledge, resulting in a lower knowledge range. • Couples are assumed to have more knowledge since two know more than one, giving them a higher knowledge range. • Families are again assumed to behave similar to couples in regard to knowledge.
Contracts	Every 3 years a new contract has to be formed between municipalities and companies. The amount of waste a municipality will search a contract for is assumed to be the average of the amount of the past 3 years. Searching for contracts is assumed to be done by the municipality based on the available throughput of the companies.
Budget	To increase the budget of a Recycling Company it is assumed that an exogenous party buys the recyclable plastic for a fixed price.
Technology	The Technology is assumed to have a lifespan of 10 years.
Plastic	The fraction plastic from the total waste is assumed to be 30%
Spatial	A spatial representation is assumed to be redundant for this model and will therefore not be taken into account

3

Formal Design

3.1. Initialization of agent

As described in Chapter 2 there are three agent classes in our system. All those classes are child classes from Mesa's generic Agent class.

3.1.1. Households

The most important behaviour of the households is the generation of waste. The waste function that is used to design the base waste is given in the assignment description and can be seen in Equation 3.1. In the equation, the t represents the time step and n is the number of persons in a household.

$$Basewaste = (40 - 0.04 * t - \text{exp}(-0.01t) * \text{sin}\,(0.3t)) * n \tag{3.1}$$

To create a more heterogeneous distribution of the waste production for different households, a random uniform distribution is used that provides a range that is respectively -5% or +5% of the base waste.

From the total amount of waste, there will be a certain part that is plastic waste, the assumption was 30% as mentioned in Section 2.6. However, that is not the only factor influencing the quantity of plastic that is separated, as mentioned in Section 2.2 the households have a certain perception and that will influence the fraction of which they actually separate. The perception is drawn from a uniform distribution, with a range that differs per household based on the assumptions made.

$$Perception = U(\alpha, \beta) \tag{3.2}$$

What is left is not necessarily all useful and recyclable plastic. That fraction depends on the knowledge of people. The knowledge is just as the perception drawn from a normal distribution with a range based on the household type.

$$Knowledge = U(\alpha, \beta) \tag{3.3}$$

3.1.2. Recycling companies

The recycling companies process the waste of the households. They first collect waste, process that waste, make a profit out of the waste and upgrade their technology. The technology has a large impact in this process. To upgrade a technology a company will:

- Look if they have a sufficient budget to upgrade a technology
- If that is the case look at the current age of a technology
- Decide if a technology needs an upgrade based on a Bernoulli distribution with the probability being the current age over the ultimate lifetime.

- If the company decides to upgrade, their technology get an increase in version, an increase in throughput of 10% and an increase in the percentage of separation it reaches according to Equation 3.4 (v is the version and p_0 is the base percentage)

$$p_{upgrade} = \frac{v}{\frac{1}{1-p_0}\sqrt{v^2+1}} + p_0 \tag{3.4}$$

- If the recycling company upgrades, the budget goes down with the cost of the upgrade and the lifetime will go to zero again.

To do the upgrades a company needs to have enough budget first. In order to get the required budget, they make money by selling the recyclable plastic:

- First the company checks the total amount of waste that is produced by the contracted municipalities that year.
- If the total amount of waste is within the throughput that their technology can deliver, they sell the plastic to an exogenous buyer and that money will be added to their budget.
- If the total amount of waste that year exceeds the possible throughput, they can sell the plastic up to the throughput limit and the rest will get burned and will also not be counted as recycled.

3.1.3. Municipalities

In the benchmark model without policies, municipalities have one main activity that contains the search for new contracts every three years. This goes as follows:

- Municipalities keep track of the waste that is being produced every year.
- Then every three years they search for a contract that can handle the average waste production of the past three years.
- They check all the companies if there is enough throughput left to handle the proposed waste production.
- If no company has throughput left, municipalities choose randomly between all companies.
- Lastly they assign them and the company they choose a contract to keep track of which company gets which municipalities' waste.

3.1.4. Time

For keeping track of the time, the Mesa Time module is used throughout the model. A stopping condition is implemented in the model that stops time at t=240, since the time step is one month and the modelling period is twenty years.

3.2. Policies

In the experimentation four different policies are implemented. A policy can be either turned off or on in our system, it is implemented as a boolean in python. Once a policy is turned on, it works from the first step and is expected to be on during the whole run.

3.2.1. Perception and Knowledge

The policy that targets on increasing the perception is modelled as a factor multiplied by the initial perception. Below, the corresponding Equation 3.5 is shown.

$$P = P + U(\alpha, \beta) \tag{3.5}$$

In this formula, P stands for perception and the alpha and beta value depend on the type of household. A uniform distribution is chosen since there will always be people that are not reached by the policy, but the majority is.
The formula of the knowledge policy is the same, except that it does not differ per type of household, since we assumed that all household types are equally capable of processing knowledge.

3.2.2. Subsidies

The last policy that is implemented is the subsidy to upgrade the technology for recycling companies. This is implemented as a drop in the price that a company pays in order to upgrade their technology. This is modelled to be municipality specific, so a company only has right on a subsidy if municipality they are in contract with has the policy turned on. For the sake of clarity this is always the same for all municipalities in the experimentation. However, it can be considered an option for further experiments.

3.3. Parameters

In Table 3.1 the parameters that are used in the current setup of the model are shown.

Table 3.1: Overview of the parameters

Parameter	Value	Reasoning
Perception range	Single: (0.4, 0.6) Couple: (0.5, 0.7) Family: (0.4, 0.7) Retired Single/Couple: (0.2, 0.5)	Assumption made to get a noticable difference per type
Knowledge range	Single: (0.4, 0.6) Couple: (0.5, 0.7) Family: (0.3, 0.6) Retired Single/Couple: (0.2, 0.5)	Assumption made to get a noticable difference per type
Household Distribution	[Single, Couple, Family, Retired Couple, Retired Single] Rotterdam: [42, 8, 20, 1, 29] Schiedam: [36, 7, 15, 24, 18] Vlaardingen: [30, 9, 42, 7, 12]	(AlleCijfers, 2021; CBS, 2021) Adjusted to get a better differentiation per type.
Plastic Percentage	30%	
Technology Lifetime	10 years	Assumption that seemed reasonable
Technology Initial Percentage	50%	Assumption made to make the effect of upgrades more clear and effective

3.4. Interface of the visualization

The visualization part of the model shows the municipalities with black grid cells on the interface. The size of the municipalities is tuned to their number of inhabitants. It is possible that cities clump together in a run, this has no influence on the output. A selection of households is placed in their municipality. Their color displays the knowledge of the households. The darker the color, the more knowledge they have. The recycling companies are presented by a grey dot. Their size grows according to the percentage of filtered plastic waste. Underneath the visualization there is a graph that shows the fraction of recycled plastic per city per step. The policies used in the run can be adjusted by the sliders at the left top corner. The interface of the model is shown in Figure 3.1

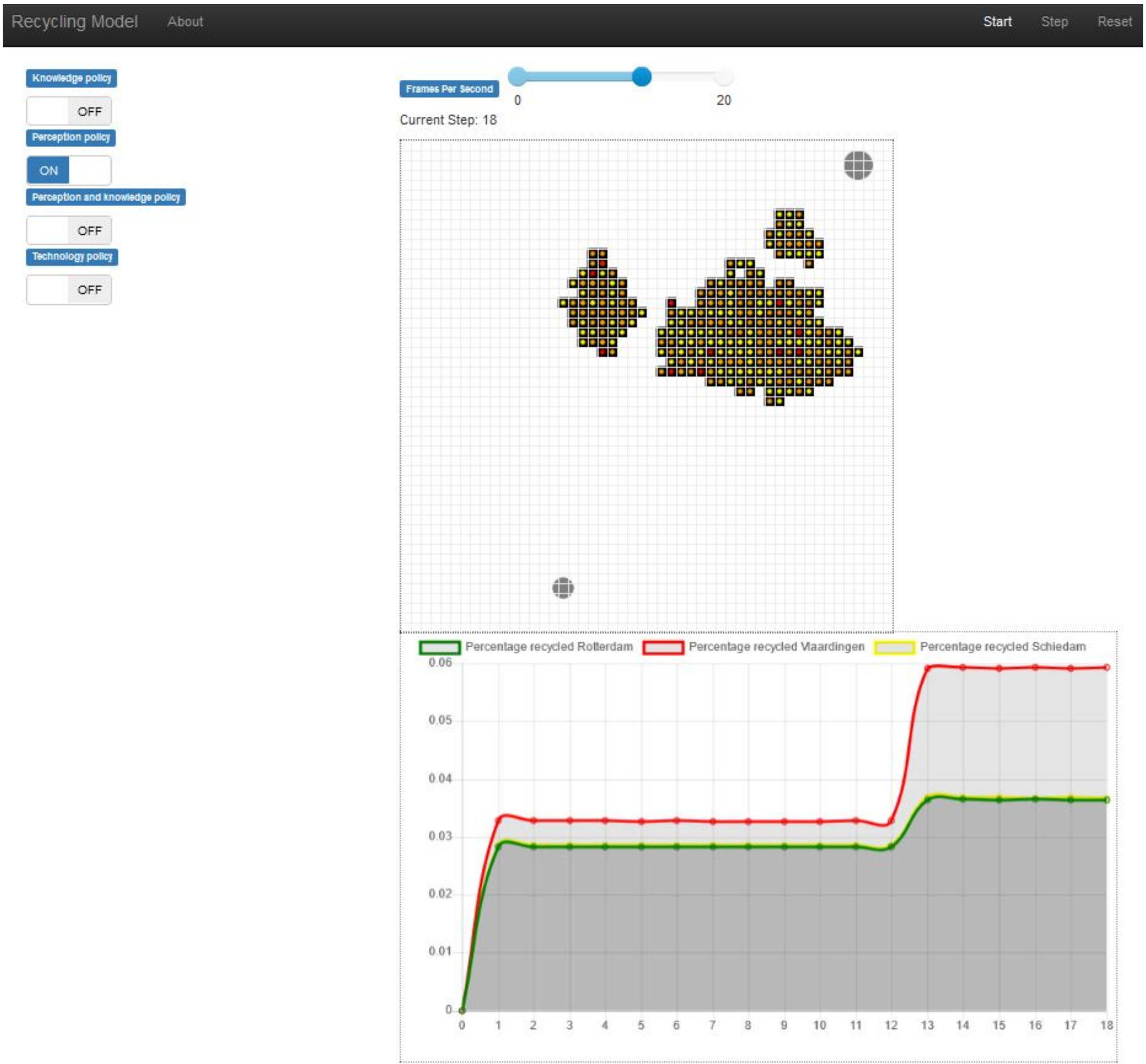


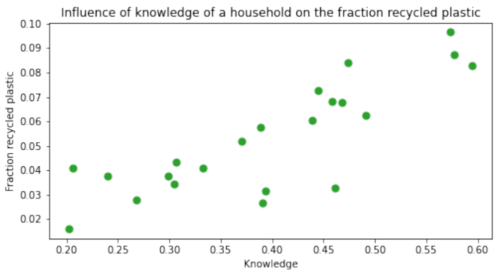
Figure 3.1: Interface of the model

4

Verification and Validation

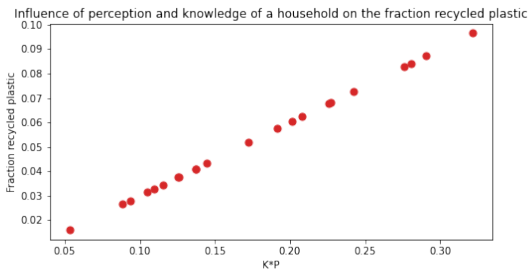
4.1. Verification

In this section is analyzed whether or conceptual model is translated correctly into the computational model. This is checked by running and printing some parameters. It was observed that waste was carried over from households to municipality. The households were checked if they got appended to the right municipality in the same way. The next step was single agent testing. In this experiment the influence of knowledge and perception per household was analyzed. For one single run all the agents were tracked. In the graphs in Figure 4.1 the results are shown.



(a) Influence of knowledge on the fraction of recycled plastic

(b) Influence of perception on the fraction of recycled plastic



(c) Influence of perception and knowledge combined on the fraction of recycled plastic

Figure 4.1: Single agent verification

Another check provided is the interaction between household en municipalities. In order to determine whether the municipalities are collecting the waste from the municipalities over time, a graph of one single run with waste collection over time per municipality is created. The outcome is shown in Figure 4.2.

These checks work up to say something about the model's fitness for purpose. It can be concluded that the agents are behaving in line with the expectations. The interaction also seems to give the expected results. The model is bug-free and can be used for experimentation.

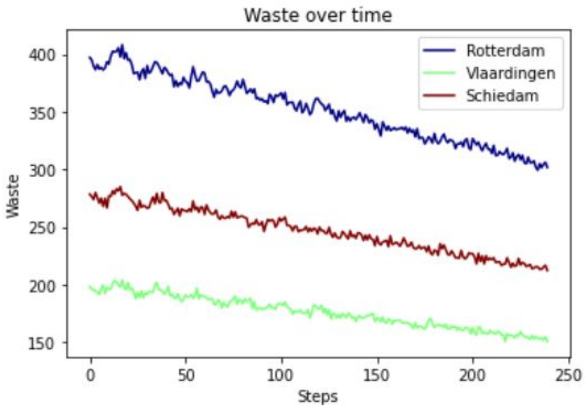


Figure 4.2: Waste per city

4.2. Validation

The goal of the model was to gain insight into the system of waste collection and relevant policy instruments. The behavior of the model is mostly based on assumptions, which makes an empirical validation difficult. Thus, to extract outcomes to reality, more real-time data should be implemented in the model. However, the model outcomes are in line with the expectations. As we can see for example in figure Figure 4.2, a larger city creates more waste than a smaller city. Therefore, the model can be used for research purposes.

4.2.1. Iterations

To define the number of iterations that is needed in our experiments, we constructed the convergence plot that it shown in Figure 4.3. It can be seen that after approximately fifty iterations, the moving average is stable. Therefore, we determined the number of repetitions to be 50.

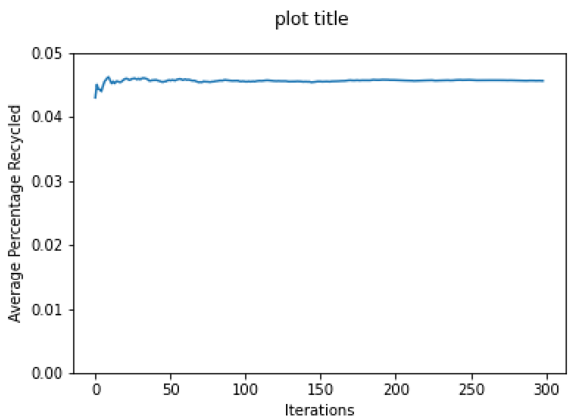
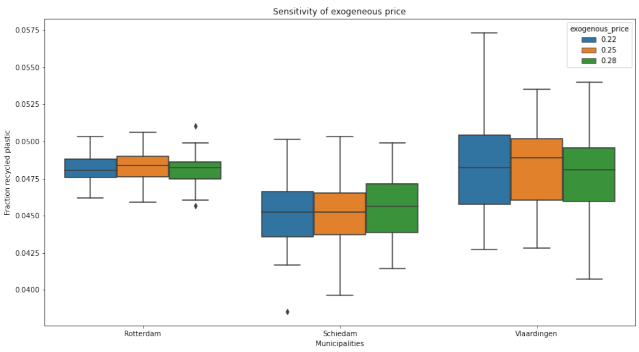


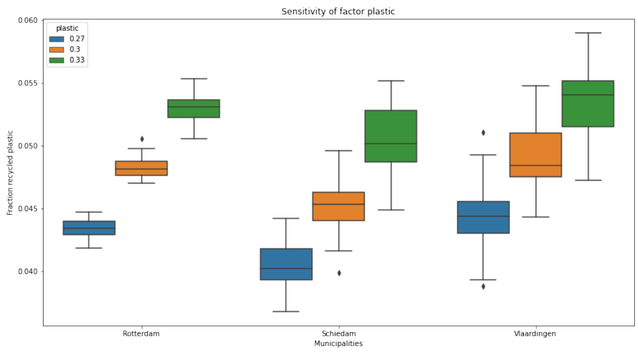
Figure 4.3: Convergence

4.3. Sensitivity analysis

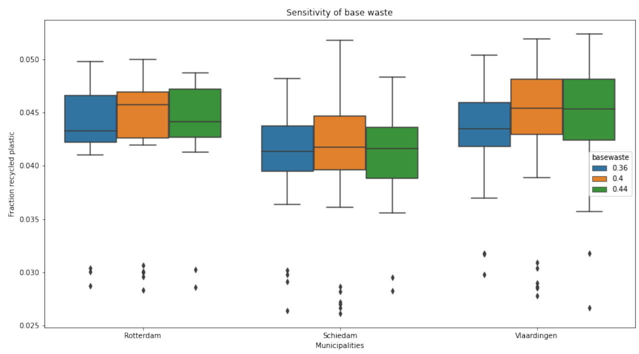
In order to tell something about the uncertainties in our model, a sensitivity analysis is provided. In this experiment 5 parameters are changed by -10 percent, 0 percent and +10 percent, over 50 runs each. The effect on the fraction of recycled plastic is measured. The results in Figure 4.4 show that exogenous price and the base waste have the least impact on the KPI. The factor of plastic in the waste and the perception and knowledge of the households have a bigger impact. Although the impact is still not much bigger than a percentage point. This means the model is not sensitive to these set of chosen parameters. The base case is robust to this particular set of parameters.



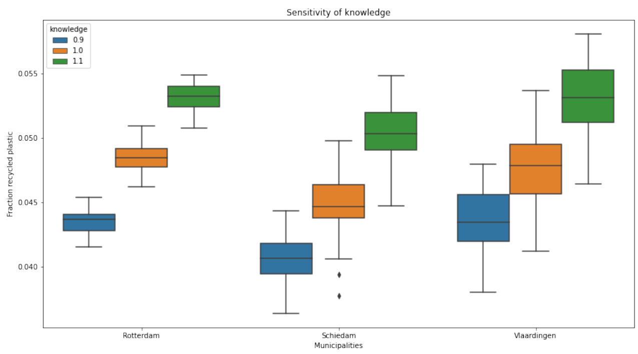
(a) Sensitivity of exogenous price



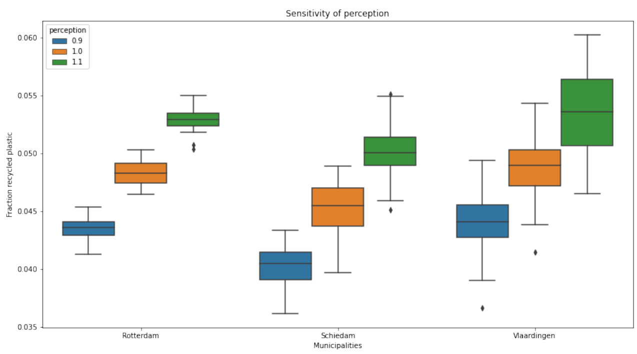
(b) Sensitivity of factor plastic



(c) Sensitivity of base waste



(d) Sensitivity of knowledge



(e) Sensitivity of perception

Figure 4.4: Sensitivity analysis

4.4. Extreme conditions test

To test whether the model is resistant to extreme values, another test is provided. In this check the values for the number of households, municipalities, companies and the budget are either set relatively low or high. The number of households was multiplied by a factor 0.1 in the minimum case and by a factor 3 in the high case. The results are shown in the box plot in Figure 4.5 It can be concluded that the spread of the KPI fraction of recycled plastic decreases when the number of households increases. This is makes sense, because more people means that the results of one run be more towards the average. In this case, there was no problem with too many households for the system to collapse. If you set the number of households even higher the model becomes really slow, so this is a pitfall of the model. It is unclear yet if the results with more households are still trustworthy.

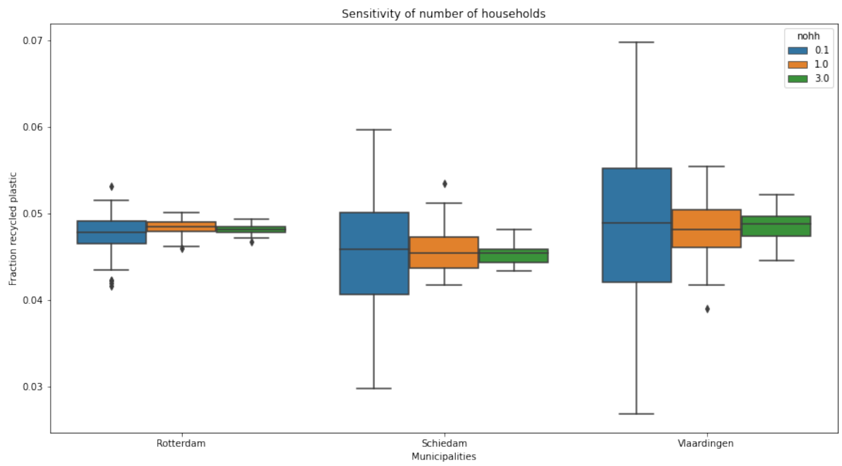


Figure 4.5: Extreme value test number of households

Nextly, the number of recycling companies are measured on their effect on the outcome. These outcomes are shown in Figure 4.6 There is not much difference in 1, 2 or 5 operative recycling companies.

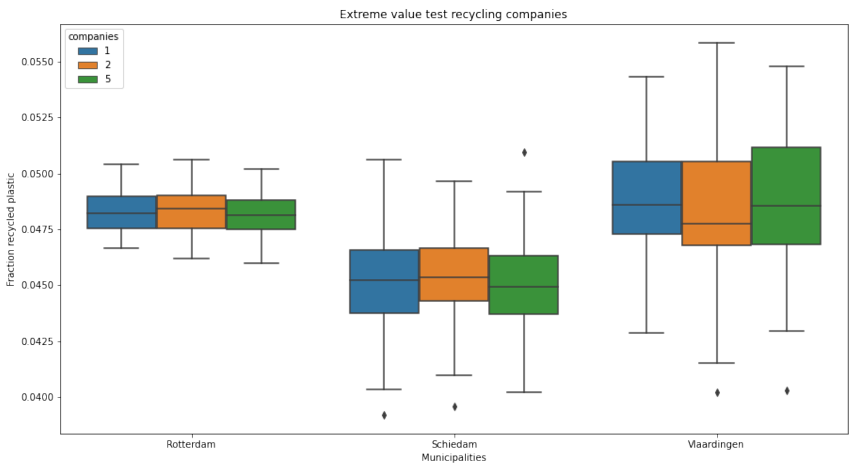


Figure 4.6: Extreme value test recycling companies

The number of municipalities is varied between 1, 3 and 5. The effects of the change are shown in Figure 4.7 Since not all the municipalities are used in the runs with 1 municipality, Rotterdam is used as benchmark. Rotterdam is used in every run. There is a really small drop in fraction when more municipalities are in in the model, but the effect is not significant enough to conclude something.

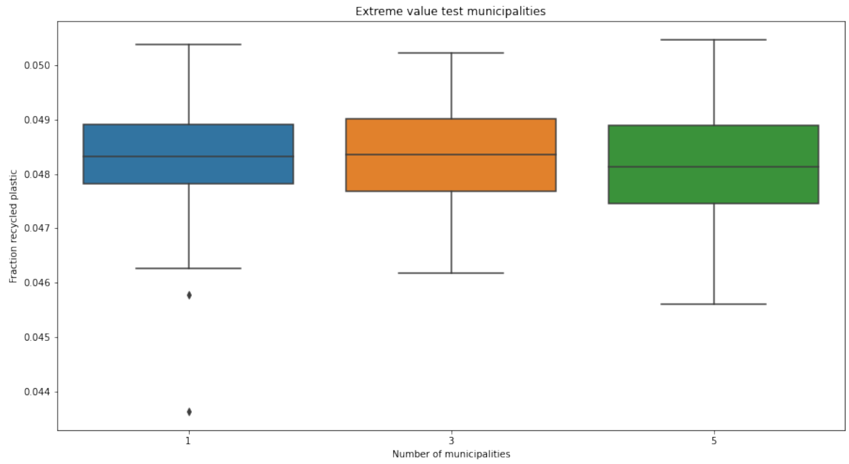


Figure 4.7: Extreme value test municipalities

In the last extreme value test the budget was multiplied by either a factor 0.1 or 10. In the Figure 4.8 it can be seen that the budget has a very small effect on the fraction of recycled plastic. This is in line with the expectation. The outcome makes a small impact. For all of the provided tests the model gives no strange behaviour, and is largely in line with the expectations.

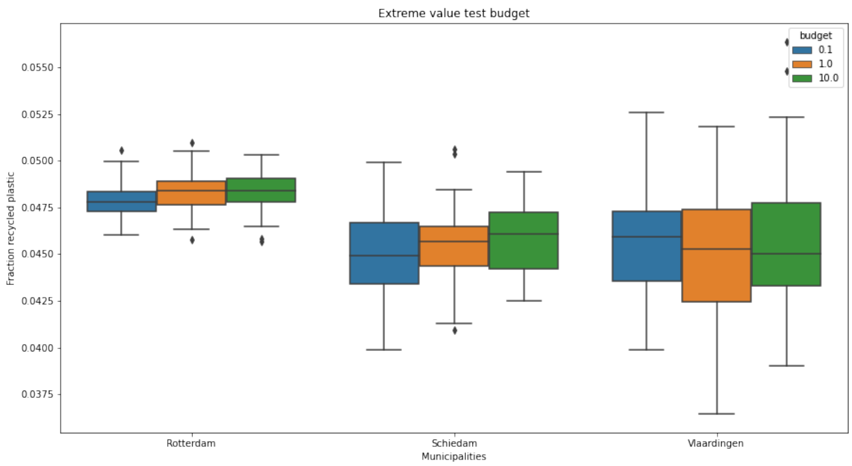


Figure 4.8: Extreme value test budget

5 Analysis

In this section, the experiments are conducted to answer the main research question mentioned in Section 1.3. To formulate an answer to this question, five experiments are performed, those are described in the experimental setup. Afterwards, the experiments are performed and analysed with python to generate meaningful insights.

5.1. Experimental design

In the analysis, five experiments will be executed containing a benchmark situation without policies and four different experiments for the implementation of the policies. In Table 5.1 the values for the parameters in the experiments are shown.

Table 5.1: Policy table

	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5
Experiment 1	Off	Off	Off	Off	Off
Experiment 2	Off	On	Off	Off	Off
Experiment 3	Off	Off	On	Off	Off
Experiment 4	Off	Off	Off	On	Off
Experiment 5	Off	Off	Off	Off	On

5.2. Analysis

In this section, the experiments are performed and analysed using the seaborn and matplotlib packages in python.

5.2.1. Quantitative results

Figure 5.1 illustrates the impact that the different policies have on the percentage of plastic that is recycled. For the bar plot, the mean of the 50 iterations is taken. It can be seen that policy 4, in which the recycling companies receive subsidies to invest in new technology has a marginal impact on the percentage. Policy 1, in which there is targeted at the knowledge causes an average increase of one percentage point in the percentage of recycled plastic. The policy in which there is targeted at perception, policy 2, has an even larger impact and can raise the percentage by two percentage points. The combination of the latter in policy 3 provides the most favourable results. It can be seen in the bar plot that the change in the percentage for policy 3 relative to the benchmark, no policy, is approximately the same as the sum of the change in policy 1 and policy 2. From this we can conclude that no emergent behaviour occurs when introducing the policies together.

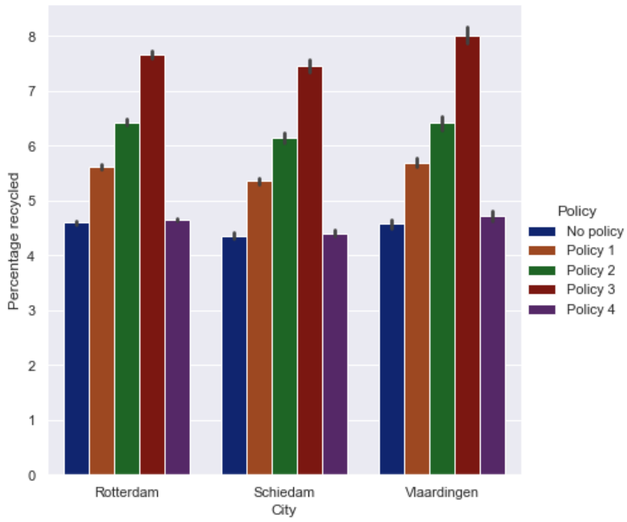


Figure 5.1: Comparison policies per city

5.2.2. Spread of results

Figure 5.2 shows the distribution of the outcomes in the different iterations. It can be seen that the spread of the outcomes is relatively small. Especially in Rotterdam, there are few outliers and the interquartile range is small. Rotterdam is the biggest city in our model, that contains the largest number of households and therefore it makes sense that outliers in households caused by randomness in the model are leveled out as the mean of the households is taken per run. Furthermore, it seems like the policies are a bit more effective for the city Vlaardingen than for the other cities. This might be the result of the high percentage of families in Vlaardingen, but since the difference is small it is hard to draw conclusions based on this. Besides this fact, the results for the different cities are relatively similar, despite the difference in demographics.

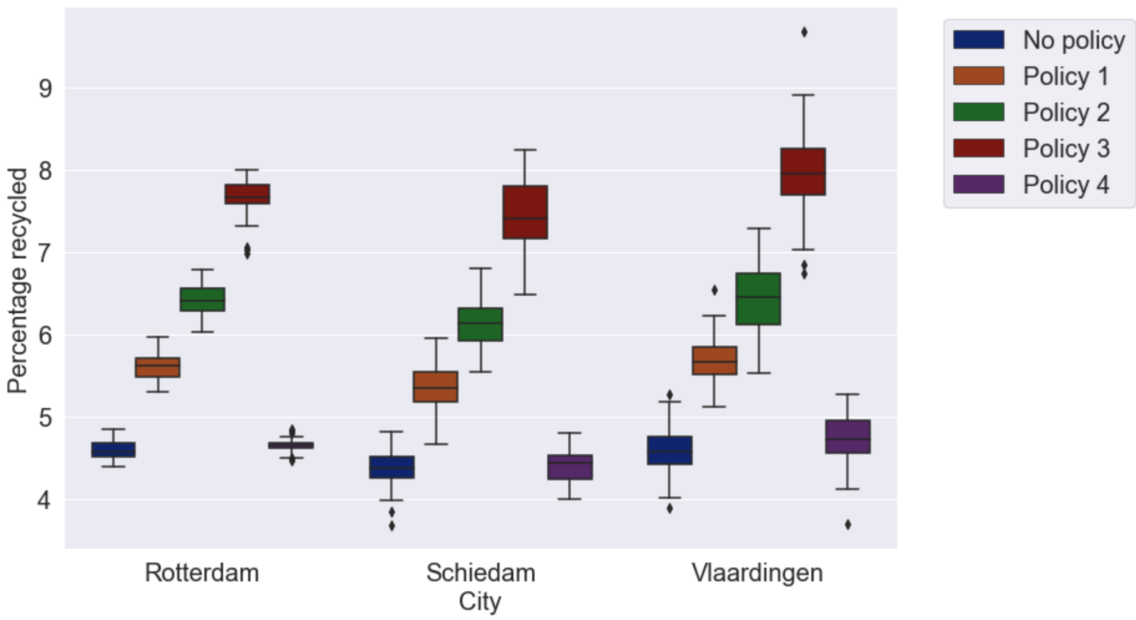


Figure 5.2: Boxplots policies per city

5.2.3. Conclusion of results

Based on the experiments, it can be concluded that the policy aimed at changing recycling behaviour of the households are the most effective. It has been seen that implementing a policy that provides subsidies to recycling companies does only result in a marginal change in the percentage of recycled plastic. Both the policies targeted at enhancing the knowledge and perception of households do produce significantly higher percentages of recycled plastic. In particular the policy that causes higher perception produces positive outcomes. The policy in which perception and knowledge are targeted at the same time performs the best, but not better than the sum of both. Furthermore, it can be concluded that the results are relatively the same for the three different cities. However, the spread of the outcomes for Rotterdam is substantially smaller than the other two cities, this is due to the fact that the mean of all the households has been taken to measure the outcomes and since Rotterdam has more households, this will level out the outliers. Despite the unique demographics per city, no large differences were distinguished between the effectiveness of the policies on the different cities.

6 Conclusion

6.1. Discussion

Within this research, it is aimed to simulate behaviour of humans when it comes to the recycling of plastic. As stated in Chapter 2, all models are wrong and this applies to our model as well. Therefore, the goal of the project was to create a model that is fit for its purpose, namely drawing conclusions about the impact of different recycling policies on the recycling system. Based on the verification and validation, we could state that the model that is created is fit for purpose. However, there are limitations to our model that should be addressed before drawing conclusions. Firstly, there have been made many assumptions about the behaviour of households when it comes to perception and knowledge. The initial knowledge and perception and the change in perception or knowledge are quantified based on our own expectations. For both factors, a uniform distribution between households is assumed, which is unfounded. Furthermore, to simulate the behaviour of the recycling companies in a more realistic way, a profit motive or a competitive element between the recycling companies should be added. Another addition to the model that would be valuable is the interaction between the households. In the current model, households do not affect each other with their recycling behaviour, where we expect that in real life there is interference between the households in this respect. The conclusions that are stated in the next section should be read with the limitations in mind.

6.2. Conclusion

The severity of the consequences that are caused by the consumption of plastic is increasing (Heidbreder et al., 2019). Although a large proportion of plastic is recyclable nowadays, the actual percentage of plastic that is recycled lags behind (Shen & Worrell, 2014). In this research, it is tried to capture the human behaviour that underlies the recycling process. This is done by the construction of an ABM model that simulates recycling behaviour on a municipal level. The research question that is addressed is the following:

> *"What are the trade-offs in the policy space of the municipalities if they wish to achieve the highest possible recycling rates?"*

In the system, three types of agents are present that interact with each other; households, recycling companies and municipalities. The households create waste, of which a certain part is plastic. Based on their perception and knowledge they separate a part of this plastic. This plastic is processed by the recycling companies that are able to reach a certain throughput, depending on their technology. The municipalities are able to affect the behaviour of the households and recycling companies by implementing policies. The first category of policies targeted on increasing the knowledge and the perception of the households in their municipality. The second category provides subsidies to the municipalities to stimulate investments in technology.

In the verification it is found that the behaviour of the agents is in line with the conceptual model, this was checked by tracking single agents and comparing their behaviour with expectations that raised from the conceptual model. Since the model was largely build upon assumptions due to restrictions in time and resources it was difficult to validate the model with real time data. The relations between the size of a city and the produced waste was validated and the model showed reasonable behaviour. The sensitivity analysis showed that the model is relatively insensitive to five important parameters. There is a change in model outcomes, but although significant, the change is relatively small. In the extreme conditions test the model showed robustness for the four tested variables. No model pitfalls could be observed in the tests.

The experiments showed that policies targeted at the perception and knowledge of the households resulted in the largest increase in the percentage of plastic that is recycled. The policy that increased the perception of households turned out to be the most effective of the two. Combining the policy for perception and knowledge generates the best results comparing to the other policies, but not better than the sum of both policies. Enacting a policy that offers subsidies to recycling companies only lead to a minor increase in the percentage of recycled plastic. Furthermore, it can be stated that the outcomes for the three cities are relatively similar. The dispersion of the outcomes in Rotterdam, on the other hand, is far lower than in the other two cities. This is because the outcomes were measured using the mean of all the households, and because Rotterdam has more households, the outliers were leveled off. Despite the fact that each city has its own demographics, there were no significant disparities in the effectiveness of the policies in each city.

6.3. Further recommendations

To gain more understanding about the effectiveness of policies targeted at the recycling of plastic, further research is required. It would be necessary to conduct further investigation in the actual perception and knowledge that households have and how this affects the system. In addition, it would be interesting to see whether the system changes whenever a competitive element is added for the recycling companies. Also, results of this research indicate that there are no large differences in the effectiveness of different policies in different types of cities with other demographic characteristics. Further research could look into whether the policies do have different impacts on the types of households in the system. Furthermore, current policies include executing campaigns and subsidies. Further research could concentrate on the effectiveness of legal instruments.

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