Plastic Recycling from Household Waste

The trade-offs to achieve the highest possible recycling rates

SEN1211: Agent-based Modelling
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Preface

This report is written as final project to complete the course 'Agent-based Modelling' as an elective for the master program 'Engineering and Policy Analysis'. The following research is done to learn about agent-based modelling. The structure of the report is according to the model development cycle. The software 'Netlogo' is used for the agent-based model and the software 'R' is used for the data analysis.

Content

1. Problem Formulation and Actor Identification

The problem, the problem owner and the research question are formulated in section 1.1, also the different actors that are interesting for this problem are mentioned. Furthermore, in section 1.2, certain modelling questions are presented that can be used to answer the main research question.

1.1 Goal- and Problem Formulation

The goal of this research is to gain insight into the different ways municipalities can manage plastic waste recycling. This report is written for the government of The Netherlands. In The Netherlands, plastic waste management and recycling is currently not organized by the national government, but it is a municipalities' own responsibility (Rijksoverheid, n.d.). However, there is a *national* recycling target and since the government has to keep an overview over the whole country, it is important for them to know if plastic waste management and recycling is working this way or if changes need to be made.

Seven municipalities with different sizes and population densities are taken into account - Amsterdam, Rotterdam, The Hague, Delft, Emmen, De Marne and Blaricum - which together form a good picture of The Netherlands, due to their different amount of households, surface and density. In the appendix the specifications of the different municipalities are given. There will be identified which combination of policies leads to municipalities meeting the recycling targets. This way, it will become clear if the government needs to push municipalities in making changes or if the government needs to set national guidelines.

The research question for this paper will be:

Does the current organization of plastic waste management and recycling in The Netherlands lead to the desired results or is it necessary to make (significant) changes?

Every municipality has a different amount and type of households. Since multiple types of Dutch municipalities are taken into account, this research can also be used for many different Dutch municipalities who want to improve their own waste management. Every household produces a certain amount of waste, of which a certain amount is plastic. These amounts differ per household and depend on the properties of the households. A municipality can choose to educate its population about plastic recycling, which can influence the fraction of plastic waste that is handed in and the recyclable fraction of the plastic waste. There are multiple recycling companies with which the municipality can conclude contracts, about how much waste is collected and what percentage of the plastic waste is recycled. A recycling company owns a certain technology, which makes them able to collect and process waste in a certain way. Technologies can become better over time.

1.2 Modelling Questions

To be able to give an answer to the research question, there are multiple sub-questions formulated. These sub-questions will be answered using agent-based modelling.

1. What are the effects of education on the knowledge of recycling, on the final recycling percentage?
2. What are the effects of education on the perception of importance of recycling, on the final recycling percentage?
3. Would a national campaign on the knowledge and importance of plastic recycling have effect?
4. Would an extra budget for the municipalities provided by the government, improve the performances of the municipalities on plastic waste recycling?
5. Does the collection infrastructure influence to what extent the national target is met?
6. What is the effect of the contract length on the amount of times the municipalities don't produce as much waste as stated in the contract?
7. What would be the effect of companies developing new technologies?

In chapter 2, the system of this problem and its boundaries will be identified. Secondly, in chapter 3, the variables in the system will be identified and shown in a schematic overview. Then in chapter 4, the actions performed by the different agents and the sequence of these actions are explained. Hereafter in chapter 5, the way the situation is modelled in the software Netlogo is presented. In chapter 6, the verification to check if the model is correct is shown. The experiments to answer the questions in 1.2 are shown in chapter 7, and the data evaluation of these experiments is shown in chapter 8. The validation - how true the model is - is shown in chapter 9 and lastly, the way the model has succeeded in answering the modeling questions is presented in chapter 10.

2. System Identification and Decomposition

In this step the system composition and boundaries are formulated. First of all, the system contains agents; the municipalities, the households within these municipalities and recycling companies. The system is analysed over 20 years and the plastic waste is collected every month. The contracts between the municipalities and recycling companies will last three years and when a recycling company wants to implement a new technology it will take one year. The growth or decline of waste production, the plastic fraction of the total waste, the amount of plastic handed in and how much of that can be recycled will be taken into account. Furthermore, the ability of new technologies to recycle plastic waste is also taken into account. The system will be further specified by the earlier mentioned agents:

Municipalities have a specific amount of households, which are divided over different types of households. The amount of different types of households per municipality is calculated using the population distributions of the municipalities. Municipalities also get a target to meet from the government which says how much of the plastic waste should be recycled. Furthermore, the municipalities have a limited budget for plastic recycling. Besides that, they organise activities for incentivizing and/or educating households about plastic recycling, in terms of more recycling and/or better recycling. For the collection of waste, they have a specific collection infrastructure and a provider of this collection infrastructure. The municipalities have one collection contract with a recycling company at a time (mentioned later). These contracts have a fixed and homogeneous length, which is set on three years. Moreover, the contracts have a fine if not a sufficient amount of plastic is presented to the recycling companies. The municipalities request offers and implement recycling services. They choose the cheapest offer that comes closest to the required recycling percentage and has an acceptable fine, but the contract must cover all plastic waste volumes. When the promised plastic waste volume targets are not met, they pay a fine per missing ton to the recycling company, which is specified in the contract.

Households are of a certain type. They can be an individual, a couple, a family or a retired couple (retired individuals are not taken into account). Households create different volumes and qualities of plastic streams. A family creates the highest volume of base waste, then a couple, then an individual and then a retired couple. Besides that, households have a yearly decreasing base waste production. This base waste is the general household waste and there is a fraction of recyclable plastic in this. A fraction of the base waste is plastic and some fraction of that is handed in, this depends partly on the infrastructure of the municipality. A fraction of collected plastic can be recycled based on the separation technology of the companies. The households have a perception of the importance of plastic recycling. When a household finds plastic recycling important, the fraction of plastic waste handed in from the total plastic waste is higher. The households also have knowledge on how to recycle plastic. When a household has more knowledge the recyclable fraction in the plastic waste handed in is higher. They are affected by information provided from the municipalities on the need to recycle and the ways how to recycle. Furthermore, households have access to specific recycling systems, which means they have access to a collection infrastructure or not. The collection infrastructure is decided by the municipality. The amount of plastic collected when there is a collection infrastructure is higher than the amount of plastic collected centralized (when households have to bring the plastic waste to a central point themselves).

Recycling companies have a specific recycling technology. The companies create offers to municipalities to process their waste. A recycling company can have more than one contract, but has a maximum capacity of waste that can be collected and processed. This is either collection at home or central point collection. They also specify a fine for not getting enough plastic waste. The companies collect the waste and also process it based on the technology they own. The recovered plastics are sold for profit, based on exogenous prices. The waste that cannot be recycled is burned for energy recovery and does not bring any money. Furthermore, the companies have the option to invest in new technologies. A new technology can either have a better ability to separate or a better ability to separate plus a larger throughput volume.

3. Concept Formalization

Now that the boundaries of the system are set and the different aspects of the system are mentioned, the next step is to formalise the conceptualisation. This is necessary, because the identified concepts may be context dependent and might not be specific enough to be understood by a computer. This can be also called an ‘ontology’ and will be presented in this chapter (Dam, Nicolic & Lukszo, 2012). Firstly, the global variables (3.1) and agents (3.2) will be listed with their coherent attributes. After this, a visualisation of the global variables, the agents and their attributes is shown to get a clearer overview (3.3). Only the variables and attributes that are essential are mentioned. Thus, derived variables or attributes, when they are solely used to help generate other, more important variables, are not mentioned. Furthermore, some variables require extra explanation which is available in the appendix. This is noted by a **(number)**, where the number refers to a number in the list of assumptions and default parameter settings.

3.1 Global Variables

- Contracts (object): list within a list **(9)**
    - has a fine (euros - int >= 0) **(10)**
    - has an amount of waste to collect (ton - int >= 0)
      Dependent on the technology
    - has a minimum percentage that can be recycled of the plastic waste stream (% - int >= 0)
      Dependent on the technology
    - has certain costs (point scale)
      Dependent on the technology
    - has a contract length (years - int = 3)
- Waste streams (object): ton - int >= 0
    - has a total weight (ton - int >= 0)
    - has a fraction of recyclable plastic in total weight (% - int >= 0)
- Government policy on ‘waste fund’ pricing (environment): list **(1)**
    - has a price per ton recycled plastic (euros - int >= 0)
- Availability of new technology (environment): binary - available or not available

3.2 Agents

Municipalities have:

- Specific amount of households (int >= 0) **(3, 5)**
- Distribution of the types of households (int per type of household >= 0) **(3, 4)**
- Surface of the municipality (int > 0) **(5)**
- Total amount of waste (ton - int)
- Recycling percentage targets given by government (% - int >= 0) **(2)**
- Collection infrastructure (decentralized or centralized - binary) **(4)**
- Budget (10 points), see paragraph: distribution budget point system
  Costs for technology-level (point scale 1 - 3)
  Payment infrastructure (2 or 4 points) **(21)**
  Investment in incentivizing (half of the budget that is left)

Investment in knowledge (other half of the budget that is left)

- Contract that covers all waste (list) **<u>(8)</u>**

  See details contract under global variables

<u>Distribution budget point system</u>

There is chosen to divide the budget of the municipality according to a point system, beneficial to keeping the budget in proportion to the municipality size. So, for example, if Amsterdam spends part of their budget on incentivizing their inhabitants, it costs more than the money Emmen has to spend to reach the same targets. By working with the point system these monetary values are standardized and can be used equally for each municipality. Every municipality will get 10 points to divide over the costs for the contract (dependent on technology level), the costs for the infrastructure that is provided by an external party (a decentralized system is more expensive than a centralized system: 4 points versus 2 points) and the investment in incentivizing and knowledge. The fine a municipality has to pay to the company when not enough plastic waste is delivered, is separate and will be paid monthly.

Households have:

- Type (list)
- Base waste production (ton - int >= 0) **<u>(17)</u>**
- Share of plastic waste (% - int >= 0)
- Share of plastic waste handed in (*importance*) (% - int >= 0) **<u>(6)</u>**
- Share of plastic waste handed in that is recyclable (*knowledge*) (% - int >= 0) **<u>(7)</u>**
- Access to recycle system (decentralized or centralized - binary)

  Dependent on the municipality **<u>(4)</u>**

Recycling companies have:

- Recycling technologies (object): list
  - has a maximum weight per month (ton - int >= 0)
  - has a recycling percentage of the total recyclable plastic waste (% - int >= 0)
  - has certain costs (point scale)

  <u>Can create a new technology:</u>
  - has a building time (years - int = 1)
  - has a better ability to separate (% - int > 0)

    Costs for investment will be distracted of the earnings
  - (and sometimes) has a larger throughput volume (ton - int > 0)

    Costs for investment will be distracted of the earnings
- Contract(s) (list)

  See details contract under global variables
- Price (% - int) **<u>(14)</u>**
- Earnings of recycled plastic (euros - int >= 0)
- Earnings of fines (euros - int >= 0)
- Total earnings (euros - int >= 0)

3.3 Schematic Overview of the Formalization

In figure 1, the different agents - households, municipalities, recycle companies -, the most important agents attributes - waste stream and technology -, the globals which determine the environment and the links made between municipalities and recycle companies -contracts- are shown. This is an overview where only the most important variables and relations are shown, but it gives a good overview of the main processes in the model.

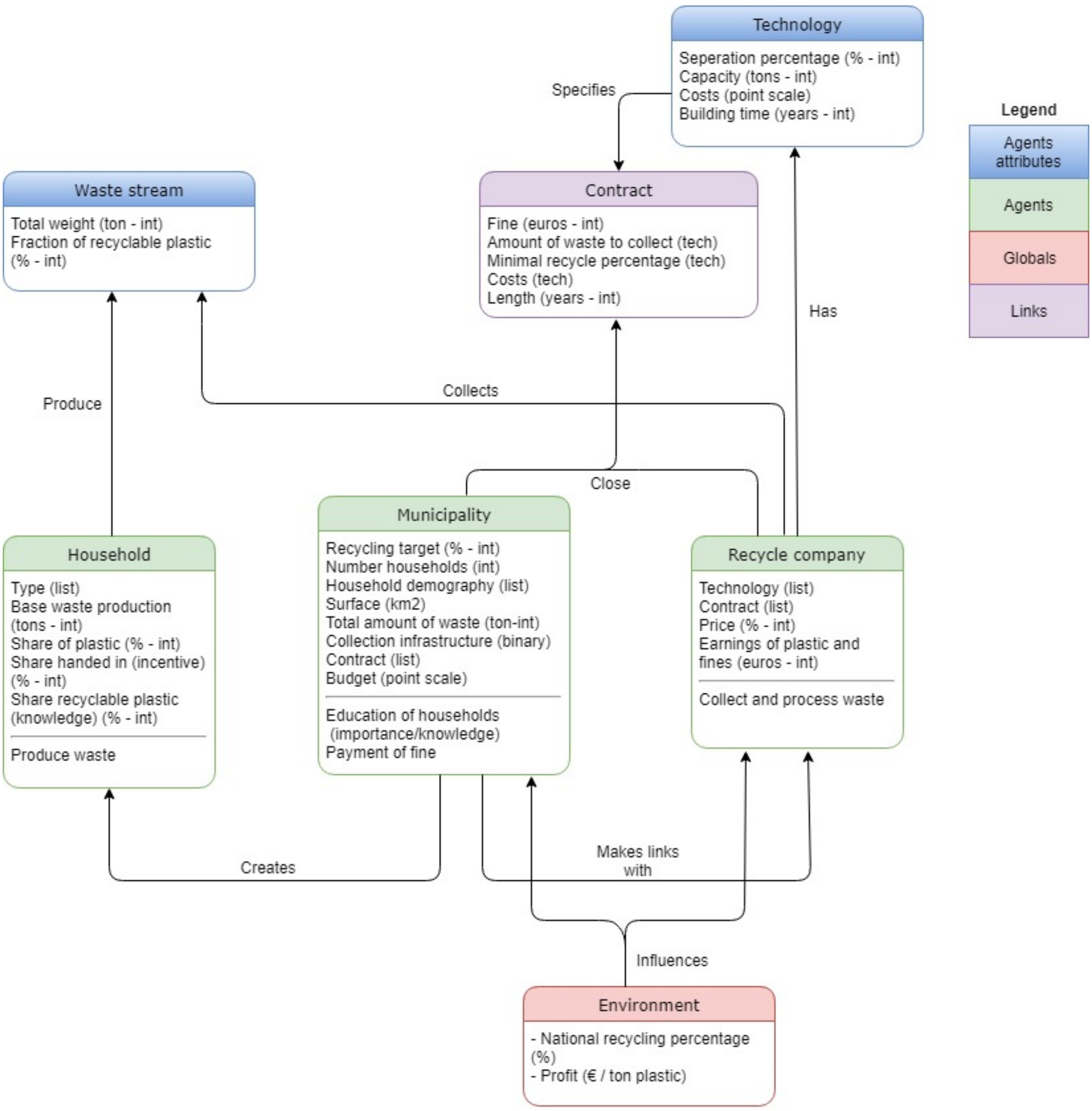


Figure 1. Formal overview of the agents, their attributes, the globals and the links between them.

4. Model Formalization

Now it is clarified 'who' and 'what' the model consists of, there will be described who does what and when. In other words, it is important to make a story of what happens in the model, in order to use this model narrative for a comprehensive translation into Netlogo. In section

4.1 a creation of a model narrative is shown. This means that the different actions of the different agents in order are presented. This clarifies the the relation with the global variables. Furthermore, when a **(number)** is placed behind a variable or attribute there is a further explanation in the appendix.

An action sequence table is shown in section 4.2 to make the different actions and interaction between agents clear. After creating a narrative it is possible to translate this behavior in a more precise algorithmic representation. This can be done using pseudo-code, this forms a bridge between the informal model narrative and the actual code used in Netlogo. In the pseudo-code mathematical and logical descriptions of the behaviour of the agents to combine the model narrative and the formalised concepts (Dam, Nicolic & Lukszo, 2012). Using the narrative for modelling in Netlogo was sufficient, so only some small parts are written in pseudocode and not used in the report.

4.1 Developing a Model Narrative

The actions done by agents are listed underneath in order of performance. The actions that are underlined are the actions that happen in the 'set-up phase'. The other actions are executed in the 'main procedure'.

Municipalities do:

- Specify the amount of households
    - The amount of households for the certain municipality (CBS, 2017)
- Specify the surface
    - The surface is the amount of km2 for the certain municipality **(5)**
- Specify the household-type distribution
    - The amount of households is divided over the four types of households (family, couple, single, old), which depends on the certain municipality (CBS, 2017) **(3,4)**
- Create the households in the municipality
    - Make sure enough of each type of the household agents are created within the municipality
- Set initial recycling percentage targets
    - Percentage given by the government , which grows by 0.25% every year and is the same for each municipality **(2)**
- Specify the infrastructure of the municipality
    - Amount of central points = surface of the municipality / amount of central points per km2 (centralpoint ratio is initially set on 1 point per km2) **(5)**
    - Households/central point = number of households / amount of central points
    - When households/central point < 1500 the municipality choses a decentralized system. **(5)**
    - When households/central point >= 1500 the municipality choses a centralized system. **(5)**
- 1. Setting the amount of plastic waste from the households

- Total amount of plastic from one municipality = sum all the plastic waste streams of the households (added to the stream from the previous weeks)

- 2. Setting the amount of recyclable plastic waste from the households
    - Total amount of recyclable plastic from one municipality = sum of all the recyclable plastic waste of the households (added to the stream from previous weeks)
- 3. Check the balance between amount of plastic handed in and the amount of plastic stated in the contract
    - When a month past (= 4 ticks)
    - Balance = total amount of plastic from one municipality - amount stated in contract
- 4. Pay fines to company
    - When a month past (= 4 ticks)
    - If balance < 0
    - Amount to pay = the fine as specified in the contract * absolute balance
- 5. Estimation of the monthly amount of plastic handed in that has to be covered in the contract
    - When three years past (= 3*52 ticks)
    - Requested waste volume collection in contract = is the total amount of expected plastic from one municipality
- 6. Rank the municipalities on requested waste volume collection in contract
    - When three years past (= 3*52 ticks)
    - Municipality with highest requested plastic waste volume collection in contract can choose a company/contract first **(16)**
- 7. Pick a contract (per municipality sequential according to the rank)
    - When three years past (= 3*52 ticks)
    - Checks if capacity of company >= requested waste of municipality (one month)
    - Select two companies with the best technology.
    - If multiple companies are available, close contract with company that proposes the lowest fine **(27)**

- 8. Check budget left (from 10 points)
    - Lower budget with contract costs (- 1 / 2 / 3 points)
    - If centralized infrastructure - 2 points
    - If decentralized infrastructure - 4 points
    - Define points left out of 10
    - Decides about the investment in importance (divide points left equally)
    - Decides about the investment in knowledge (divide points left equally)

Households do:

- Specify the type of household
    - Select between family, couple, single or old (dependent on the municipality)
- Set initial share of plastic waste

- base waste * percentage plastic from base waste: 6.8% (Milieucentraal, n.d.).
- Set initial share of plastic waste handed in
  - Dependent if the municipality is decentralized (60%) or centralized (40%) **(9)**
- Set initial share of plastic waste handed in that is recyclable
  - Random percentage between 40% - 60% **(10)**
- 1. Produce an amount of base waste per week (x is the current month)
  - Base waste (x) = household-specific (%) * (40 - 0.04 * x – exp(-0.01 * x) * sin(0.3 * x)) **(7, 17)**
- 2. Generate a certain plastic waste stream
  - Plastic waste stream = base waste * percentage plastic from base waste * share of plastic waste handed in
  - If plastic waste stream > amount stated in contract, then:
  - Set extra waste = plastic waste stream - amount stated in contract (added to the previous total extra waste)
  - Set plastic waste stream = amount stated in contract
- 3. Learn from incentivizing activities
  - When a month past (= 4 ticks) **(15)**
  - When a municipality invested in incentivizing activities
  - Increase of the share of plastic waste handed in (1% point per point per 3 year, so 1/39 % points per month) **(18)**
- 4. Learn from knowledge activities
  - When a month past (= 4 ticks) **(15)**
  - When a municipality invested in knowledge activities
  - Increase of the share of plastic waste handed in that is recyclable (1% point per point per 3 year, so 1/39 % points per month) **(18)**

Companies do:

- Specify a technology
  - Which specifies the maximum weight per month, i.e. the maximum capacity of this company (for low capacity: 10%* total plastic production by the municipalities, for medium capacity: 25% total, for high capacity: 50%* total) **(19)**
  - Which specifies if the company has a high/middle/low level of technology
  - Which specifies the recycling percentage of the total recyclable plastic waste (for high: random int between 85% - 95%, for middle: random int between 75% - 85%, for low: random int between 65% - 75%) **(20)**
- Set the expensiveness of a company (expensive/average/cheap)
  - Level 1: Recycle percentage low, capacity low = cheap (1 point)
  - Level 2: Recycle percentage middle, capacity middle = average (2 points)
  - Level 3: Recycle percentage high, capacity high = expensive (3 points)
- 1. Collect waste of municipalities
  - When a month past (= 4 ticks)
  - When there is/are contract(s)

- Total plastic waste collected by the company = sum of total amount of plastic from municipalities where the company has a contract with.

- 2. Setting the amount of plastic waste to 0 of the municipality (because it is collected)
  - When a month past (= 4 ticks)
- 3. Process the waste
  - When a month past (= 4 ticks)
  - Recycled waste by the company = amount of plastic produced by connected municipalities * the recycling percentage of the total recyclable plastic waste of the company * the knowledge of the municipality
- 4. Check earnings plastic
  - When a month past (= 4 ticks)
  - Earnings plastic = earnings plastic so far + (amount of recycled plastic * government policy on 'waste fund' pricing = €788,-/ton)
- 5. Check earnings fines
  - When a month past (= 4 ticks)
  - If balance with one or more municipalities < 0
  - Earnings fines = earnings fines so far + (the fine specified in the contract * absolute balance)
- 6. Offer (new) contracts
  - In the same tick, if three years past (= 3*52 ticks)
  - When the maximum capacity is not yet reached (capacity left > 0), propose new contract to next municipality in list
  - Capacity left = maximum weight per month - specified weight in concluded contract (requested waste)
  - Fine per missing ton (specific per contract) = government policy on 'waste fund' pricing per ton * price of the company (the price of the company is a number between 0.7 and 1 that specifies if it is cheap, medium or expensive) **(14)**
- 7. Investment in new technology
  - When 5 years have past (= 5*52) **(22)**
  - If the earnings are bigger than 0.4 times the average earnings: small investment **(23)**
  - Waiting one year before investment can be implemented (= 52 ticks) **(25)**
  - Increase the technology level with 0.5, increase the separation technology percentage random between 5 - 10% and increase the price random between 1 - 5% **(26)**
  - Set the earnings * 5/6 **(26)**

  or
  - If the earnings are bigger than 0.6 times the average earnings: large investment **(24)**
  - Waiting one year before investment can be implemented (= 52 ticks) **(25)**
  - Increase the technology level with 1, increase the separation technology percentage random between 5 - 10%, increase the price

random between 5 - 10% and increase the capacity random between 1/3, 2/3 or 1 times the current capacity **(26)**

- Set the earnings * 4/6 **(26)**

4.2 Action sequence table

Now the actions are defined and it is clear in which order the actions happen for the agents itself it is useful to visualise in what sequence the actions happen taking all agents into account. This is done in a sequence table (Table 1), the numbers used in the table are related to the number in front of the actions in section 4.1. This table shows how the main procedure in Netlogo is structured. The action 7 from the municipality and action 6 from the company happen for the agents after each other. The municipalities are ranked and the one ranked first can pick a contract first. After a contract is picked the corresponding company has to change the capacity to the residual capacity. The other actions can happen for the agents that belong to the same breed at the same time. Furthermore, the actions that happen every three year will also happen right in the beginning after the set-up procedure, because the contracts are not formed in the set-up phase. Lastly, action 7 from the companies is not presented in the sequence table, because it does not happen standard every week, every month, every year or every three years.

Actors	Every week		Every month			Every year	Every three years			
Municipality		1,2		3,4			5,6	7*		8
Households	1,2					3,4				
Companies			1,2,3		4,5				6*	

*this actions happen per municipality/company after each other

Table 1. Sequence table.

5. Software Implementation

In this step the model is implemented in a modelling environment. The tool that is used for this is the software 'Netlogo'. This software is easy to use, mainly due to the easy programming syntax, and can still handle the complexity of the model specified in the previous steps. Underneath the sections 'how it works' (5.1) and 'how to use it' (5.2) under the 'info' tab in the Netlogo model are shown. The full model can be find in a separated file.

5.1 How It Works

The model code starts with a specification of all the global variables. After that three breeds, which are agents, are formed: municipalities, households and recycling companies. For the agents are 'turtles-own' variables specified. Then the set-up phase is coded, among other things the globals are set-up. For the agents this is done separately and corresponds with the underlined actions in chapter 4. Also a set-up of the technologies is done, here for example the price, recycling percentage and the capacity is specified. In the set-up a technology is assigned to a company.

In this model, seven Dutch municipalities are modelled, together with ten recycling companies. The different households of the municipalities produce waste, of which a certain part is plastic. A certain part of the plastic is handed in by the households. Municipalities close contracts with companies to collect their plastic waste. The goal of this model is to gain insight into the current market of plastic waste management, where the main output to evaluate is in terms of % recycled plastic of the handed in plastic waste.

In the main procedure there is a separation made in the weekly, monthly, yearly and three yearly actions as can be seen in the sequence table shown in chapter 4. Every week, which is one tick, the households produce waste. It depends on the type of household how much is produced. Every month the hand in plastic waste is collected by the companies at the municipalities they have a contract with. There is checked if the municipalities delivered enough plastic waste, as stated in their contract. If this is not the case, a process is started that the municipality has to pay a fine for the missing tons. Furthermore, the companies process the waste and get money for the recycled plastic from the government. In the end the company adds all the earnings from the fines and the recycled plastic, so the total earnings of the companies can be calculated. Yearly the households within the municipalities learn from the incentivizing and knowledge activities (if the municipality invested in this, which will be mentioned later). Every three years, old contracts are broken and new contracts are closed. First is defined which municipality can choose a company first. This is determined by the requested amount of plastic the municipality want to have collected. Then, following the order the municipalities can form contracts, is checked which companies have the capacity to collect the requested amount of plastic by the municipality. After that is checked if the technologies of those companies can meet the target set by the government taken into account the knowledge of plastic recycling the households have for the specific municipality. The two companies that match the best will be considered by the municipality. The company (one of the two) with the lowest fine is chosen and a contract is closed. Everytime a contract is closed the company lowers its remaining capacity with the requested amount of plastic stated by the municipality. Lastly, the municipality distributes the residual budget over investments in incentivizing and knowledge. This will happen for all the municipalities sequential. There is also a procedure included that makes sure the model stops running when twenty years passed.

In addition, the model includes the option of investment in technology by the recycling companies. When the companies have built up five years of earnings, they can check if their earnings are large enough to upgrade their technology, and if the maximum technology is not yet reached. An investment can be small, which means that only the separation technology (recycle percentage) improves, or large, which means that both the separation technology improves and the capacity becomes bigger.

5.2 How To Use It

1. Adjust the slider parameters (see below), or use the default settings.
2. Press the ‘setup’ button.
3. Press the ‘go’ button, the simulation will start.
4. Look at the monitors to see how the plastic waste collection develops over the years.

Parameters:

- Ability-to-invest; the default setting is set on ‘true’, which means that the companies have the option to invest in new technologies. It is also possible to choose to set this variable on ‘false’ and then the companies do not invest in new technologies.
- CP-ratio; the default setting is set on ‘1’, which means that there is 1 central collection point per km2. If this ratio is set low the infrastructure of the municipalities is more likely to be decentral and if the ratio is set high the infrastructure of the municipalities is more likely to be central.
- Contract-length; the default setting is set on ‘3’, which means that the contracts between the municipalities and the companies last for three year. The contract length can be set shorter.
- Initial-percentage-knowledge; the default setting is set on ‘40’, this means that all the households start with a knowledge percentage of 40%, which means that 40% of the handed-in plastic recyclable plastic is. The initial percentage knowledge can be set higher or lower.
- Initial-percentage-incentivizing; the default setting is set on ‘0’, this means that all the households start with an importance percentage of 40% for a centralized infrastructure and 60% for a decentralized structure (see appendix, point 4). The initial percentage incentivizing can be set higher or lower, this means the starting percentage of handed-in plastic increases or decreases.

There are a couple of monitors to show the development of the plastic waste collection over the years. First of all, four output variables are shown as monitors, which will be further explained in chapter 7. Also the current year and the national recycling target set by the government are shown in monitors. Furthermore, some different graphs are shown, like the earnings of the companies, the remaining capacity, the development of the base waste of the households, the amount of recycled plastic in total and per month, the level of the technologies and the development of education (knowledge and incentivizing).

The model stops when twenty years passed. When the year turns from 2038 to 2039 the model stops running.

6. Model Verification

To check whether the conceptualisation of the model is translated right in Netlogo it is important to verify the model. The values given to different variables in the set-up phase should be correct. The behaviour of the agents is observed while running the model to see if they (inter)act the way they are intended to act. All steps in the model are verified and underneath the most important and interesting ones are shown. While verifying some mistakes in the model were found and were immediately corrected.

- The seven chosen municipalities - Amsterdam, Rotterdam, Den Haag, Delft, Emmen, De Marne & Blaricum - should be included in the model. **Confirmed** (Represented in the visualization)
- The 7 municipalities should be located on the left-side, based on the code. **Confirmed**
- Every municipality should produce the right amount and type of households. **Confirmed**
- The different types of households should be recognizable by different shapes. **Confirmed**
- The collection infrastructure should influence the hand-in percentage. **Confirmed** (Checked with the inspection tool, decentralized infrastructure generates a lower initial hand-in percentage)
- The 10 companies should be located on the right-side, based on the code. **Confirmed**
- The three different technology options should have the correct capacity and recycle percentage. **Confirmed** (Checked with the inspection tool)
- Municipality-names should be shown if the switch ‘show-municipality-name?’ is turned on. **Confirmed**
- Amount of households per type should be shown if the switch ‘show-amount-households?’ is turned on. **Confirmed**
- Every 52 ticks (weeks) the year counter should count one extra year. **Confirmed** (1040 ticks for 20 years)
- The recycle target given by the government should increase by 0.25% every year. **Confirmed**
- Every type of household should produce the right amount of waste. **Confirmed** (Checked by hand)
- The plastic household waste (without the effect of the amount of plastic handed in) should decrease over time, because the formula for general household waste is a decreasing formula. **Confirmed** (Plotted)
- Waste should be collected every month. **Confirmed** (Plotted month production shows a drop to 0 ton every month)
- The model should run for 20 years. **Confirmed** (After 20 years a pop-up shows up with the message ‘20 years have past!’)
- Municipalities should close a contract with only one company. **Confirmed** (10 runs: in the interface a municipality never has more than one link, which represents a contract, to the companies)

- Companies can close a contract with one or multiple companies, but can also close no contracts at all. **Confirmed** (10 runs: in the interface a company has one, more or zero links that connects it to municipalities)
- Companies should not close contracts for a bigger waste volume than their capacity. **Confirmed** (10 contract bargains: remaining capacity of the company is always bigger than the requested waste of the municipality)
- Contract length should be 3 years. So after 3 years, municipalities should close new contracts. **Confirmed** (Each 156 ticks (= 3 years), the the links between municipalities and companies change and thus the contracts between them change).
- The municipality with the biggest expected amount of plastic handed in should choose a contract first. **Confirmed** (When asking to show the municipality-name of the choosing company, Amsterdam always comes first, followed by Rotterdam, The Hague, Emmen, Delft, De Marne and at last, Blaricum. This logically follows from the number of households per municipality, with Amsterdam having the largest amount of households.)
- Knowledge and incentivising should increase over time due to investments. **Confirmed**
- Investments in knowledge should lead to a higher percentage of recyclable plastic. **Confirmed** (Plotted)
- Investments in incentive should lead to a higher percentage of plastic handed in. **Confirmed** (Plotted)
- When there is at least 1 central point available for every 1500 households (following from the amount of central points per square kilometer), there is chosen to implement a central infrastructure to collect waste. **Confirmed** (Calculated by hand for each municipality)
- The earnings of the companies should be calculated justly. **Error: after 151 ticks, the earnings did not increase anymore. This was because some companies work for multiple municipalities that simultaneously ask them to update earnings . After restructuring this process (asking municipalities one by one), the earnings increased every month with the wanted amount. Solved**
- Municipalities should pay fines if necessary. **Confirmed** (Balance is checked with the rise of earning of municipalities' my-company)
- Month production should not be larger than the amount of recycled plastic. **Error: because of the fact that the points that were distributed to increasing knowledge and education, were not in converted to percentages, the recycled-plastic increased to quick. Solved**
- The sum of all technologies should never exceed 30. **Confirmed** (10 runs: sum plotted).
- The amount of produced waste of households should decrease. **Confirmed**
- The share of plastic recycled waste of the total plastic waste stream should increase due to investments in knowledge and technology. **Confirmed** (Recycled plastic waste / produced plastic waste increases)
- Amount of recycled waste should never exceed the amount of produced waste. **Error: because of the fact that the requested waste decreased every week, which should be each month. Solved**
- The capacity of companies can only increase, because of investments in technology. **Confirmed** (10 runs: plotted)

- The times that a company pays a fine has to be equal to the times that the balance between month production - requested production is negative. **Confirmed** (10 runs: compared)
- When target-not-met increases a point, a municipality's percentage of all plastic handed in * knowledge * the separation percentage of its company, should be lower than the national recycling percentage. **Confirmed** (10 runs)
- When the initial knowledge decreases, the amount of recycled plastic should also increase. **Confirmed** (10 runs: plotted)
- The waste production should start at week 1, and continue until the final tick. **Error: the waste production starts in week 4 due to no initial value of the production-equation that is updated after one month. Placed this equation in the setup-globals. Solved**
- The amount of recycled plastic per month can never be more than the amount of total plastic per month. **Error: with summing up the different values, imperfections occurred. For this reason, and because the experiment-output focus lies more on this, the cumulative values of production and recycling are put central in the comparison between both. Solved**

The whole code is verified. When errors occurred during the verification, the errors were solved and the verification on this specific part was executed again and the confirmation was given when no errors occurred anymore. Now the model is free of errors it is possible to use the model for generating different experimentations.

7. Experimentations

To be able to find out what variables have a significant impact on the outcome of the model, experimentations are conducted. There are input variables stated in chapter 3 and 4 which can be varied. Some of these variables will be varied in the experiments. It should be noted that the parameters that are not mentioned, stay in the default settings. The experiments are determined using the modelling questions stated in section 1.2. The questions are repeated underneath and after that the parameter settings are presented for the experiments. After that interesting output reporters are listed and explained. As last, the run length of the experiment is stated.

1. What are the effects of education on the knowledge of recycling, on the final recycling percentage?
2. What are the effects of education on the perception of importance of recycling, on the final recycling percentage?
3. Would a national campaign on the knowledge and importance of plastic recycling have effect?
4. Would an extra budget for the municipalities provided by the government, improve the performances of the municipalities on plastic waste recycling?
5. Does the collection infrastructure influence to what extent the national target is met?
6. What is the effect of the contract length on the amount of times the municipalities don't produce as much waste as stated in the contract?
7. What would be the effect of companies developing new technologies?

7.1 Parameter Settings

Experiments on budget, to answer questions 1, 2 and 3:

- Starting percentage of knowledge set on 20, 40 and 60 %
- Starting percentage of incentive set on -20, 0 and +20 %
- Budget of municipalities set on 10, 12 and 14 points

Experiments on infrastructure to answer questions 4:

- Centralpoint ratio (amount of central points per km2) is set on 0.5 (all municipalities have a decentralized infrastructure), 1 (default) and 500 (all municipalities have a centralized infrastructure)

Experiments on contracts and innovation to answer questions 6 and 7:

- Contract length set on 1 and 3 years
- Investments in technology set on true or false

7.2 Outputs Evaluated and Run Length

Underneath first the output variables that will be evaluated are listed and also the run length of the experiment is stated.

Output evaluated:

- Final recycled percentage of total plastic waste handed in (total amount of recycled plastic / total plastic waste handed)
- Number of times the target of the government is not met (counter per month per contract)
- Plastic waste companies could not process (total amount of not processed plastic handed in)
- Number of times a fine had to be paid (counter per month per contract)

One important output variable, interesting for the Dutch government, is the percentage recycled plastics of the total plastic waste. The Dutch government namely set a target for this and wants to evaluate if this target has potential to be reached (Rijksoverheid, n.d.). The second output variable correlates with the first one: it counts the number of times the target of the government is not met. This variable gives more insight in the performances of the municipalities over the 20 years. This is done to not only look at the end result over the 20 years. Thirdly, the amount of waste (kton) that could not be processed by the companies will be used as an output variable, because it is important for the government that all handed in plastic waste is collected. This is to prevent the country from getting spoiled with plastic waste. Furthermore, because it is interesting to know if there is more potential for the plastic market than currently used. Lastly, the number of times a fine had to be paid is evaluated. Per month is checked per contract if the municipality had to pay a fine. It is interesting to see if more investment in incentivizing will make sure enough plastic waste is handed in, even though the base waste volume is decreasing over the years.

Run length:

- 20 years (1 tick is 1 week, so 1040 ticks)

The instruction indicated that the research is done for the next 20 years and therefore also the experiments are carried out for the next 20 years.

8. Data Analysis

The data generated by the behavior space experiments carried out in 'Netlogo', as described in chapter 7, is analyzed using the software 'R'. In Netlogo, the six input variables mentioned in chapter 7 are varied over different values and from every combination 10 replications are made, which gives a total of 3240 runs. In a second experiment, the values of initial percentage of knowledge and the values of initial percentage of incentivizing have been varied in steps of 5% on the four output variables, which gives a total of 450 runs (5 replications). Due to limits of the capabilities of our processors, these two experiments are runned separately instead of as one big experiment.

From the first analysis on the end values of the output variables, it becomes clear the four output variables differ greatly with the different combinations of values of the input variables (see Figure 2). This shows a research to what combinations of policies (input variables) are possible is useful, since some combinations are clearly better than others.

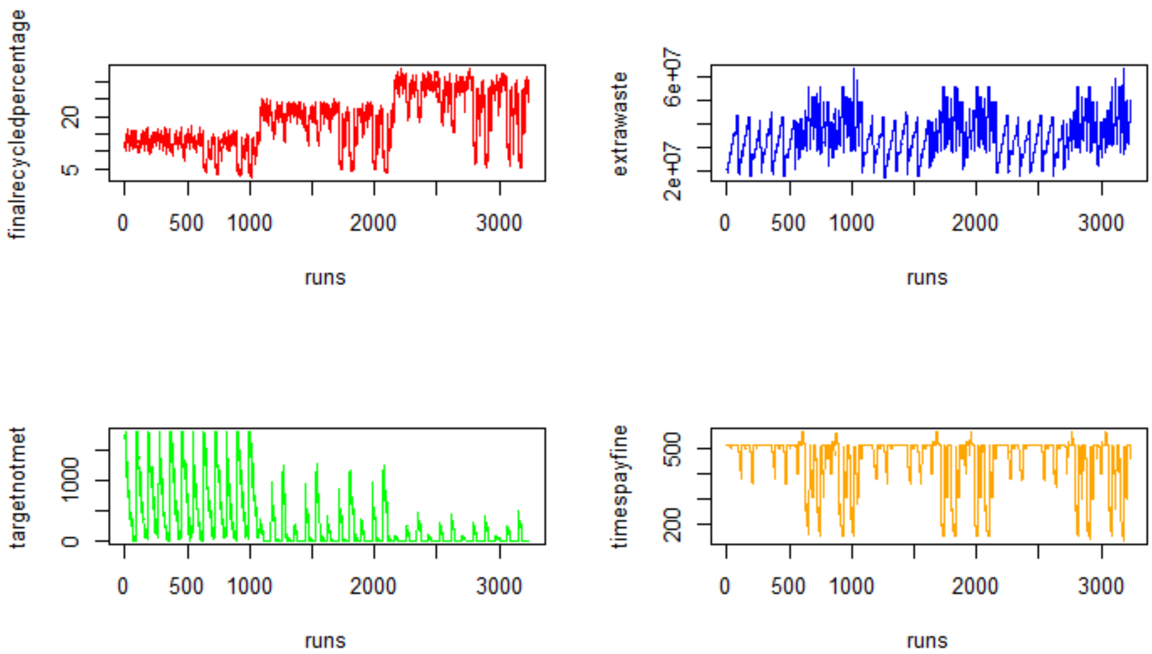


Figure 2. Output of the four output variables over the 3420 runs, only the value of the last tick considered.

In figure 3, the frequence table of the final recycled percentage is shown. Notable, is the fluctuation of the frequencies over the different percentages. What directly and indirectly causes this oscillating output to occur, is unclear at this point of the analysis. However, this diagram does imply that the recycle percentage is influenceable. Therefore, it is interesting to analyze how different parameters affect the recycled percentage. How does policy affect this level? Which governance would be most adequate? Before municipalities can take action to increase the percentage of plastic waste recycled, these knowledge gaps have to be cleared.

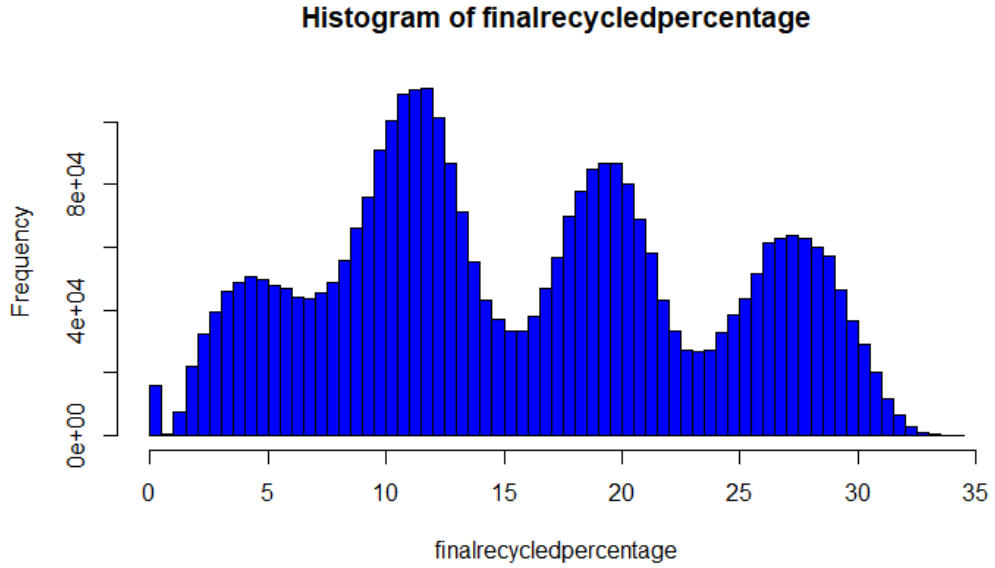


Figure 3. Frequence table of the final recycled percentage

The remarkably high frequency at 0 recycled percentage (Figure 3) originates from the first four weeks, where there is no waste collected yet, thus no waste is recycled.

1. **What are the effects of education on the knowledge of recycling, on the final recycling percentage?**

To be able to answer this research question, the results from the second experiment are analysed. In this experiment, the starting percentage of knowledge is varied from 20% - 60%, in steps of 5%. The output variable on which this input is evaluated, is the final recycled percentage (total amount of recycled plastic / total plastic waste handed). A boxplot is made where the different initial knowledge percentages and the final recycled percentages over the runs are plotted (Figure 4). From this analysis, it appears a higher initial percentage of knowledge leads to a higher final recycled percentage. The connection between these two percentages can easily be declared: if the knowledge is higher, the recyclable fraction of the plastic handed in is higher. This way, a higher percentage of the handed in plastics can be recycled by the companies.

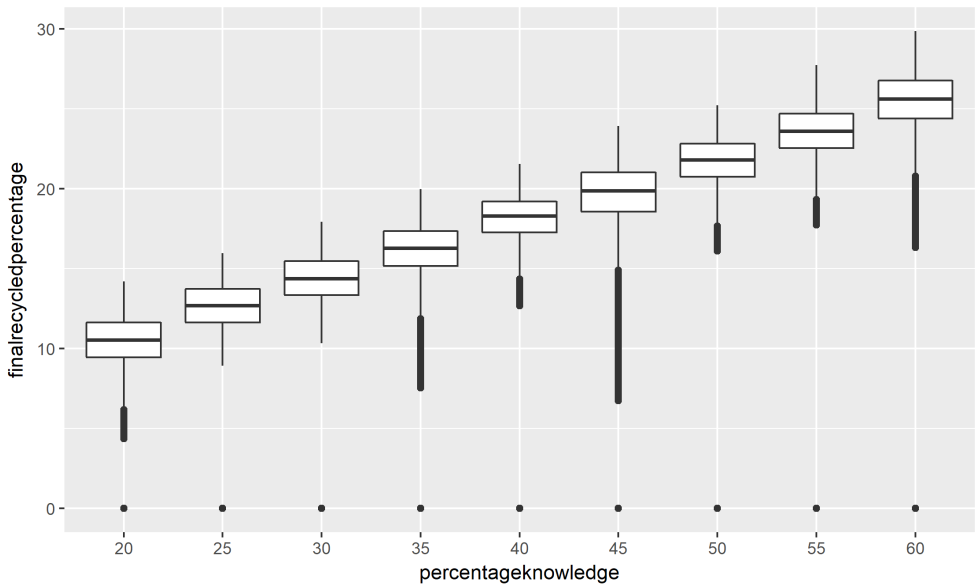


Figure 4. Boxplot of the influence of percentage of knowledge on the final recycled percentage.

The same analysis has been done with the output variable ‘target not met’ (Figure 5). From this analysis, it appears a low initial value for the percentage of knowledge leads to many municipalities not meeting the recycling target from the government. From an initial percentage of 35% and onwards, the most municipalities almost always meet the recycle target.

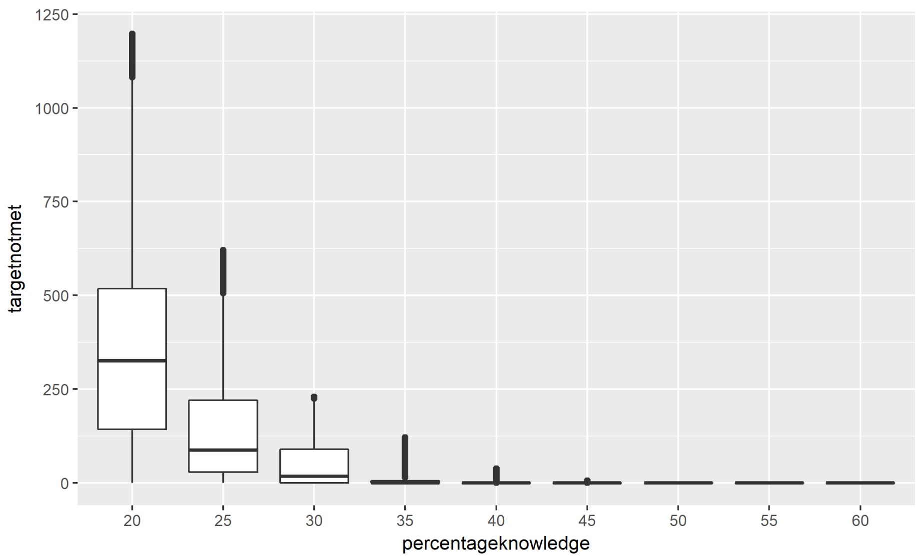


Figure 5. Boxplot of the influence of percentage of knowledge on the final recycled percentage.

2. **What are the effects of education on the perception of importance of recycling, on the final recycling percentage?**

To be able to answer the second research question, again the results from the second experiment are analysed. In this experiment, the value of initial percentage of incentivizing is varied from 0% - 20%, in steps of 5%. It should be noted that the incentivizing percentage influences the % of plastic handed in. The first output variable that is considered in this analysis is the final recycled percentage. A boxplot is made where for the different initial incentivizing percentages, the final recycled percentages over the runs are plotted (Figure

6). From this figure, it becomes clear the initial percentage of incentivizing barely influences the final recycled percentage. This can easily be declared by the way the final recycled percentage is defined, namely: total amount of recycled plastic / total plastic waste handed in. The percentage incentivizing influences the amount of plastic handed in. If more plastic is handed in, it appears the amount of recycled plastic increases almost proportionally, since the fraction (total amount of recycled plastic / total plastic waste handed) does not change.

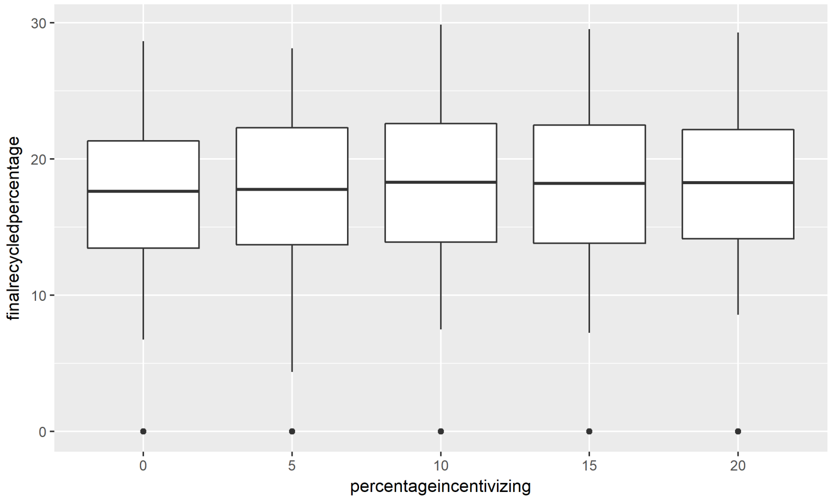


Figure 6. Boxplot of the influence of percentage of incentivizing on the final recycled percentage.

A second analysis is done to check if the initial percentage of incentivizing influences the amount of times the recycle target given by the government is not met. Just as for the first analysis for this modeling question, a boxplot has been made (Figure 7). From figure 7 it appears the median values for the times the target is not met are almost the same for the different values of initial percentage of incentivizing. In the generated data-set, it became visible the times the target is not met is often 0, so that declares the low median of this value. However, from the outliers visible in the boxplot, it appears if the initial percentage of incentivizing is 0%, the times the target is not met can be up to 1200, where if the initial percentage of incentivizing is 20%, the times the target is not met can be only up to 250. From this, the importance of a high initial percentage of incentivizing can be conducted: A low initial percentage of incentivizing can lead to the target not being met way more often than a high percentage.

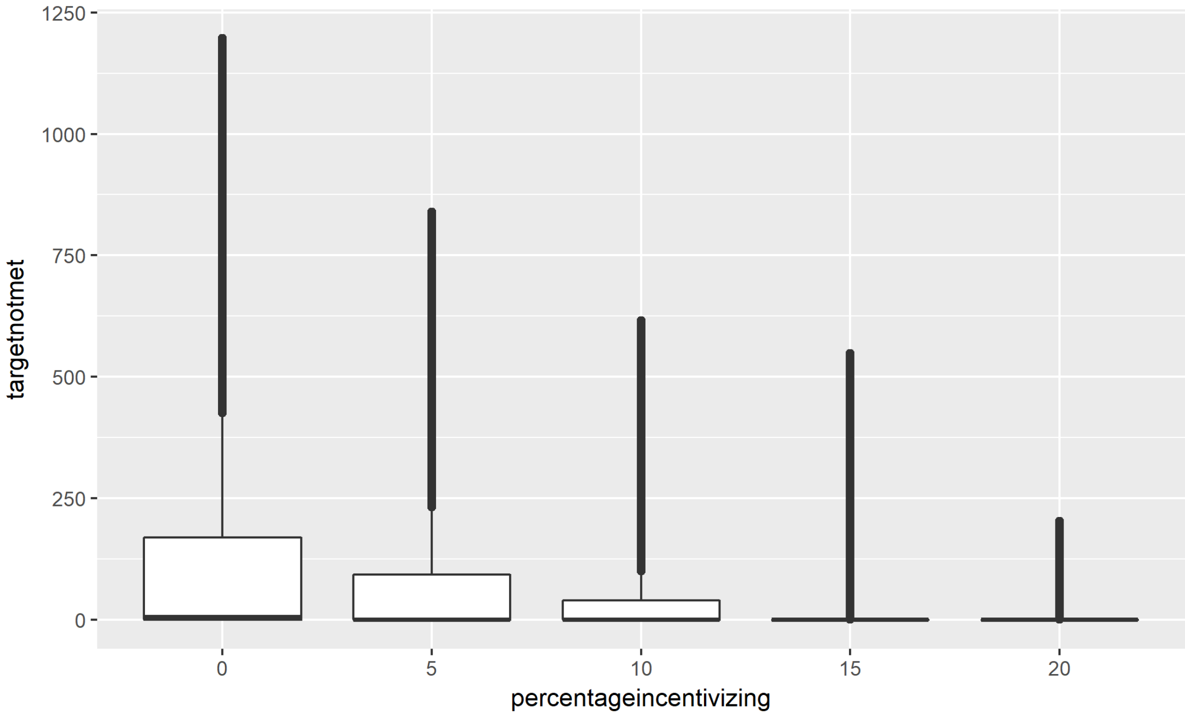


Figure 7. Boxplot of the influence of percentage of incentivizing on the amount of times the target is not met.

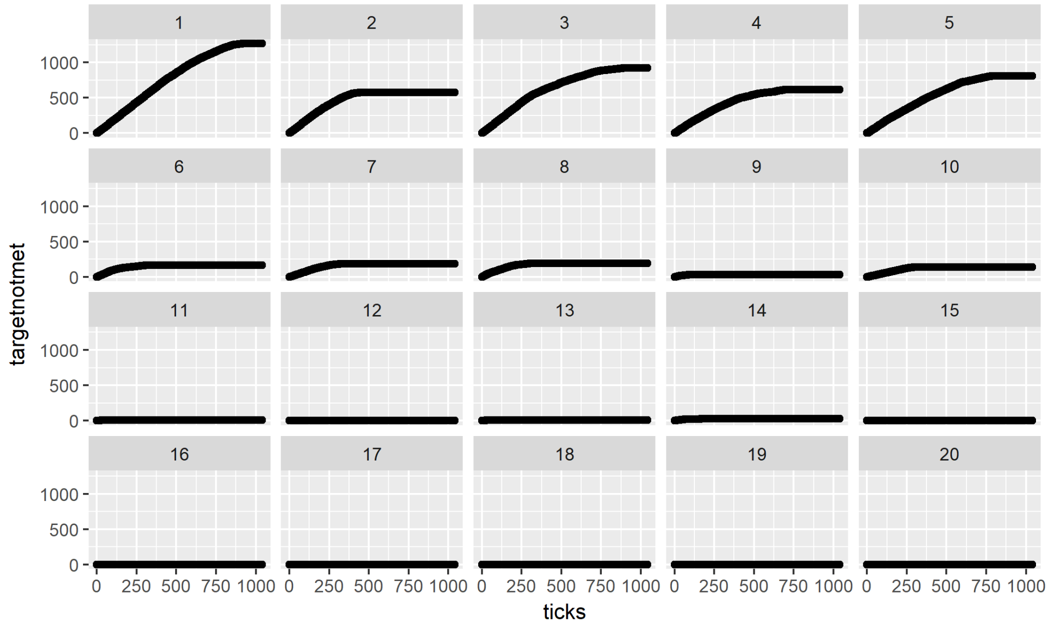
3. **Would a national campaign on the knowledge and importance of plastic recycling have effect?**

The analysis done to answer question 1 and 2 can be combined to form an answer to this modeling question. From the analysis on question 1, it appears a higher initial percentage of knowledge leads to a higher recycled percentage (Figure 4) and less times a municipality does not meet the government target (Figure 5). From this can be concluded that there is a positive link between knowledge and recycled percentage. A national campaign on knowledge, where the value of knowledge increases over the 20 years, will thus have a positive effect.

From the analysis on question 2, it appears a higher initial percentage of incentivizing does not lead to a higher recycled percentage (Figure 6). If the government wants to increase the recycled percentage (total amount of recycled plastic / total plastic waste handed), they should *not* educate on incentivizing. However, from another analysis done for question 2 (Figure 7), it appears a higher initial percentage of incentivizing does lead to less chance of municipalities having a high value for the amount of times the target is not met. This means there is a positive link between incentivizing and municipalities meeting the recycling targets. A national campaign on incentivizing, where the value of knowledge increases over the 20 years, will thus have a positive effect on the municipalities meeting the recycling targets.

To check if a *combination* of education on knowledge and incentivizing has effect, another analysis has been done, where these two variables are combined. The output variable used in this analysis is the amount of times the target is not met. The output is analysed over a run (per tick) (Figure 8), while in the earlier experiments the value at the end of the run was used. This way, the influence of these variables over 20 years is shown. From the analysis, it appears a low percentage of knowledge (20%) and a low percentage of incentivizing (0%)

leads to many municipalities not meeting their targets, while a high percentage of knowledge (40%) and a high percentage of incentivizing (20%) lead to no municipalities not meeting their targets during the 20 years. So an education on both incentivizing and knowledge will, according to the model results, lead to almost no municipalities not meeting the recycling target, which is what the government wants. Thus it is advisory to, if there is enough budget, educate the whole country on incentive and knowledge of plastic recycling.



Row	Initial percentage knowledge	Initial percentage incentivizing
1	20%	0%
2	20%	20%
3	40%	0%
4	40%	20%

Figure 8. Influence of knowledge and incentivizing on the amount of times the target is not met, over a run (per tick)

4. **Would an extra budget for the municipalities provided by the government, improve the performances of the municipalities on plastic waste recycling?**

By having an extra amount of money to invest in education and knowledge, it is possible that the recycled percentage of plastic waste is influenced. Figure 9 shows how, for a specific initial knowledge level, the final recycle percentage changes for different extra budgets. Looking at extra budgets of 0, 2 and 4 points, it can be stated that the extreme values of final percentage recycled are not influenced. However, the values in between become more diffuse when the extra budget increases. With no absolute increase of decrease of the final recycle percentage, it is needed to look at the median within a boxplot to give conclusions on the effect of a increase of extra budget for a specific initial knowledge level.

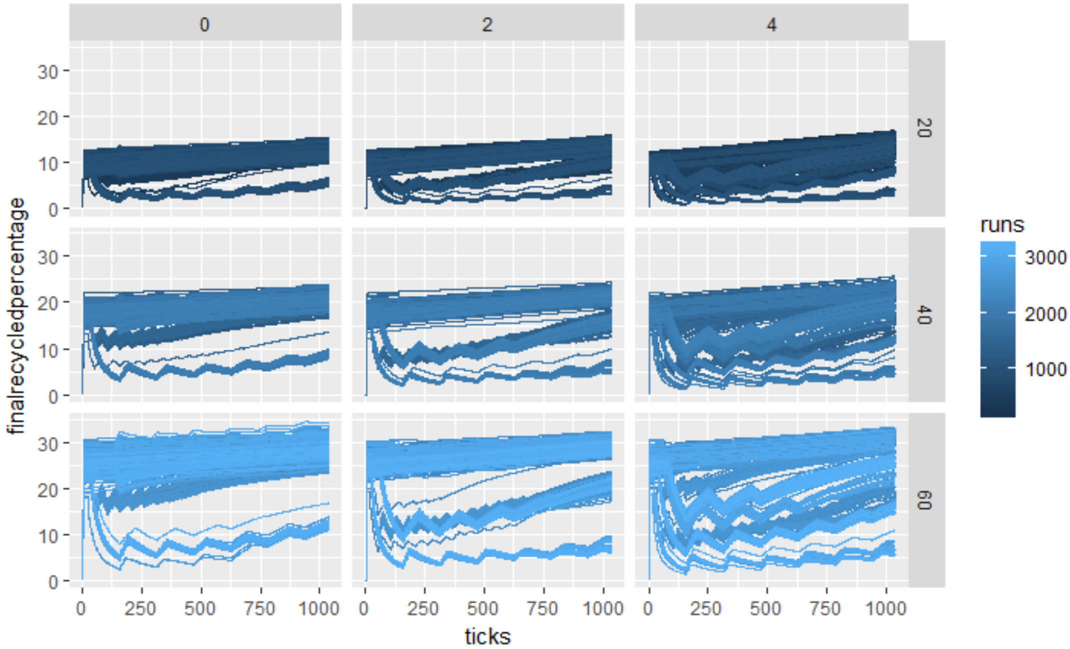


Figure 9. The influence of an extra budget on the final recycled percentage for different values of knowledge, over a run (per tick).

From figure 10 follows that the median does not differ greatly with an increasing extra budget. However, the quartiles expand and with a decrease of the amount of outliers, it is possible that these outliers shift towards the area where most other values are generated. This causes the outliers to disappear and the quartiles to expand.

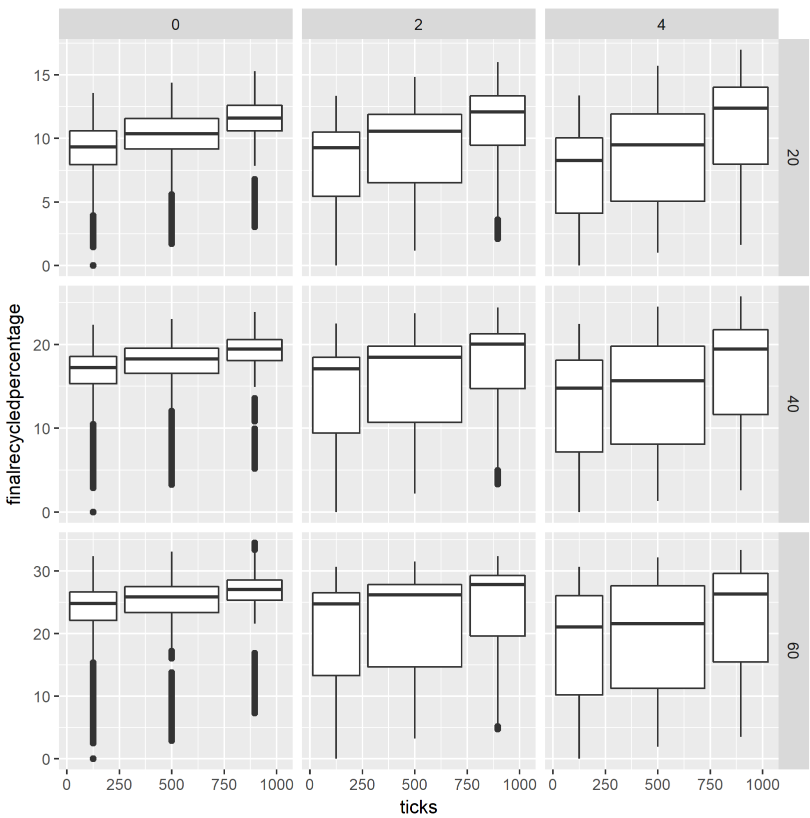


Figure 10. Boxplots of the influence of an extra budget on the final recycled percentage for different values of knowledge.

From the outcomes of this analysis, no firm conclusions can be drawn on the exact influence of extra budget on the final recycle percentage. Because this is an important aspects for the municipalities to decide how much they are willing to invest, it is recommended that this will be analyzed in further research.

5. **Does the collection infrastructure influence to what extent the national target is met?**

To test if the collection infrastructure influences to what extent the national target is met, the relation between an all decentral organized country (cp-ratio = 0,5), a 'normal' country where densely populated municipalities are central and not densely populated municipalities are decentral (cp-ratio = 1) and an all central organized country (cp-ratio = 50) are analyzed (see figure 11). From this analysis, it becomes clear that if all municipalities have a centralized collection infrastructure, the target is relatively more often not met, than if all municipalities have a decentralized collection infrastructure. From this analysis, the recommendation follows to insist the municipalities on having a decentral collection infrastructure if possible, because it is clear that the recycle targets (given by the government) will almost always be met.

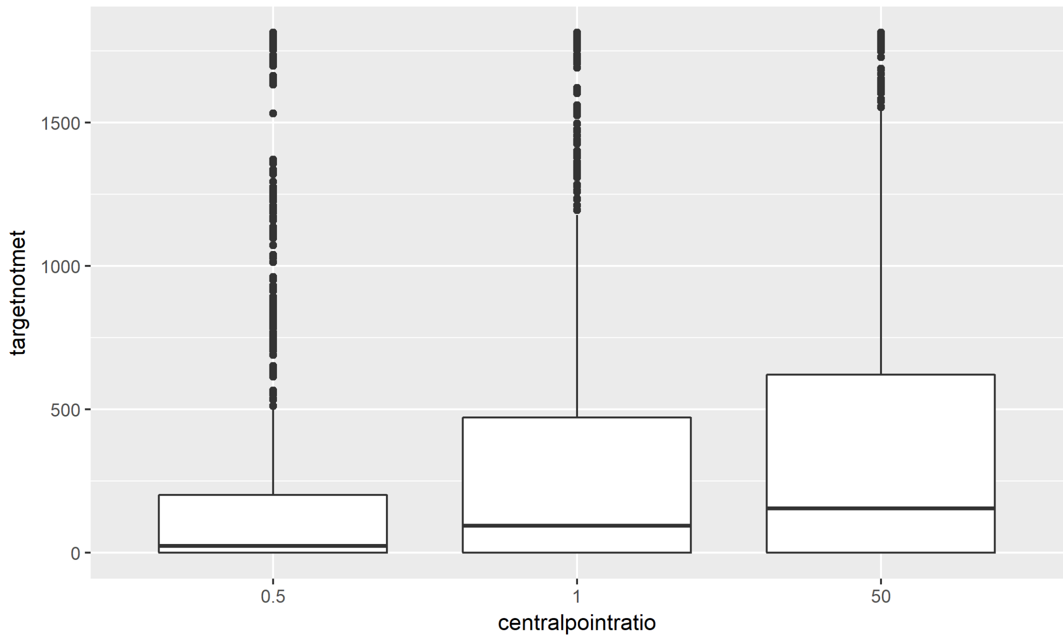


Figure 11. A boxplot which shows the relation between collection infrastructure and the extent to which the target is not met.

6. **What is the effect of the contract length on the amount of times the municipalities don't produce as much waste as stated in the contract?**

To answer the sixth research question, the two different parameter settings for the contract length - 1 and 3 years - are analyzed for the output variable 'times pay fine', during the run of a model over the ticks (Figure 12). The reason the output variable 'times pay fine' is used for answering this research question, is because if municipalities do not produce as much waste as stated in the contract, they have to pay a fine. From this analysis, it appears the range of the output variable times pay fine is larger for a larger contract length. So if the contract length is smaller, the amount of times a fine has to be paid can more easily be predicted. This can follow from the fact that companies and municipalities adjust their needs more often to each other when the contract length is shorter. Then the municipalities choose a company that best matches their demand every year, instead of being dependent on the same company for three years. However, from this analysis, nothing can be said yet about whether the 'times pay fine' is bigger or smaller with a shorter contract length.

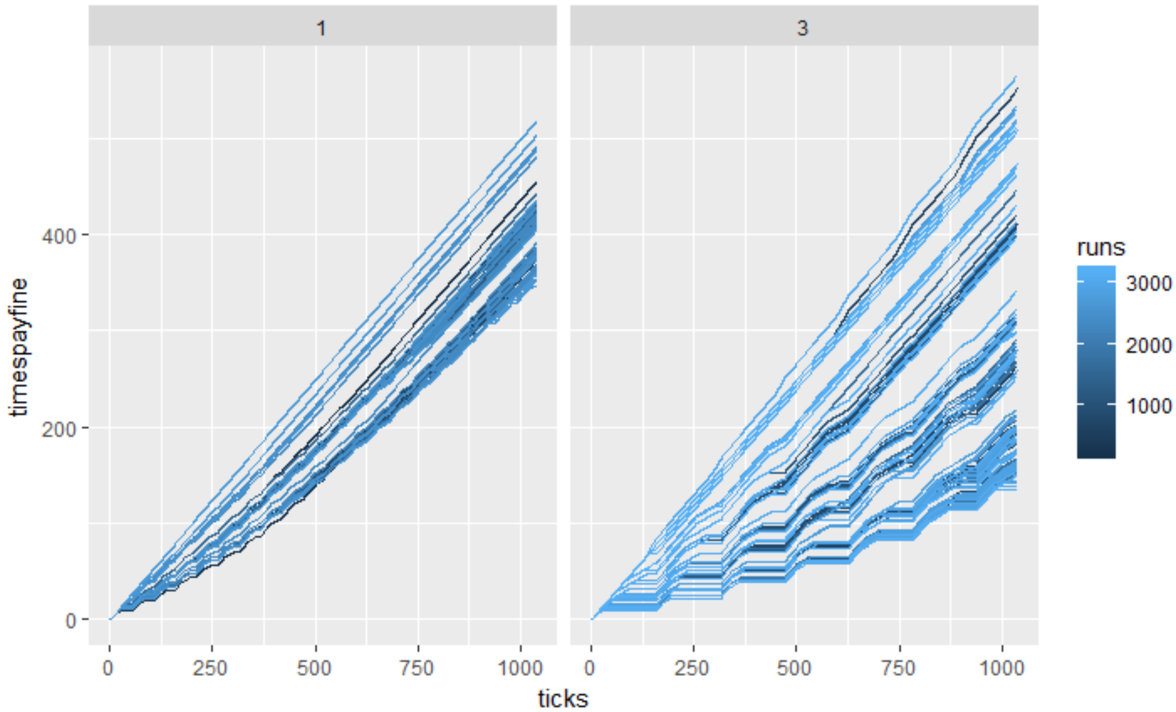


Figure 12. A plot which shows the value of 'times pay fine' for two different contract lengths, over ticks.

Therefore, the median value of 'times pay fine' for the two different contract lengths - 1 and 3 years - is calculated and shown in a boxplot (Figure 13). From this plot, it becomes visible (just as in figure 12), the range over which 'times pay fine' varies is bigger for a bigger contract length. However, it also becomes visible that the median value for 'times pay fine' is a bit lower with a larger contract length, but this difference is small. The contract length has no clear influence on the amount of times municipalities do not produce as much waste as stated in the contract.

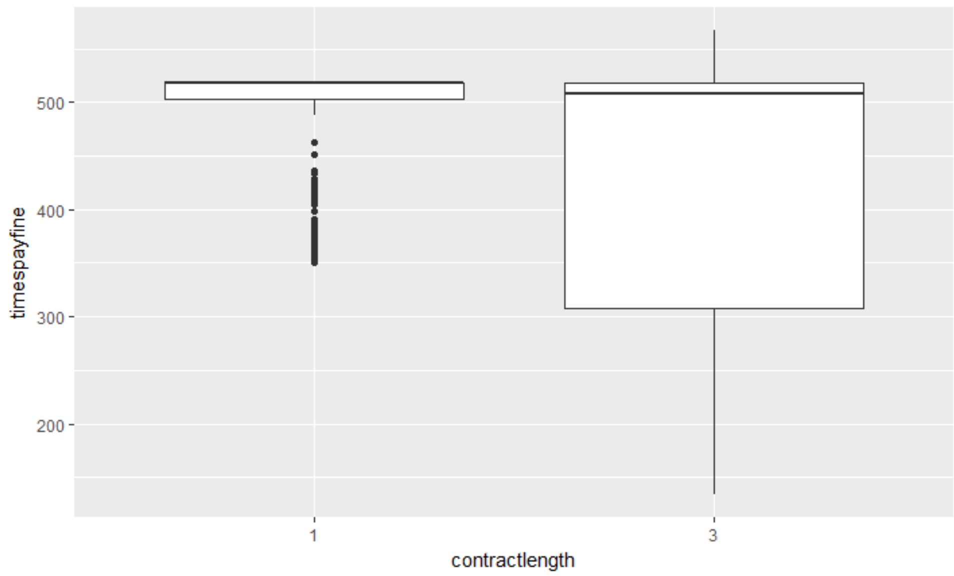


Figure 13. A boxplot which shows the value of ‘times pay fine’ for two different contract lengths.

7. **What would be the effect of companies developing new technologies?**

To be able to answer the last modeling question, the influence of companies being able to invest in new technology on the final recycled percentage is analyzed. In figure 14, there are values of final recycle percentages for different values of extra budget for the scenario where companies can invest or cannot invest in a new technology. It is expected that with the investment in a new technology, the final recycle percentage will increase. However, this cannot be concluded from figure 14. Comparing the ability to invest on true or false, there is no difference on the final recycled percentage. An explanation for this behavior could be found in the fact that with investing in a new technology, the price of a company also increases with the higher fine that they propose in a contract. Because of this, the companies can be overruled by cheaper companies and competed away. Therefore, these newer technologies may be not put in practice. To check this assumption, there has also been done an experiment where the competition between companies is active or not active. The results of this experiment are shown in figure 15.

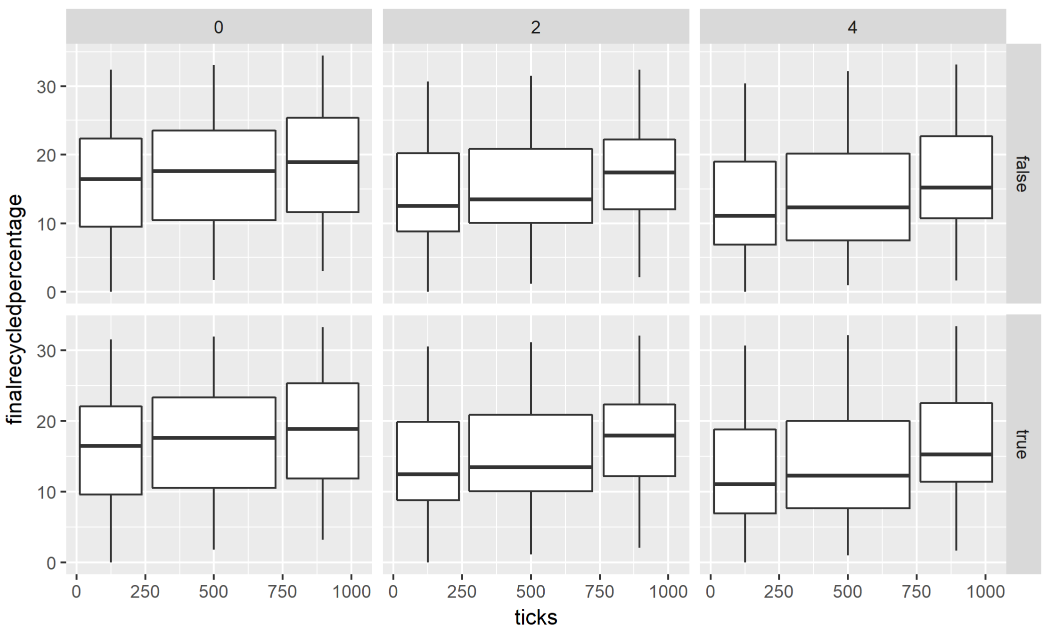


Figure 14. Boxplots of the influence of an extra budget and companies being able to develop new technologies on the final recycled percentage.

From figure 15 can be concluded that when companies have the ability to invest, more outliers on the lower scale of final recycled percentage are found. Therefore, competition most probably leads to the overrulement of the previous best performing companies due to their higher price. This causes more cases of a low final recycled percentage to occur. Still further analysis on the investment of companies is recommended, because no clear results can be extracted from this experiment.

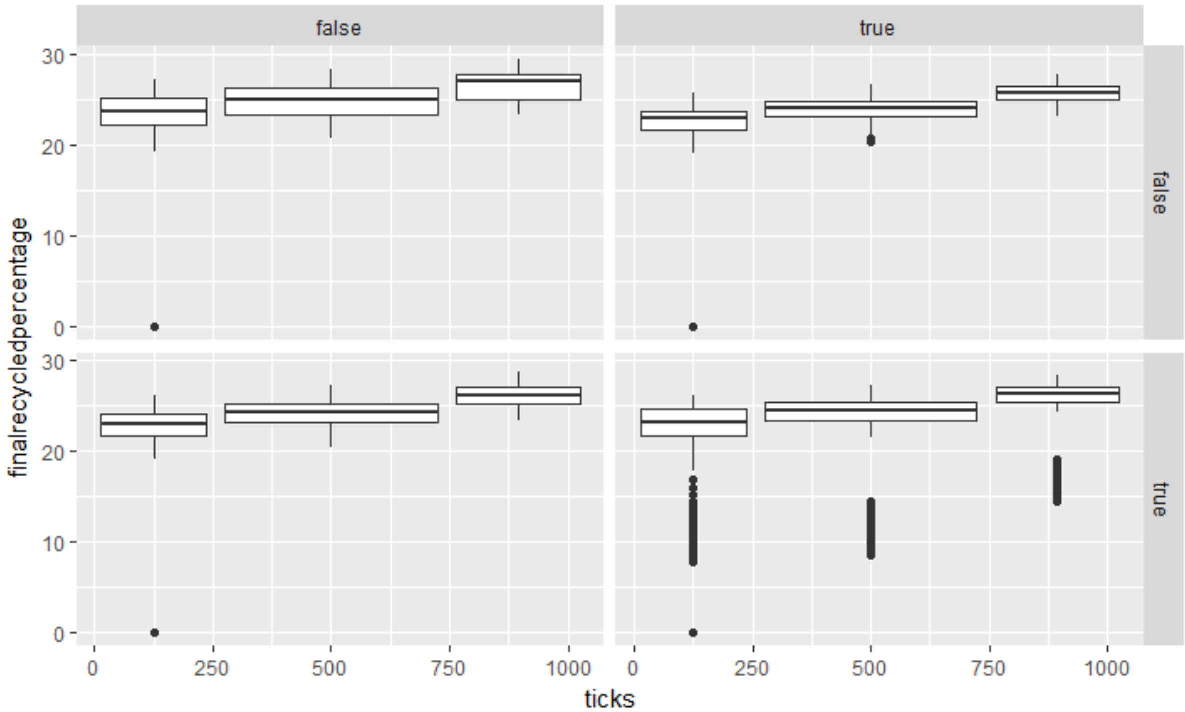


Figure 15: Boxplots of the influence having the ability to invest (y-axis) and the presence of competition (x-axis).

9. Model Validation

In this step is checked how realistic and useful the model actually is. As stated by George Box (1976), every model is wrong, but some models are useful. But how wrong is this model? A lot of assumptions and decision were taken to find the right scope for the model (See appendix). For many variables, no exact values were available so estimations based on literature have been made. The choices that were made were done according to the researchers' viewing point and might change totally from another researchers' viewing point. Knowing that every choice and assumption will work through in the model, this model can be stated to be far from reality. But that does not matter when considering the reason why this model is built; the reason why this model is constructed is to get better insight in the recycling plastic waste in The Netherlands. The aim of this research was not to get one clear answer, but to get an idea of the space of options and solutions that are possible and what kind of factors might be important to take into account for the Dutch government while trying to understand if the recent system of plastic recycling waste will satisfy the aims the government set for the future. The model is used as a tool to answer the research question, but nevertheless the shortcomings of the model should be discussed (at least some). These shortcomings can be taken into account in other analysis and gives the client, the Dutch government, a good insight to what extent this model is right, or better said: wrong.

First of all, just some of the Dutch municipalities were taken into account in the model and also just some companies were included. In fact there are about 380 municipalities (Ernst, n.d) in The Netherlands with all different features, like the amount of households, surfaces and densities. Although, the seven municipalities that are included in the model have different features, it is not convincing this model represents all the Dutch municipalities. Another shortcoming of the way the municipalities are modeled, is that in this model, assumed is that there is one type of collection infrastructure per municipality: either central or decentral. In reality however, there are municipalities where some neighbourhoods of the municipality have a central collection infrastructure, and some a decentral. For a more convincing advice for the government of The Netherlands, it would be best if all municipalities from The Netherlands with their right collection infrastructures would be taken into account.

Secondly, one of the output variables is 'final-recycled-percentage', which measures how much of the handed in plastic is recycled. In reality, more plastic is recycled than only a part of the handed in plastic: the plastic that is not separated is 'searched' out of the waste to recycle as well. Since this model is only about the waste separated and handed in by the households, the total amount of recycled plastic is underestimated.

Thirdly, there are some variables which are static in the model, but which are in reality dynamic. In the model, the population is static and does not change over time. Another variable that is kept stable, but is actually dynamic, is the part of the base waste that is plastic. A last important variable that might change over time is the composition of the population; because of the increase in ageing population in The Netherlands, this composition will probably be different. In this model, these dynamic variables are kept stable to make the model easier. Besides, no big changes in these dynamic variables were expected since the model only runs for 20 years. However, to get a better insight in the ‘real’ future, is would be better to let these variables change over time.

Furthermore, the municipalities only had the option to have a contract with one company. When the municipality estimated the wrong amount of plastic waste that must be collected by the company, this could not be changed anymore for three years. It was not possible to adjust the amount, but it was also not possible (when there was too much plastic handed in) to close another contract.

Lastly, competition is not taken into account very realistically. For example, this can be seen in the determination of the fine. The fines specified by the companies are all influenced by the price, i.e. expensiveness, of the company. There are random numbers allocated to to company to make the fines differ, but these are not related to the performances of the company. To model the competition more justly this should be taken into account.

10. Model Use

The modelling questions, stated in the first section, cannot all be answered totally clear with the created agent-based model. This is due to the fact that a lot of assumptions had to be made to make it possible to model the plastic waste collection, as explained in chapter 9. Of course, a simplistic version of the reality is modelled, but that is how modelling works. Besides this, the choices made to simplify the model and the assumptions that were made are done very thoughtful and everytime is questioned how it would work through in the model and if this would be crucial for the results the model would generate. Therefore an answer on the research questions and some recommendations are formed.

The research question is stated in the introduction as follows:

Does the current organization of plastic waste management and recycling in The Netherlands lead to the desired results or is it necessary to make (significant) changes?

From the analysis done to answer this research question, it appears if nothing will be done to improve the organization of plastic waste management and recycling in The Netherlands, there is a high chance municipalities often will not meet the recycling target given by the government, recycle companies will not recycle as much as they could and there is a significant amount of plastic waste not recycled and sold, which implies here lies chance to improve the Dutch plastic market. So making some changes will certainly improve the plastic waste management and recycling in The Netherlands.

The question is what changes lead desired results. From the analysis in the seven modeling questions, it first appears the knowledge and the incentivizing of households in municipalities influence the situation. More knowledge of the households leads to a higher recycling percentage (of the handed in plastic) and to less municipalities not meeting the government target. A higher incentive of the households leads to less municipalities not meeting the government target. A national campaign of the government, to educate the households on the importance and the how to recycle plastic, will lead to more municipalities meeting the government target and would thus have a positive effect.

Secondly, from this analysis, the effect of providing an extra budget for the municipalities to improve the recycling infrastructure does not become clear. It appears there is no effect if extra budget is provided, but this does not seem acceptable. Since many assumptions have been made (see chapter 9 and the appendix), the way the investments have been modeled might be too far from realistic to draw good conclusions from it. Because this is an important aspect for the municipalities to decide how much they are willing to invest, it is recommended that this will be analyzed in further research.

Moreover, from the analysis it appears municipalities with a decentral collection infrastructure clearly more often meet the government targets. This can be declared by the fact that with a decentral collection structure, the part of the households that hand in their plastic is higher. Based on this result, it is advisory for the government to recommend the municipalities to set up a decentral collection infrastructure, instead of a central one. Since a decentral collection infrastructure is more expensive, the government might want to financially support municipalities to build a decentral collection infrastructure.

Next to this, from the analysis, it appears the contract length does not have a significant influence on the amount of times the municipalities have to pay a fine to the companies. Expected was that with a shorter contract length, the municipalities would less often have to pay a fine since they could more often adjust the contracts to a different waste volume, but this appeared not to be true.

Lastly, the effect of new technologies seems to depend on the presence of competition. When the new technology causes an increase in the price of contracts these companies propose, it is possible they will not be chosen any more by the municipalities due to competition. Therefore, it has to be taken into account that investing in a better technology has to be paired with a not too big increase in price to be effective. From this can be concluded the government should advise the companies to not raise their prices too much when improving their technologies. The government can even decide to subsidise the companies for not raising their prices when investing in a new technology, because this appears to be most beneficial for the market of plastic recycling as a whole.

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Appendix

Assumptions and default parameter settings

1. The government policy for waste fund pricing specifies one single price per ton plastic (euros/ton). In practice, these prices differ per type of plastic (Nedvang, n.d.), but in this research an average price will be taken: €788,-.
2. The starting percentage of the recycling target in 2018 is 12.5%. The total target of the government is 47% (KIDV, 2016). However, here is taken into account that of the not (separately) handed in plastic of the total waste, a large share still is recycled. From the base waste, plastic is filtered out with machines. In this model, there is assumed that the starting percentage of knowledge is between 40-50% and the starting percentage of plastic handed in 50%. So as starting percentage of the recycling target, the value 47%*45%*50*= 12.5%.
3. The population does not grow over the 20 years.
4. To determine the share of retired households, the percentage of retired people per municipality is multiplied with the amount couple-households. Thus, the retired population is proportionally linked to the number of couple households. Then, the in literature given amount of couple households is recalculated by abstracting the amount of retired households.
5. In the set-up there is decided if a municipality would be better off using a centralized or decentralized infrastructure. This is done by first checking how big the surface of the municipality is, how many households there are per km2 (see table 2), and then the amount of central collecting points is calculated proportionately (default setting: at least 1 point per km2). When the division of the number of households divided by the amount of central collecting points is higher than 1, it is better to have a decentralized infrastructure. The infrastructure (centralized or decentralized) is the same for the whole municipality.

Table 2. Amount of households per km2.

	#Households	Surface (km2)	Ratio
Amsterdam	462328	165	2801,98788
Rotterdam	319780	206	1552,3301
The Hague	257190	83	3098,6747
Delft	57195	23	2486,73913
Emmen	48284	337	143,275964
De Marne	48284	167	289,125749
Blaricum	4525	11	411,363636
		Average	1540,49959

6. The decision if a municipality would be better off with a centralized or decentralized infrastructure only happens at the beginning of the simulation. Because this decision

is not being revised, the ‘sunk costs’ of building central points or getting the decentralized bins and changing again after three years can also be left out because of this.

7. The average waste production per household is given in the project description. The different households do not produce the same amount of waste. Given is: waste old < single < couple < family. Assumed is the ratio old:single:couple:family is 0,5:0,75:1,25:1,5. This way the average waste production of this ratio is 1.
8. When the infrastructure is decentralized all households are connected to this infrastructure. The same counts for the centralized infrastructure, but this follows logically from the fact that everyone can go to a central point in the municipality (but when it is far, it is less likely to hand in the plastic waste).
9. The initial share handed in is dependent on the *type of system*: central or decentral. It is assumed that the share of plastic waste handed in for a decentral system is higher than for a central system, because if plastic waste is collected at home (decentral), it takes less effort for people to separate plastic than if they have to bring it to a central collection point. The average percentage of waste that is handed in seperately is 50% in The Netherlands (Milieucentraal, 2015). That is why in this report, a hand-in percentage of 40% for a central system and a hand-in percentage of 60% for a decentral system is taken.
10. The initial share of plastic waste handed in that is recyclable depends on the *knowledge*. Do people know what is plastic and what is not? It appears nowadays, half of the amount of plastic handed in is not recyclable. In this report, the start value of the variable knowledge is assumed to be random between 40% and 50% (NOS, 2017).
11. A municipality has one contract, it does not let more companies collect their households plastic waste at the same time.
12. A company can have contracts with multiple municipalities, but has a maximum capacity of waste it can process per month (which is specified in the technology it uses). The capacity of waste per month can increase when the company does a large investment.
13. The contract proposed by a company, is not specific for the infrastructure of a municipality. In other words: contracts can both be accepted by municipalities with a central of a decentral infrastructure.
14. The fine proposed in the contract is calculated according to the earnings that the company would miss out on when enough plastic waste is delivered (per collecting moment). This can be calculated according to the ‘waste fund’ pricing (fee) of the government. Assumed is not all recycling companies are as expensive as the others; some are ‘just’ more expensive, which may be caused by for instance a good reputation. This price per recycling company will be 70-99%. This price determines the value of the fine; the fine is either (70%-99%) * fee. This was, there is more variation created on the market of the recycling companies which is more realistic.
15. One tick is one week, so 52 weeks is 1 year. Since in this model a month is 4 weeks, a year consists of 13 months, the waste is collected 13 times per month.
16. Assumed is that the municipality with the highest requested plastic waste volume can choose a company first, because assumed is a company wants to process as much plastic as possible so they want to do business with the largest municipality first.
17. The average waste production per household per week is given by the function: 40 - 0.04 * x – exp(-0.01 * x) * sin(0.3 * x (Agent Based Modelling, 2017). The variable ‘x’

stands for months. The model runs for 20 years, which is 240 months. The waste production over 20 years is shown in the following figure 16.

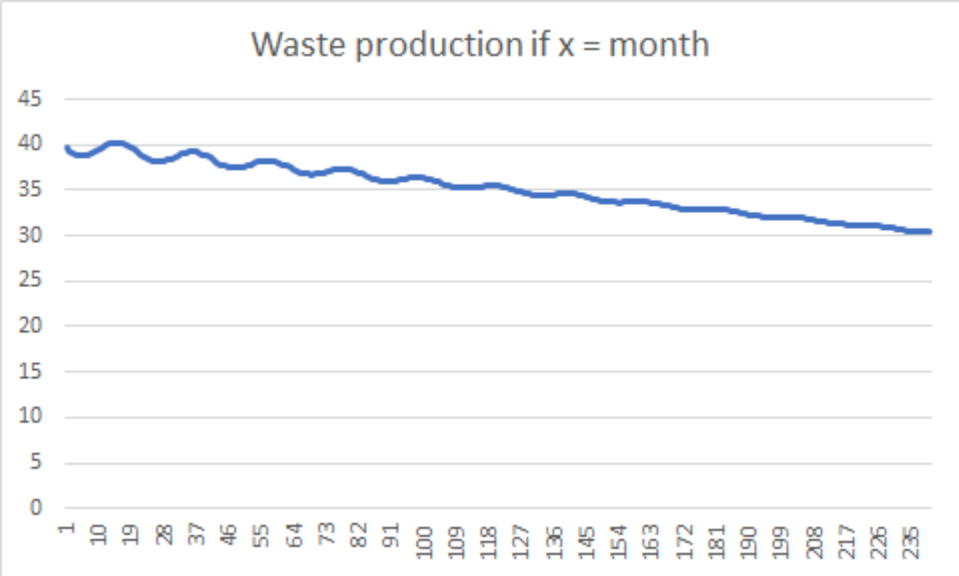

Figure 16. Waste production if x = month.

18. Assumed is that the investment of 1 budget point in either incentivizing or knowledge, will result in a 1 % point increase in incentivizing or knowledge per 3 years. In this model, there are 13 months per year, so 1% point increase per 3 years means a 1/39 % point increase per month.
19. Assumed is that a company with a low capacity has a capacity equal to the total plastic production by the municipalities * 10%. This way, it can handle one 'average' municipality. A company with a medium has a capacity of 25% * total plastic production by the municipalities and a company with a large capacity has a capacity of 50% of the total plastic production by the municipalities. This way, it is made sure every municipality, even the biggest ones, can find a company to process their waste
20. Assumed is that a company with a 'bad' technology has a recycling percentage of 65-75%, a company with a 'middle' technology has a recycling percentage of 75-85% and a company with a 'good' technology has a recycling percentage of 85-95%. These percentages are recycling percentages of the total *recyclable* plastic waste.
21. The costs for the recycle infrastructure vary per type: a central structure is cheaper (2 points) than a decentral structure (4 points). With a decentral structure, each household has its own bin and the garbage trucks have to collect the waste at each household, instead of at a central point. The costs for the extra bins and extra effort of the companies who collect the waste make a decentral structure more expensive than a central structure.
22. The first investments can be made after 5 years, because the Return on Investments needs to be at least 5 years (as given in the lecture slides).
23. A small investment in new technology will be made if the earnings of that company are at least 40% of the average earnings of all companies. This way, the competition between the companies is taken into account. If a company's performance is lower than average, but still well enough compared to the other companies, it will at least make a small investment.

24. A large investment in new technology will be made if the earnings of that company are at least 60% of the average earnings. This way, only the companies top layer of companies, can do a large investment.
25. The new technology takes 1 year to build (as given in the lecture slides).
26. The increase of separation percentage and price and the decrease of the earnings of a company, are determined by trial and error. These values eventually gave the most logical incremental effect on the total technology levels.
27. If there is only one company with a sufficient remaining capacity, this company is chosen. If there is no company that can meet the requested waste in terms of remaining capacity, the municipality closes a contract with the company with the highest remaining capacity and repeats this, until all its plastic waste will be collected.