The background of the entire page is a dense, repeating pattern of various mobile phones, including smartphones and feature phones, in various colors and orientations. A semi-transparent black rectangle is overlaid on the top left, containing the title and author information. A vertical blue bar is on the left side, containing the text 'Master of Science Thesis'.

# Economic and Environmental Assessment of Extended Producer Responsibility and No Reuse Policies in Mobile Phone End of Life Networks

using Agent Based Modeling and Exploratory Modeling Analysis

Pim Bernard Bellinga

Faculty of Technology, Policy and Management  
Section Energy & Industry

Master of Science Thesis

**Cover picture:** Chinese artist Liu Bolin paints his entire body to exactly match the scenery behind him. He is camouflaged so well it is sometimes almost impossible to spot him. His latest exhibition, Hiding in the City, at the Eli Klein Fine Art gallery in New York, shows him melting into various urban backdrops, including a picture of a variety of mobile phones.

Picture: Eli Klein / Barcroft Media

Source: The Telegraph <sup>1</sup>

Student number: 1365487

First Supervisor (Agent Based Modeling):	Dr. ir. Igor Nikolic
Second supervisor (Exploratory Modeling Analysis):	Dr. Erik Pruyt
Supervising Professor:	Prof. Dr. ir. Paulien Herder
External supervisor (Content Expert):	Dr. Vered Blass

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<sup>1</sup><http://www.telegraph.co.uk/culture/culturepicturegalleries/9793057/>

[The-invisible-man-Liu-Bolins-latestcamouflage-artwork-Hiding-in-the-City.html](#)



**Economic and Environmental Assessment of Extended Producer  
Responsibility and No Reuse Policies in Mobile Phone End of Life  
Networks**

using

Agent Based Modeling and Exploratory Modeling Analysis

**Pim Bernard Bellinga**

A Thesis submitted for the degree of Master of Science  
in Systems Engineering, Policy Analysis and Management

Faculty of Technology, Policy and Management  
Delft University of Technology

August 2013



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# Abbreviations

Acronym	What it stands for
EPR	Extended Producer Responsibility
NRP	No Reuse Policy
NP	No Policy
EOL	End of Life
ABM	Agent Based Modeling
EMA	Exploratory Modeling Analysis
OEM	Original Equipment Manufacturer
LHS	Latin Hypercube Sampling
PRIM	Patient Rule Induction Method
WEEE	Waste Electrical and Electronic Equipment
E-Waste	Electronic Waste
OECD	Organisation for Economic Cooperation and Development
CED	Cumulative Energy Demand
LCA	Life Cycle Assessment
CLCA	Consequential LCA
ALCA	Attributional LCA
RL	Reverse Logistics
CLSC	Closed Loop Supply Chains



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# Summary

Over the past decades, the number of mobile phone subscriptions has increased tremendously. Over three-quarters of the world population now has access to mobile communication. With an average usage time of 1 to 2 years, the number of mobile phones in circulation is even higher. But this increase has also negative consequences. When mobile phones reach their End of Life (EOL) phase, they become Electronic Waste (E-Waste). When E-Waste is not properly processed, it has negative consequences for human health, the environment and reserves of precious metals.

Governments have responded by adopting various types of legislation, aimed to increase the amount of phones that are properly processed. A common paradigm is Extended Producer Responsibility (EPR). EPR places financial responsibility for the collection and processing of EOL products on the producers. The legislation has two goals: 1) to increase the collection rate. 2) provide producers incentives for the redesign of their products so that they can be processed more easily.

Companies have also responded in various ways. Three company policies (Destroy-Only, Simlocks and Demand Cannibalization Avoidance) have been identified as effectively being No Reuse Policies (NRP), which mean that they prohibit the reuse of phones.

Currently, the economic and environmental effects of EPR and NRP in Mobile Phone End of Life networks are unknown and not well researched. Partly because the effects cannot be directly attributed to the policies. Instead, the policies have consequential effects. This requires larger system boundaries which include relevant dependencies and market mechanisms. The objective of this thesis is to assess the consequential economic and environmental effects of EPR (confined to EPR goal 1) and NRP.

This research question is explored by developing an Agent Based Model (ABM). An ABM represents a system by the interactions and behavioral rules of agents, where agents are defined as

individuals that have a state and rules to change their state. Conceptually, the model in this thesis consists of two layers: a *process* layer and a *choices* layer. The process layer describes how phones flow through the system, from their moment of creation till their final destination. All the steps in the process layer have different economic and environmental effects. The summation of the individual flows of the phones determine the total effects. How phones flow through the system is determined in the choices layer, by four key choices. A formal hypothesis was developed which describes how EPR and NRP theoretically can affect these choices and consequentially, economics and the environment (the *effect* chain). The objective of the model is explore and analyse the workings and outcomes of the effect chain, and in doing so, gain insights into the effectiveness of EPR and NRP.

It is assumed that under EPR manufacturers outsource the collection to third party refurbishers and under EPR/NRP to recyclers. Analyses from the model show that: 1) EPR and EPR/NRP both lead to lower relative energy demands. 2) Under low collection rates, NRPs have no significant effects on economics and the environment. 3) EPR/NRP lead to negative economic effects for refurbishers as well as recyclers. 4) the analyses provide some support for the hypothesis that the type of collection infrastructure influences economics and the environment. 5) Finally, the model provides generative evidence on how EPR can lead to higher collection rates. However, all these effects are very dependent on the disposal decisions of consumers and purchasing logic of refurbishers and recyclers.

Combining the insights and observations from the problem analysis, model design and model analysis, it is concluded that 1) EPR is in 35% of the scenarios an effective policy for increasing collection targets with positive effects for economics and the environment. 2) The combination EPR/NRP should be avoided. It has negative financial implications for refurbishers, recyclers and manufacturers. This means that manufacturers should outsource their collection to refurbishers. 3) the effects of NRP under collection rates lower than 40% are not significant. It is not imperative to focus on minimizing NRP. Recommendations for further research are: 1) The model should be supported with more empiric evidence, in particular on consumer disposal choices and purchase decisions of refurbishers and recyclers. 2) Additional analyses should be performed to investigate the effects of EPR and NRP along the effect chain. 3) Finally, service providers are not included in the current model. Their role and impact should be analysed to see if it is necessary to include them.

# 1 | Introduction

Over the past decades, the amount of mobile phone subscriptions has increased from 11.1 million in 1990 (Geiger and Mia, 2009) to 6 billion subscriptions globally in 2012. This has provided three-quarters of the world population the ability to communicate. (Worldbank, 2012) But the ubiquitous presence of mobile devices also has a negative side. When mobile phones are discarded, they become electronic waste, called E-Waste. In 2010, in the United States alone, 150 million mobile devices reached their End of Life (EOL). (US Environmental Protection Agency, 2011) Without proper waste treatment procedures, E-Waste from mobile phones and other sources has negative consequences for human health and the environment (Ongondo et al., 2011). This problem is gradually recognized. Increasing environmental concerns have led to a growing awareness that electronic waste has severe negative implications for the environment. (Widmer et al., 2005) In addition, depletion of precious metals has become a second driver for change.(Bollinger et al., 2012)

Governments began to respond. In 2003, the European Union was one of the first, by adopting the WEEE legislation. (Directive 2002/96/EC, now Directive 2012/19/EU) It is based on the principle of Extended Producer Responsibility (EPR). This means that producers<sup>1</sup> are made responsible for the processing of their discarded products. The EPR paradigm was adopted with two functions in mind: a) to relieve [auth: share with] municipalities of the financial burden of e-waste management, and to provide incentives to producers to b1) reduce resources<sup>2</sup>, b2) use more secondary materials, and b3) undertake product design changes to reduce waste. (OECD, 2001) This article investigates the effects of EPR through (a), (b1) and (b2). Effects through product design changes (b3) are explicitly not investigated, as there have already been studies into the effects of EPR through (b3). (Atasu et al., 2009)

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<sup>1</sup>Who the producers are, manufacturers and/or importers, differs per country

<sup>2</sup>Interpreted in this thesis as meaning reducing resources required for collection and processing operations; efficient operations



This thesis also investigates the effects of company policies termed No Reuse Policies (NRP). We have identified three company policies that are in effect NRP:

1) *Destroy-Only policies*: because of *phone data security concerns*, some companies (users) do not allow their phones to be reused. Instead, they require their phones to be shredded. (E-Cycle, 2011) This is a clear example of a NRP.

2) *Simlocks*: phone companies (called Service Providers) often place a *simlock* on their phones. (Huffington Post, 2013) Although this means that returning the phone to the Service Provider would still allow the phone to be reused, the phone cannot be returned through third party channels and be reused by third parties. Therefore, it can be thought of effectively being a NRP.

3) *Fear of competition*: some Original Equipment Manufacturers (OEMs) may not allow their phones to be reused, out of fear of competition of reused phones with their new phones. (Geyer and Doctori Blass, 2010) This is called *demand cannibalization*. Although no observations of this have been reported in the literature, it is interesting to explore the consequences of such a NRP.

In order to design efficient legislation and policies, the effects need to be known. Therefore, the research question this thesis answers is:

**What are the economic and environmental effects of Extended Producer Responsibility and No Reuse Policies in Mobile Phone End of Life Networks?**

The remainder of this thesis is structured as follows: Chapter 2 reviews the relevant literature. Chapter 3 explains the choice for ABM and structures the research by developing subquestions. The problem is analysed further in Chapter 4. Based on this problem analysis, a model is presented in Chapter 5. Chapter 6 analyses this model. Based on the insights from Chapters 4, 5 and 6 conclusions are drawn in Chapter 7. Chapter 8 closes by proposing interesting directions for further research. Figure 3.2 visualizes the structure of the chapters and supporting appendices.

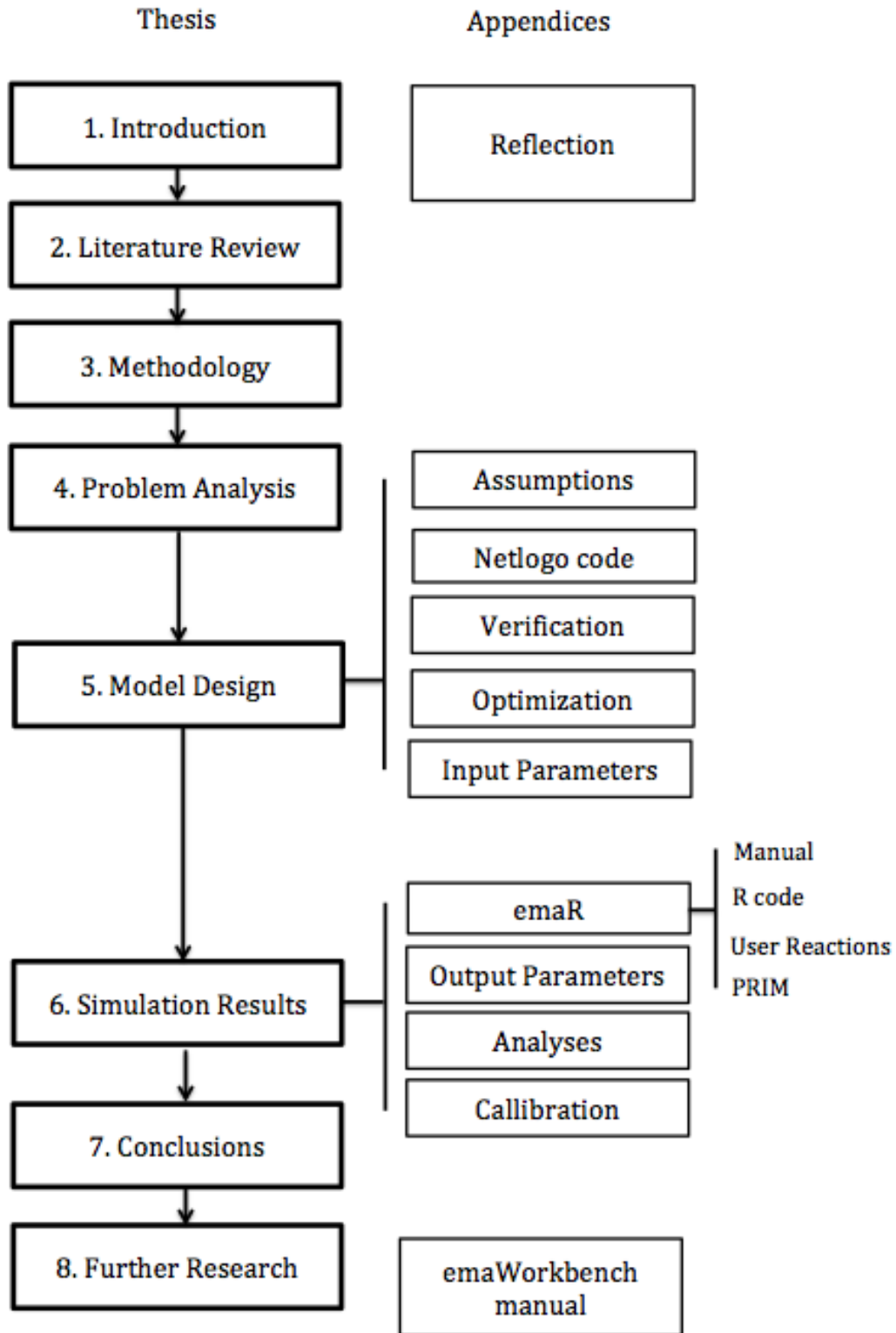


Figure 1.1: Chapter Structure and connected Appendices



## 2 | Literature Review

The purpose of this chapter is to demonstrate a relevant gap in the literature. This chapter will show that there are no studies that investigate the effects of EPR and NRP on economics and the environment. It starts by reviewing three broad research fields in which this thesis is situated: E-Waste research in Section 2.2, Reverse Logistics research in Section 2.3 and E-Waste policy research in Section 2.4. Section 2.5 then it highlights the most relevant contributions that are related to this thesis and shows that there is no current literature that has already answered the research question. The last Section 2.6 describes additional literature that will be introduced in the remainder of the report.

### 2.1 Research fields

The first field to be reviewed is the research on different aspects of (1) **Waste Electrical and Electronic Equipment** (WEEE). In order to be processed after the initial consumption of the product, EOL products have to be returned from the consumers to organizations capable of processing these products. The logistics of returning products from the consumers instead of bringing them to the consumer is called (2) **Reverse Logistics** (RL). RL has been defined by Rogers and Tibben-Lembke (1998) as *the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing or creating value, or for proper disposal*. RL closes the loop from production and consumption to processing and reuse of the products or its materials. Therefore this arrangement is also known as **Closed Loop Supply Chains** (CLSC). Thirdly, this research is about the effects of policies. Thus the third area of literature that has been reviewed is the literature on the effects of (3) WEEE and CLSC **policies**.

As a final note before reviewing the literature: sometimes certain papers can be placed into multiple categories. In those cases, the papers have been categorized according to the subject most related.

## 2.2 E-Waste

Mobile phones are a subset of E-Waste/WEEE. The research on WEEE covers the following main topics and authors:

- **Environmental, Health and Management problems with WEEE;** in general: (Ongondo et al., 2011), (Schluep et al., 2009), in the United States: (Saphores et al., 2009), in developing countries: (Osibanjo and Nnorom, 2007), (Widmer et al., 2005), in China: (Streicher-Porte and Yang, 2007) and in the UK (Canning, 2006).
- **Economics of mobile phone EOL networks;** (Geyer and Doctori Blass, 2010) and economic sustainability (Yang et al., 2011).
- **EoL management;** (Doctori Blass et al., 2006), in the United States (Kahhat et al., 2008), in China (Yang et al., 2008) and lessons from the United States and prospects for Brasil (Silveira and Chang, 2010).
- **Environmental and economic impact of EOL mobile phones:** (Quariguasi Frota Neto et al., 2010), (Quariguasi-Frota-Neto and Bloemhof, 2012), environmental and economic impact of reuse and recycling processes (Sundin and Tyskeng, 2003), (Huisman et al., 2004), effects of remanufacturing for product + service firms (Ovchinnikov et al., 2013).
- **Simulations of Mobile Phone EOL networks:** Two agent based models: EOL Waste management in Bangalore (Sheoratan, 2011) and of metal flows in the Mobile Phone EOL system (Bollinger et al., 2012), (Bollinger and Blass, 2012), (Bollinger, 2010). A System Dynamics model on sustainability of Mobile Phone EOL system (Gnoni and Lanzilotto, 2012).

## 2.3 Reverse Logistics

Research on RL has expanded and evolved quickly over the past decade (Rubio et al., 2008), (Guide and Van Wassenhove, 2009), (Sasikumar and Kannan, 2009). Again, the literature has been divided into categories, focussing on the following aspects:

- **RL frameworks:** (Brito et al., 2003), Strategic framework: (Dowlatshahi, 2005), Integrated framework (Yang and Wang), Multi-tiered framework: (Nagurney and Toyasaki, 2003)
- **RL case studies and practices:** (Brito et al., 2005), (Brito et al., 2003), Practices: (Rogers and Tibben-lembeke, 2001), India: (Sharma and Panda, 2011)

- **RL design;** (Souza, 2013), (Jayaraman et al., 2003), Commercial returns (Blackburn et al., 2004), Constraints (Geyer and Jackson, 2004), Configuration (Beamon and Fernandes, 2004), Structure (Wang et al., 2010), (Fleischmann, 2001), (Krikke, 1998), Arrangements (Kawa and Golinska, 2010), Recycling options and Efficient Policies (Calcott and Walls, 2005).
- **RL simulations:** collection of RL applications in Sydney (Kara et al., 2007), Closed Loop Supply Chains as Complex Adaptive Systems (Surana et al., 2007).

## 2.4 E-Waste Policies

In this thesis, one type of government legislation is studied: *Extended Producer Responsibility* (EPR). Secondly, one company policy is studied, the *No Reuse Policy* (NRP). This section starts by reviewing the literature on governmental WEEE policies. Several policies have been adopted by governments to decrease the negative effects and increase the opportunities. Overall, there are three main paradigms of legislation that have been adopted or proposed:

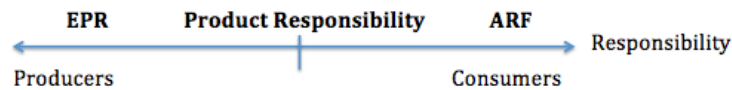


Figure 2.1: Policy paradigms placed along a responsibility axis.

The first legislative paradigm is EPR, which has already been introduced. The second paradigm is at the other end of the spectrum: *Disposal Fees*, which demand the consumer to pay a fee which pays for the collection and disposal of the product. This fee can be paid at the moment of disposal or in advance. In the latter case they are called *Advanced Recycling Fees* (ARF). (Nixon and Saphores, 2007) The third type is *Product Responsibility*. This is a variation on Producer responsibility and disposal fees. Instead of only holding the producer or the consumers responsible for the collection and processing of the product, all the agents involved in the production and consumption of the product pay their share. (Lindhqvist and Lifset, 1997) In this literature review, only the research on EPR will be reviewed.

EPR legislation has been studied extensively. Four major research areas have been identified. Summarising the key publications:

- **The capabilities of EPR:** (Manomaivibool, 2011),(Manomaivibool, 2009), (Zoeteman et al., 2009), (Mcdonough, 2007).
- **Impact of EPR in different countries:** in the United States (Nash and Bosso, 2013), in Thailand (Manomaivibool and Vassanadumrongdee, 2011), in Germany (Walther and Spengler, 2005a), (Walther and Spengler, 2005b), (Walther et al., 2009)
- **Theoretic studies on several effects of EPR and EPR implementation choices:** Effect on Design for Remanufacturing (DfR) between Individual or Collective EPR (Atasu and Subramanian, 2011), Effect on Quality (Atasu and Souza, 2011), Design Implications (Mayers, 2007), (Walls, 2006), (Walls, 2003), the effects on Product Introduction (Plambeck and Wang, 2009).
- **Key issues and considerations in implementing EPR:** Key Issues in Swiss (Khetriwal et al., 2009), Implementation of EPR (Gui et al., 2012), (Mayers et al., 2012), Stakeholder perspectives (Atasu and Street, 2012) and finally a comparison between EPR and Product responsibility (Lindhqvist and Lifset, 1997).

## 2.5 Literature Gap

This literature review on the three research fields: e-waste, reverse logistics and e-waste policies, shows that all fields are studied extensively. However, no research has been identified that addresses the environmental and economic effects of EPR and NRP. In this thesis it will be argued that in order to study these effects correctly, one needs to:

- take into account the dependencies between the different agents in the system (See Process and Agent Analysis in Chapter 4)
- take into account the role of collection channel infrastructure (See Effect Chain in Chapter 4)
- define the policies precise enough so that relevant/practical conclusions can be drawn

In this section a condensed summary of the literature review will show that existing literature addresses part of the research question, but none of it addresses all three requirements.

Sundin and Tyskeng (2003) and Huisman et al. (2004) have studied the environmental and economic effects of refurbishing and recycling and conclude that in most cases, refurbishing is economic and environmentally preferable. However, they do not investigate the effects of policies on the amount

of phones that refurbished and recycled.

Ovchinnikov et al. (2013) study the environmental and economic effect of remanufacturing (auth: refurbishing) for product + service firms and find again that in most cases, refurbishing is preferable. However, they only study the implications for product + service. They do not take into account the dependencies on other agents and the implications of remanufacturing for other agents.

Bollinger (2010) and Gnoni and Lanzilotto (2012) model the same Mobile Phone EOL system which is the target system of this thesis. However, Bollinger (2010) does not study the effects of policies. Gnoni and Lanzilotto (2012) do, but they only study abstract push and pull policies. This does not yield insights that can be extended to EPR and NRP.

In conclusion, the main gap is that there is little researched that looked into the effects of policies on the full system of agents together. Thus an integrative study is required to study these effects correctly. Given the environmental concerns and depleting reserves of precious metals, there is a social demand to better understand the Mobile Phone EOL system. In order to design effective policies, the effects of EPR and NRP need to be known. As this section demonstrated, there is a gap in the literature on these effects. Given that there is a social demand and no sufficient description yet of Mobile Phone End of Life systems, this gap is deemed relevant. This thesis will attempt to start closing this gap and provide the necessary tools (model) for future research.

## 2.6 Additional literature

The literature presented in this chapter has been used to show that a relevant gap exists in the literature. In addition to demonstrating this gap, literature is also used to support the argumentation through out this thesis. This literature is introduced when it is required. Literature on the various topics is presented at the following chapters in the report: Agent Based Modeling (ABM) in Chapter 3. Observational data on the Mobile Phone End of Life (EOL) system in Chapter 4. A focused selection of literature on Exploratory Modeling Analysis (EMA) is presented in Chapter 6. Finally, research that has been used to support the assumptions is presented in Appendix 11.





## 3 | Research Methodology

The purpose of this chapter is to explain *how* the research question will be answered. As one of the first in this field research, this thesis uses Exploratory Modeling Analysis to explore Agent Based Models. This is described in Chapter 6. Section 3.2 explains what ABM is, the choice for the choice for ABM and how ABM will be used. Section 3.3 argues why and how the economic and environmental effects are researched. Finally, Section 3.4 decomposes the main question into subquestions. These subquestions are then used to structure the research in the remainder of the thesis.

### 3.1 Motivations for Modeling

Fundamentally, there are two ways to assess the effects of EPR and NRP: making *observations* or construct a *theory*. Observations have the obvious advantage that the claims of the study are about reality. An example of an observational study is an econometric study, which measures the correlation between policies and economics/environment. Observational studies on the effects of policies have two disadvantages: the first is that to attribute the differences in economics/environment to specific policies, similar test and control groups are required. This can be hard to achieve due to the many differences between countries. Secondly, an observational study on effects will only provide a correlation instead of a *causal story*. To explain a correlation, a theory is required.

This leads to possibility two: theory. With the obvious disadvantage that initial conclusions are only valid for the constructed (mental) model, the advantage is that the assessment is supported by a theory. Again, there are two choices: reasoning (mental models) or constructing (computer) simulation models. This thesis opted to construct a computer model. The next question is: why (computer) model? Why not save the time spend in coding to reason or calculate the effects by hand? This question is the subject of Epstein (2008). There are three advantages: 1) Epstein notes that in case of systems with feedback loops, a large number of influencing factors and heterogeneity,

reasoning becomes impractical<sup>1</sup>. Simulation is used as a tool to which makes it practical to explore the consequences of the assumptions one has made. 2) Modeling makes the assumptions *explicit*. This means that the assumptions are presentable and therefore debatable by others. 3) Modeling can make a theory *coherent*. This means the assumptions lead to the hypothesized outcomes. This idea of *generative evidence* is captured by the motto: "if you did not grow it, you did not explain it" (Epstein, 1999). In addition to these properties, Epstein (2008) names sixteen reasons for using modeling other than prediction. Seven are highlighted as they are applicable to this thesis: 1) Guide data collection 2) Illuminate core dynamics 3) Discover new questions 4) Promote a scientific habit of mind 5) Bound outcomes to plausible ranges 6) Illuminate core uncertainties 7) Expose prevailing wisdom as incompatible with available data.

These characteristics form the motivation for choosing modeling as the research approach. The next question is which type of modeling is chosen and for what reasons.

## 3.2 Agent Based Modeling

The research method that is selected for this thesis is Agent Based Modeling (ABM).

### 3.2.1 What ABM is

Parunak et al. (1998) provide a concise description of equation-based models and agent-based models: "In equation-based modeling (EBM), the model is a set of equations, and execution consists of evaluating them. In agent-based modeling (ABM), the model consists of a set of agents that encapsulate the behaviors of the various individuals ("agents") that make up the system, and execution consists of emulating these behaviors. Simulation is the general term that applies to both methods, which are distinguished as (agent-based) emulation and (equation-based) evaluation."

So an ABM is a model of interacting agents. But what is an agent? "An **agent** is a persistent thing which has some state we find worth representing, and which interacts with other agents, mutually modifying each other's states. The components of an agent-based model are a collection of agents and their states, the rules governing the interactions of the agents and the environment within which they live." (Shalizi, 2006) Figure 3.1 shows a visualization of the parts that make up an ABM. The interested reader is referred to (Dam et al., 2012) for a more elaborate description of Agent Based Modeling of Socio-Technical Systems.

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<sup>1</sup>as Chapter 4 will demonstrate, the effects of EPR and NRP in Mobile Phone End of Life Networks display all three properties

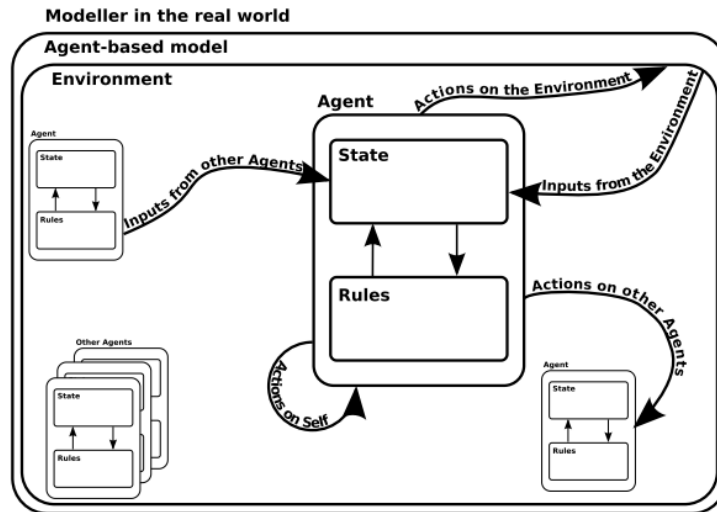


Figure 3.1: Visualization of an Agent Based Model framework displaying interactions between the different parts of the model. Source: Nikolic (2009)

In ABMs, time proceeds in discrete steps, called **ticks**. Every tick, the agents change their states according to the rules that have been specified. The order in which the agents change their states is random. As the rules in ABMs are often very dependent on the states of the other agents, this randomness introduces the issue that with the same input values, an ABM can generate different output values. ABMs are therefore not *deterministic*. Instead, they are *stochastic*. This feature of ABMs forces the modeler to run the model multiple times under the same input values to obtain a representative set of output values. (For more information see Section 6.1)

### 3.2.2 Advantages of using ABM

- **Heterogeneity:** ABM allows to specify different rules and values for every agent. This qualifies ABM for modeling systems with a lot of heterogeneous parts (agents).
- **Based on behavioral rules:** The modeling in an ABM requires the modeler to specify behavioral rules and interactions for every agent. These rules are often easy to understand: "if X, do Y." If the behavior of agents and their interactions are known, than the emergent macro effects can be estimated using simulations. In addition, using behavioral rules instead of abstract equations make the model easier to communicate to laymen compared to other types of modeling.

- **Spatially explicit:** ABM allows one to place the agents on positions in space and let them interact with other local neighboring agents.
- **Bounded rationality:** there is a lot of flexibility in the specification of rules for agents. There is no technical need to adhere to strict rationality requirements.

### 3.2.3 Disadvantages of using ABM

- **Replications and computation intensive models make exploration difficult:** because of inherent randomness in the order in which agents are controlled and path dependent effects, two runs with exactly the same input values can/will generate two different outcomes. This requires one to replicate runs and work with distributions of outcomes. This makes the exploration of models with many different combinations of input values very computationally intensive.
- **Large number of assumptions required, making it difficult to replicate model by others:** The heterogeneity and flexible rules which are the strengths of ABM, are also the foundation this weakness: they require a large number of assumptions. Often there is no room to communicate all these assumptions in one paper, which makes it difficult to replicate the modeling efforts of other researchers.
- **Long time to build:** programming the agents and all their rules and then testing them to see if they perform as expected, takes a lot of time. This makes ABM less suitable for rapid problem exploration.
- **Causal structures not immediately identifiable** because of the use of individual agents and their independent decision capability, ABMs do not have the property that based on the output, the modeler can trace the causal structures that caused the output. To identify the causal structure, different sets of analyses have to be performed. In the case of complex system with long effect chains, this can be a notable challenge.

### 3.2.4 How ABM will be used

The objective of this thesis is to study the environmental and economic effects of EPR and NRP in a Mobile Phone End of Life system consisting of connected and dependent agents. The economic effects will be investigated from the perspective of different agents in the system. It is emphasized that this does not mean to accurately predict the effects in reality. Instead, the objective is to explore the consequences of a set of data-driven assumptions.

Goal	Indicator	Unit
<b>Environment</b>	Energy Demand [CED]	MJ
<b>Economics</b>	Agent profit	\$
	Combined agent profits	\$
Social	Access to communication	% consumers with phones
Reverse logistics performance	Collection rate in %	

Table 3.1: Overview of Performance Indicators

### 3.3 Focus on Economic and Environmental effects

This thesis frames the problem as a societal problem. This choice forces one to study the behavior of multiple actors and take into account the goals of the actors involved. Because this research will have to limit itself to the study of the effects of policies on a small set of indicators, a choice needs to be made on which indicators are important. This thesis assumes society is concerned with the overall sustainability of the mobile phone end-of-life system. Following Gnoni and Lanzilotto (2012), sustainability is translated into the Triple Business Line principle: minimize environmental impact, maximize economic impact and maximize positive social impact. Based on these three goals, three concrete indicators are identified. This thesis does not study the social impact. One indicator is added, which indicates the overall success of the reverse logistics system: the collection rate. The collection rate is the amount of phones collected through different collection channels, as a percentage of the total market. Collection rate is not the focus of this thesis, but is used at some points in this thesis.

#### 3.3.1 Cumulative Energy Demand as proxy

There is more than one way to measure environmental impact. In this thesis the approach by Neto and Bloemhof (2009) and Ovchinnikov et al. (2013) is followed. These studies use the Cumulative Energy Demand (CED) as a proxy for the entire environmental impact. CED is used because it is a simple, compact indicator to use, and often converges with other, more elaborate, indicators. (Quariguasi-Frota-Neto and Bloemhof, 2012; Huijbregts et al., 2010)

### 3.4 Subquestions

The objective of this thesis is to study the environmental and economic effects of EPR and NRP in a Mobile Phone End of Life system consisting of connected and dependent agents. The economic effects will be investigated from the perspective of different agents in the system. In order to investigate these effects, first a theory is required. The mechanisms through which EPR and NRP can affect economics and the environment need to be identified. The first subquestion is thus:

**SQ1:** *How can EPR and NRP, in theory, affect economics and the environment?*

SQ1 is answered in Chapter 4, where hypothesis H1 is presented that states how EPR and NRP can affect economics and the environment. It introduces a theoretical *effect chain*. Because Mobile Phone EOL Networks are complex (See Chapter 4) a model will be constructed to explore hypothesis H1. SQ2 addresses what such a model should include:

**SQ2:** *What are the requirements for modeling the environmental and economic effects of EPR and NRP in Mobile Phone End of Life Networks?*

The requirements specified in SQ2 mainly consist of Hypothesis H1 and choices in scope and system boundaries. Based on these requirements, an ABM is constructed:

**SQ3:** *How does an Agent Based Model look like that fits the requirements specified in SQ2?*

Notice that SQ3 represents a design artifact. The ABM is presented in Chapter 5. In Chapter 6 this model is analysed. The main question is splitted into the economic effects (SQ4a, SQ4b, SQ4c) and environmental effects (SQ5a, SQ5b, SQ5c):

**SQ4a:** *What are the economic effects of EPR in the model specified in SQ3?*

**SQ4b:** *What are the economic effects of NRP in the model specified in SQ3?*

**SQ4c:** *What are the economic effects of EPR/NRP in the model specified in SQ3?*

**SQ5a:** *What are the environmental effects of EPR in the model specified in SQ3?*

**SQ5b:** *What are the environmental effects of NRP in the model specified in SQ3?*

**SQ5c:** *What are the environmental effects of EPR/NRP in the model specified in SQ3?*

SQ4a – SQ5c are answered in Chapter 6.

### **3.5 Thesis Structure**

The subquestions and the modeling framework described by Dam et al. (2012) have been combined into one thesis structure. Figure 3.2 displays a visual overview. In general, there are three parts: the problem analysis, model design and finally the model analysis. Insights from these three parts are used to draw conclusions about the economic and environmental effects of EPR and NRP.



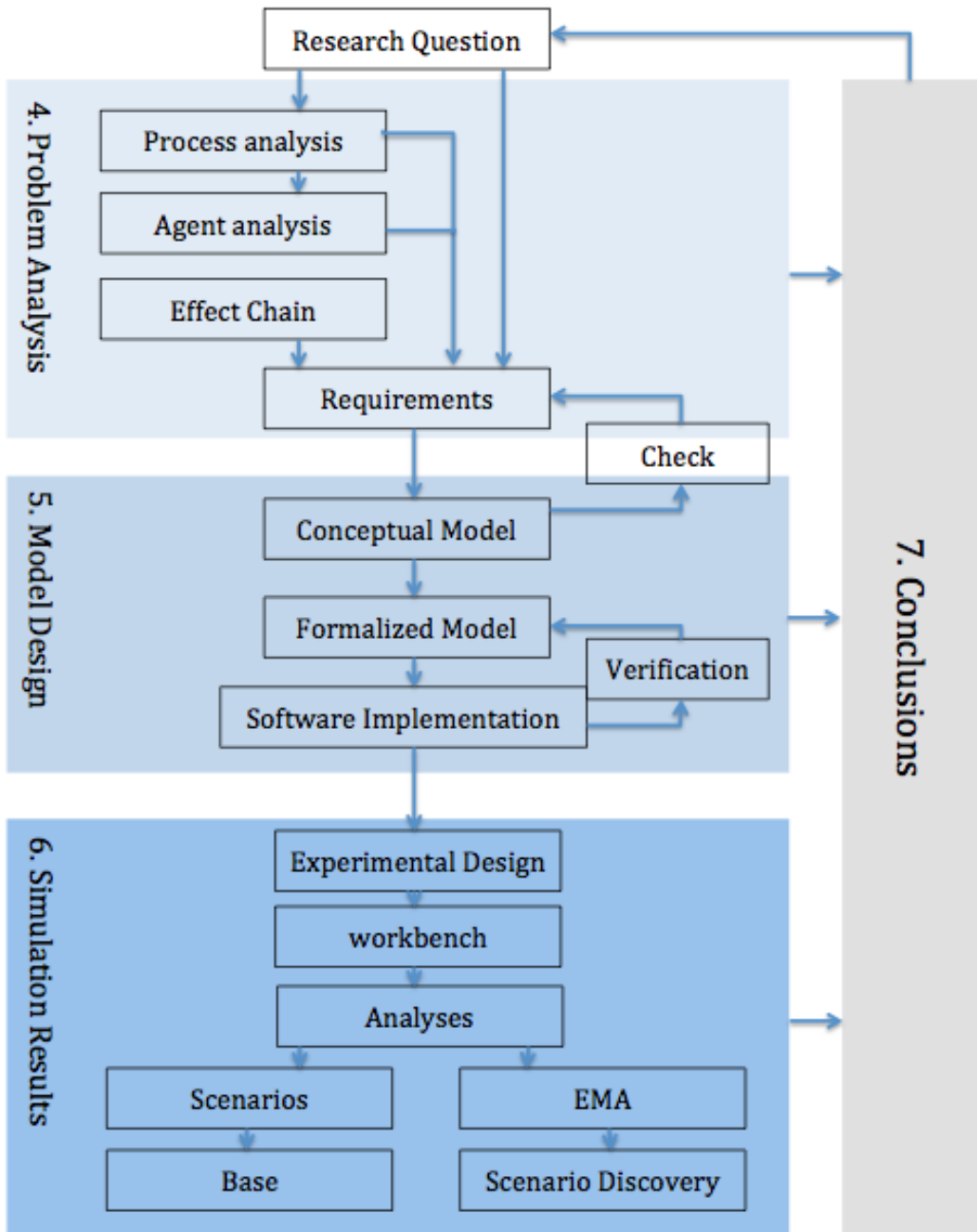


Figure 3.2: Thesis Structure

## 4 | Problem Analysis

The purpose of this chapter is to describe the existing knowledge on Mobile Phone End of Life networks, in a condensed manner to facilitate model design. First, Section 4.1 describes the Mobile EOL network from a process perspective. Section 4.2 describes the agents that perform the activities in the process including the goals the agents are assumed to have. Both sections frequently use observations reported by Geyer and Doctori Blass (2010). Section 4.3 argues that the EOL system is a complex network. Next, Section 4.4 explores how in theory EPR and NRP policies can affect economics and the environment. Using the insights described in these sections, a list of requirements is presented in 4.5. These requirements have to be met to model the effects of the policies on Mobile Phone EOL Networks and determine the required scope of the model.

### 4.1 Process Analysis

This section describes the activities and flows of the Mobile Phone End of Life process. The process diagram, presented in Figure 4.1, is based on the process diagram of Doctori Blass et al. (2006). Most of the activities are performed by one type of agent. However, some activities, for instance the collection, can be performed by multiple agents. For this reason, activities are discussed separately from the agents. The Agent Analysis is presented in the next section.

**1. Manufacturing** The process starts with the manufacturing of phones. Inputs such as metals, plastics, glass and energy are converted into different types of phones, ranging from low-end *feature phones* to high-end *smartphones*. In order to attract more consumers, manufacturers keep increasing the technological features of their phones. Increasing technological requirements can make older phones obsolete, well before their physical life ends.

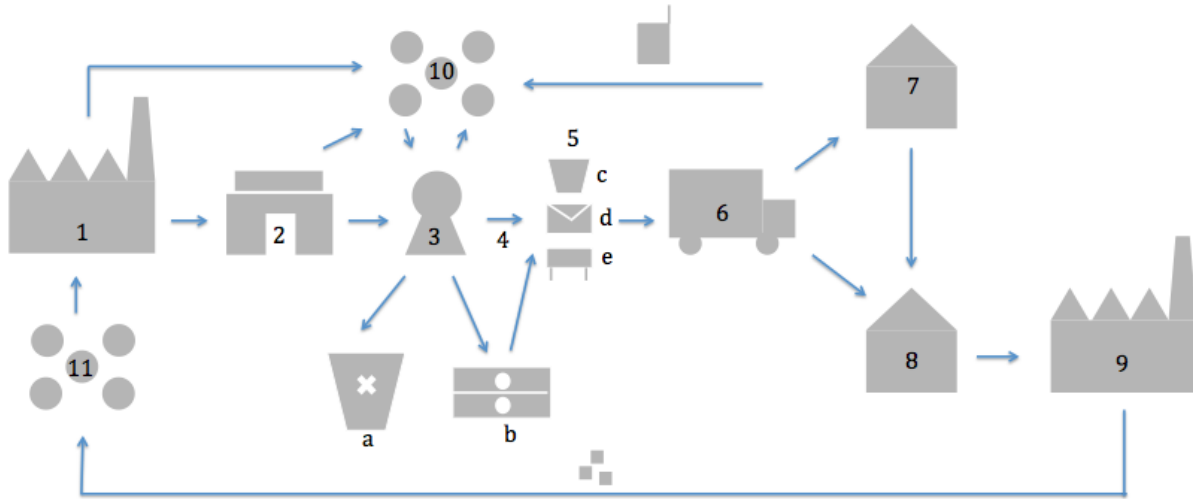


Figure 4.1: Process Diagram of Mobile Phone End of Life Network

**2. Sales** Next the phones are sold to consumers and companies. Mobile Phones are commonly sold in combination with a (data) plan. (Ovchinnikov et al., 2013). In addition to the sales of new phones, also refurbished phones are sold to consumers and companies, in most cases without a data plan. In the case the sale of a refurbished phone displaces the sale of a new phone, this is called *demand cannibalization*. Besides the registered sale of refurbished mobile phones, consumers also sell phones to each other (10). The size of this grey circuit of second-hand phones is unknown, but probably quite large. Finally, new innovative business concepts may change the process diagram presented in Figure 4.1. For example, some companies, mainly Service Providers, recently started a new type of activity: they lease the phone for a fee per month. When consumers want a new phone, their old phone is still owned by Service Provider and they are obliged to return the phone. This business strategy is called *servicizing*. It is currently unknown how many servicizing arrangements are present in the Mobile Phone industry and what the impact of such arrangements will be.

**3. Consumption** When consumers and companies buy a phone, they use it on average between twelve and twenty-four months before they dispose of it. (Wilhelm et al., 2011) This is fast, considering the lifetime is claimed to be up to ten years.(Nokia, 2005)

**4. Disposal** Disposal means the disposal of a phone. It includes points a-e, shown in Figure 4.1, which are further described in the next paragraphs.

**a. Landfilling** If mobile phones are thrown away and the trash processing agents do not get out mobile phones from the trash, then the mobile phones are landfilled with the other trash. From an environmental and health perspective, this is the worst option (Geyer and Doctori Blass, 2010), since the metals and acids in the mobile phones have long term detrimental effects for the environment and for human health. In addition, from a closed loop perspective, the metals contained in the mobile phones are lost.

**b. Hibernation** When consumers do not use their retired mobile phones anymore, they often do not throw them away or dispose of them. Instead, they stockpile them at home. (Saphores et al., 2009) This stage is called *hibernation*. The phones have not left the system and still have the potential to be reused or recycled. There is a lack of comprehensive studies that investigate why consumers prefer to hibernate their phones and how much phones are currently hibernating in the drawers and basements of consumers. Tanskanen (2009) does report a survey containing reasons from consumers on why they did not recycle their phone. Having a phone as back-up (33%), not knowing that recycling was an options (20%) or not knowing where to hand in the phone (17%) were frequently mentioned reasons.

**5. Collection** There are several collection methods. They can be classified in the following manner:

- (c) Collection bins: these are bins where a consumer can drop off their phone. There are very large bins (capacity: 1.000 phones) and there are smaller bins (capacity: 30 phones). (Doctori Blass et al., 2006).
- (d) Envelopes: Consumers may also have the option to send their phone in using an envelope. Sometimes this envelope was included in the box when the phone was shipped. Other times the consumer can send in the phone using a regular envelope.
- (e) One Day Events: Events that are organized to collect as much electronic devices as possible.

It depends on the specific arrangement whether consumers receive money for their phone. If they do this it is called *targeted buybacks*. A targeted buyback program is often combined with envelopes as a collection method because the envelopes make it possible to keep track of the individual phones. Consumers can look up online what their phone is worth, given its condition. If this price is high enough, the consumer can choose to send in the phone. The collection company checks if the phone matches the reported condition. In that case, the money is transferred to the consumer. This is the

strategy that is used by many refurbishers.

Collection methods and strategies followed by companies are not static. Innovative companies are exploring new combinations all the time. An illustration of such an innovation is the ecoATM. (The Economist, 2012) It is a combination of an automated collection bin and an Automatic Teller Machine (ATM). Consumers place their phone in the machine. It uses advanced technology to verify the condition of the phone. It then places the phone on an online market on which multiple companies can place bids. Within seconds, the bids are made and the highest bid is offered to the consumer. If the consumer accepts the bid, the phone is collected and the consumer immediately receives the money offered by the highest bidder. Currently there are around 500 ecoATMs stationed in the USA, most of them in California. By combining multiple activities of the process diagram presented in Figure 4.1, innovations such as the ecoATM illustrate that technology and new business concepts have the potential to quickly create a major change in a system such as Mobile Phone End of Life Networks.

**6. Transport** When phones have been collected, they have to be transported to their next destination. The economics and environmental impact strongly depends on the distance between the disposal location and the next destination of the phone. Practices have been reported where electronic waste is transported to Africa to be processed. (Osibanjo and Nnorom, 2007) Besides the fact that in some cases these processes have had a negative impact on health and the environment, it also affects the environmental and economic performance of the processing. In addition to distance, the method of transportation is also a factor of influence. (Doctori Blass et al., 2006)

**7. Refurbishing** When phones get to a refurbishing facility, the first step they pass is the *fate-determination*. In this step the decision is made whether a phone is refurbished or not, which depends on the condition of the phone and the market demand for that type of phone. Many phones only receive some minor cosmetic operations and are then ready to be resold. (Geyer and Doctori Blass, 2010) Component reuse or large fixes are less common, although these practices may change if phones and their materials become more expensive.

**8. Recycling** Currently recycling of mobile phones concentrates on (precious) metals. Metals account for roughly 15% - 20% of the mass of the phone, where copper, aluminum and iron account for most of the metal mass. On average, only four metals are recycled: Copper, and precious metals gold, silver and palladium. (Geyer and Doctori Blass, 2010)

**9. Smelting** In the current recycling practices, all handsets are crushed without prior disassembly. Then they are smelted in ovens and finally the metals are regained again. There is a large difference in smelting practices between the OECD countries and the emerging markets. In large modern metal smelting facilities the purity of the metals is high (up to 95-99%, Rochat et al. (2007)). This is much higher than the purity of the metals in smelting facilities in the emerging markets, which is at an average purity of 25% much lower.(Sheoratan, 2011) After the smelting, the metals are most often sold to the commodity market (11) where they can be purchased again by manufacturers.

## 4.2 Agent Analysis

This section describes the agents that perform the activities from the Mobile Phone EOL process and the goals they are assumed to have.

Manufacturing	Sales	Consumption	Collection	Refurbishing	Recycling	Smelting
Manufacturers	Service Providers	Consumers Companies	Municipalities NGOs Refurbishers (Recyclers)	Refurbishers	Recyclers	Smelters

**Original Equipment Manufacturers (OEMs)** Manufacturers make profit when they sell new phones. Therefore, the goal of manufacturers is stated as profit maximization through maximization of phone sales. These phones will mainly be new phones, but could also be refurbished phones. (Ovchinnikov et al., 2013) In order to attract consumers, OEMs increase the functionality of their phones. The new functionality often requires new technology, making the phones with other/older technologies obsolete. (Ovchinnikov et al., 2013)

**Service Providers** Service Providers make most of their profit from selling contract and data plans. They use new mobile phones to attract new customers. This is one of the drivers for consumers to dispose their old phones. (Wilhelm et al., 2011) If consumers renew their contract, they get large discounts on a new phone.

**Consumers** With already more than 6 billion phones world wide, (Worldbank, 2012), it can be assumed that almost every consumer has a need for communication and some type of mobile device.

Consumers make two choices: to buy a phone and to dispose their phone. A behavioral study showed that there are four segments of consumers which all have different preferences on which phones they prefer to buy. (Ovchinnikov et al., 2013) The disposal behavior of consumers with regards to collection channels is not studied in detail. The disposal behavior in general is reported by Wilhelm et al. (2011), Nixon et al. (2008) and Darby and Obara (2005).

In addition to consumers, companies also often buy phones and dispose the phones of their employers. It is unknown how large this percentage is and how the behavior of companies differs from consumers.

**Municipalities** The role of municipalities in processing EOL phones lies in the collection of phones, mainly through curbside pick-ups. Their goal is stated as being able to collect at lowest cost. In a lot of countries, municipalities are responsible for the collection of waste. To constrain the landfilling of electronic products, landfill bans have been affectuated. The agent that wants to dispose the electronic products now has to pay heavy fines for the disposal. Combined with the extra collection infrastructure that is required for electronic products such as mobile phones, this placed an extra financial burden on municipalities. Therefore, one of the main reasons for implementing EPR has been to relieve municipalities of this duty.

**Non Governmental Organizations** Non Governmental Organizations (NGOs) are involved in the collection of phones as well. Their motivations are a) to protect the environment b) sell the collected phones to recyclers or refurbishers to raise money. NGOs most often organize One Day Events or place Collection Bins. Their goal is often to collect as many phones as they can, regardless of quality.

**Refurbishers** Refurbishers are mainly independent refurbishers, such as ReCellular<sup>1</sup>. Refurbishers collect mobile phones from OEMs, companies, other collectors and consumers directly. Their goal is to obtain as many phones in good condition and with a profitable demand for the phones. To estimate the demand the refurbishers often have large and detailed databases containing information on the willingness to pay for different types of phones. Refurbishers often use targeted buybacks to collect the right type of phones from consumers. The price they offer depends on the condition of the phone and the willingness to pay estimated using their database. Phones that are not in good condition or which cannot be sold for other reasons, are often transferred to recyclers. Often this is

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<sup>1</sup><http://www.recellular.com/> Last viewed: 2013-07-22

free, or at low cost, although actual prices depends on the specific circumstances and agreements.

**Recyclers** For recyclers, the recycling of mobile phones forms only a small portion of their business, as they process many types of electronic waste. (Geyer and Doctori Blass, 2010) The recyclers only consolidate and pre-process the mobile phones before sending it to large smelting facilities. As they are paid by the amount of metals they send to the smelting facility, the goal of recyclers is to collect as many phones as possible. Geyer and Doctori Blass (2010) report a small profit of \$0.5 for a recycled phone, provided the collection activity is performed by a different agent, otherwise the costs would be too high. When considered that older phones had higher metal concentrations (Geyer and Doctori Blass, 2010), the goal of recyclers is to obtain as many old phones as cheap as possible.

**Smelters** There is a very limited number (2 - 3 for Europe, similar numbers for the United States) of facilities that are able to smelt mobile phones at high efficiencies. An example is Umicore in Belgium. (Bollinger, 2010) In other continents there are more small-scale smelters. These smelters however process at lower efficiencies and qualities.

**Governments** Governments are not included in the Agent analysis as they are not part of the EOL process. However, governments are stakeholders in this issue as they create and enforce policies. The goal of governments is to ensure that mobile phone operations are environmentally sound.

### 4.3 Mobile Phone End of Life Systems as Complex Networks

This section argues that Mobile Phone EOL systems are complex networks. This statements is based on the findings from the Process and Agent analysis. To summarise those findings into words, definitions are required.

First the term systems is explained. This thesis defines **systems** as "a simplified representation of reality as a set of connected functional parts within clearly defined boundaries." It is argued that to study the effects of EPR and NRP correctly, the parts need to be studied together. The reason is that the parts are connected, as demonstrated in the Process analysis. The process steps each have different functions. The perspective should be a systems perspective because EPR and NRP affect economics and environment through the multiple connected parts, instead of only one part. Secondly, it is argued that the Mobile Phone EOL system is a special type of system. It is a network. This thesis defines a **network** as being "a system with multiple connections and/or dependencies



between its parts". The Mobile Phone EOL system is a network because recyclers and refurbishers are connected, but recyclers can also be connected to consumers directly. Refurbishers are connected to consumers and to manufacturers. The network character is amplified by the fact that there are multiple parties that perform the activities.

The fact that there are multiple agents is one of the factors (1) that lead to the argument that Mobile Phone EOL networks are complex. The other factors are that the agents are autonomous (2) and they have different goals (3) (an example is that refurbishers want high quality phones with less focus on costs, while recyclers focus mainly on costs and metal content) and that the agents are dependent on each other (4) (under NP, recyclers need other parties to perform the collection). There is a multitude of definitions of complexity. This thesis defines **complexity** as the property of problems that display factors 1-4 and are therefore not strictly optimizable.

The notion that End of Life Networks are complex has been one of the main reasons for the development of a simulation model.

## 4.4 EPR and NRP Effect Chain

This section answers subquestion SQ1: How can EPR and NRP, in theory, affect the environment and economics?

The answer is based on what EPR and NRP are supposed to do, combined with a hypothesis. The hypothesis connects EPR and NRP to economics and the environment. The way EPR and NRP can affect economics and the environment is called the **effect chain**. The objective of the model which will be presented in Chapter 5 is actually to find out whether this effect chain actually produces the results as stated in the hypothesis. But first, the workings of EPR and NRP are described:

The EPR paradigm was adopted with two functions in mind: a) to relieve municipalities the financial burden of e-waste management, and to provide incentives to producers to b1) reduce resources, b2) use more secondary materials, and b3) undertake product design changes to reduce waste (OECD, 2001) This thesis investigates the effects of EPR through (a), (b1) and (b2). Effects through re-manufacturing (b3) are explicitly not investigated, as there is already literature that has studied the effects of EPR through (b3). (Atasu et al., 2009)

NRP means that phones cannot be refurbished. This affects the fate-determination choices of refurbishers. In addition, some NRP (such as simlocks) can stop consumers from freely reusing or

returning the phone. Summarised, NRP affects the flow of phones.

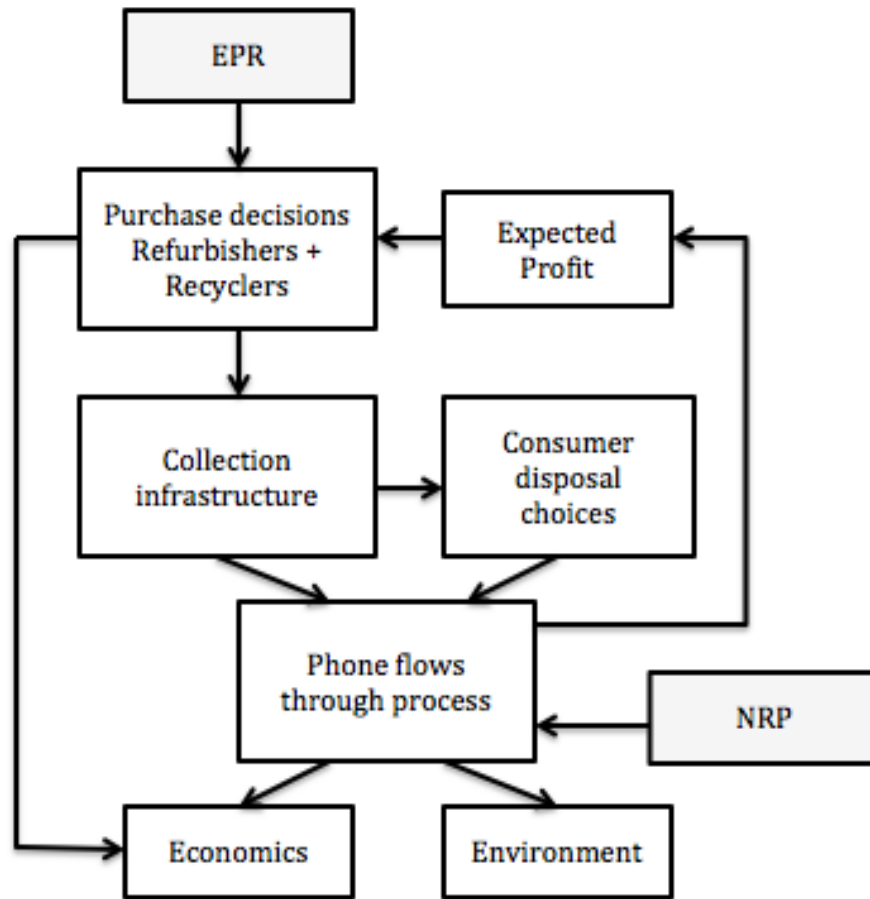


Figure 4.2: Effect chain of EPR and NRP on economics and environment as stated in Hypothesis H1. Note the feedback loops between decisions of refurbishers, recyclers, consumers and phone flows.

It is important to state which type of economic and environmental effects of EPR and NRP are researched in this thesis. The descriptions show that EPR and NRP do not have relevant *immediate* effects that can directly be attributed to these policies. An example of what an immediate economic effect would be are the costs of issuing new legislation. Those costs could be directly attributed to the legislation but are not of interest for this thesis. Instead, the effects of EPR and NRP are **consequential**. Based on the findings and choices described in the Process and Agent analysis, hypothesis H1 is formulated on how EPR and NRP consequentially affect the environment and economics.

**Hypothesis H1:** *EPR and NRP affect choices of manufacturers, refurbishers and recyclers. Their choices determine the collection channel infrastructure. The availability of collection channel types partly determines the disposal choices of consumers, which in turn affect the collection channel purchase choices of refurbishers and recyclers. Combined, the collection channel infrastructure and disposal choices of consumers direct the flows of mobile phones through the different steps of the process. Because the different process steps have different economic and environmental effects, EPR and NRP affect economics and the environment.*

One of the motivations for constructing a simulation model is to find if there is generative evidence for this effect chain.

The effect chain requires the following phenomena to be true:

- H1a: different types of collection channels attract different types of mobile phones
- H1b: the flow through the process depends on the type of mobile phone
- H1c: the economic and environmental effects of the processes are sufficiently large and significantly different
- H1d: collectors make rational collection channel purchase decisions based on profits or costs.

The problem analysis indicates that H1b is true: for some phones (for example, phones that are still relatively new) consumer demand exists and thus these phones will be refurbished. Phones that are too old can only be recycled. To support the hypothesized effect chain, it should be researched whether there is also evidence that suggests H1a, H1c and H1d are true. This falls outside the scope of this thesis and is noted as an interesting direction for further research.

## 4.5 Model Requirements

This section falls between the problem analysis and model design. The requirements contain important choices on what and what not to take into account. The model that will be designed has to include:

- the most important requirement is that the model should be able to test the effect chain specified in section 4.4. This requirement leads to the specification of consumers, manufacturers, refurbishers and recyclers and their choices. Specifically, a mechanism/logic has to be implemented that allows changes in the purchase decisions of refurbishers and recyclers.

- the dependencies between the agents, in particular between refurbishers and recyclers
- include (market) mechanisms that connect the sales of new phones to sales of refurbished phones and the mining of new metals with recycled metals.
- include the relevant steps from the process analysis and the agent described in the agent analysis. Here the choice has been made not to include Service Providers and phone/data plans. In addition, usage is confined to consumers and smelting process can be performed by the recyclers.
- make it possible to specify multiple segments in collection channels, consumers and phones.

If these general requirements are elaborated, this will lead to a large list of detailed requirements. Combined with rules that state the required decision mechanisms, this will form the description of the conceptual model, which is presented in the next chapter.



# 5 | Model Design

This chapter presents the computer model that has been constructed to study the economic and environmental effects of EPR and NRP on the Mobile Phone EOL network. First Section 5.1 presents the conceptual model, starting with a narrative and then the most relevant agent choices are explained. Then Section 5.2 formalizes the model in pseudocode and states the assumptions that underpin the model. Section 5.3 contains a brief formal check of the model requirements. Section 5.4 briefly explains how the model was implemented in software. Section 5.5 described issues in scaling. Section 5.6 verifies whether the software model works as specified in the formalization. Finally, Section 5.7 closes by reporting initial optimization efforts to increase the speed of the computer simulations.

## 5.1 Conceptual Model

### 5.1.1 Purpose of the model

The purpose of the EOL model is to investigate the implications of the implementation of the EPR and NRP policies and strategies regarding the collection of end-of-life mobile phones. The use of the model is thus restricted to answering these questions; all other effects and interactions that occur in reality have been omitted, in order to simplify the model and improve its usability.

### 5.1.2 Narrative

The EOL model is based on the behavior and interactions of agents involved in the mobile phone end-of-life system. Figure 5.1 shows a visual depiction of the process that forms the backbone of the model. All phones flow through this process. The process starts with *manufacturers of new mobile phones* (1), the Original Equipment Manufacturers (OEMs). These new phones have a *function*, which is related to the *current technology trend*, and a *price*, which is set according to its

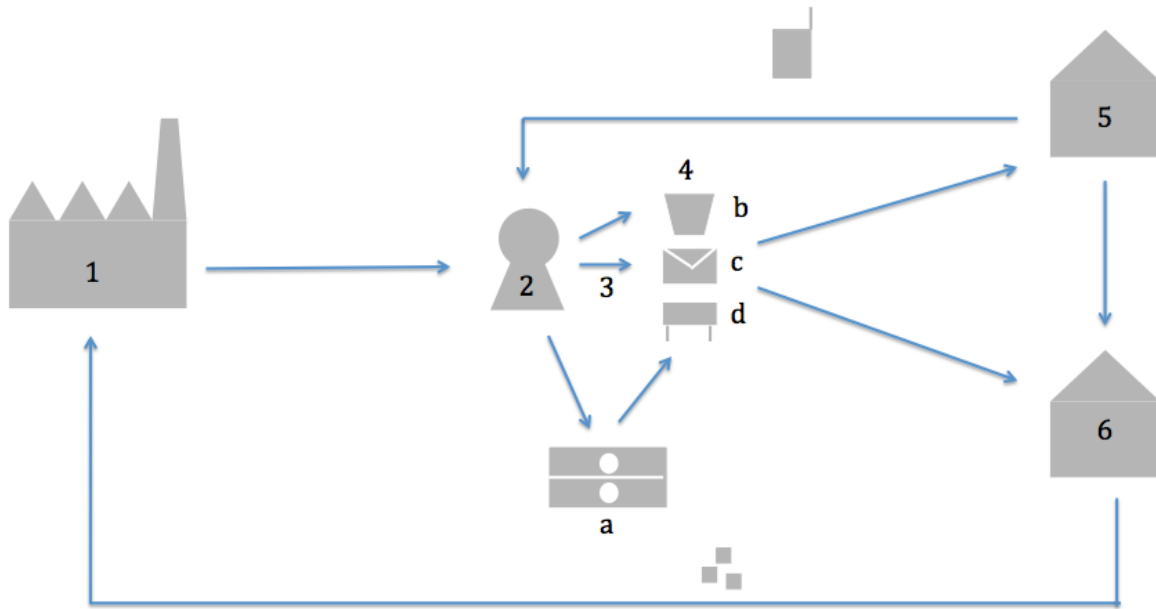


Figure 5.1: Simplified Mobile Phone EOL process, based on the process diagram in Chapter 4, that is used as the backbone of the model

function. Phones are sold to the *consumers*. Consumers (2) are assumed to always have a need for communication. They scan all the phones which are on sale, then buy the phones which, according to their preferences, have the best combination of price and function. When they have bought a phone, they will use it for a number of months, until the function of the phone drops below their growing minimum *function threshold*. This means the phone no longer serves their needs and it is time to dispose the phone (3). Consumers now have three choices:

- put the phone in their *drawers* (a) and let it hibernate for an unspecified time.
- they can put it in a *collection channel* if one is available to them: either a *collection bin* (b), in an *envelope* (c) or hand it in at an *one day event* (d).

In addition to disposing the phone to collection bins, envelopes and one day events, there is another way that a phone can be collected: If a one day event is organized and a consumer has access to the event, the consumer uses the opportunity to return all the phones that are hibernating in its drawer. If the phone is disposed in a collection bin or an envelope, the phone will be collected (4) and delivered to the owner of the collection channel: this can be a *refurbisher* (5) or a *recycler* (6). In the case the phone gets to a refurbisher, it needs to make a choice: will I refurbish the

phone or pass it on to a recycler? This choice is called the *fate-determination*. If it decides to refurbish the phone, the phone is set back on sale. Now a consumer who is looking for a phone, can also buy this phone. If a consumer does so, the refurbisher gets the revenue. To attract the desired phones, refurbishers can put buy-back prices on certain types of phones. It is assumed they can only do this with envelopes. This *targeted pricing* will increase the disposal revenue of the envelope, making it more attractive for consumers. Some phones however, cannot be refurbished. Their function is too low to make it attractive to refurbish. These phones are passed on to the Recyclers. A Recycler *smelts* the phones and sells the metal back to manufacturers. Manufacturers will now use the recycled metal instead of mining new metal. When the phone is smelted it again leaves the model and its initial and monthly energy demand, which has been added with each step of the process, is added to total energy demand.

With every tick the economics, energy demand, collection rates and collection channel usage are registered.

### 5.1.3 Model Layers

The model conceptually consists of two layers: a Process Layer and a Choices Layer. Figure 5.2 visualizes these layers. The environmental and economic effects are largely determined in the process layer. How the phones flow through the process layer is determined in the underlying choices layer.

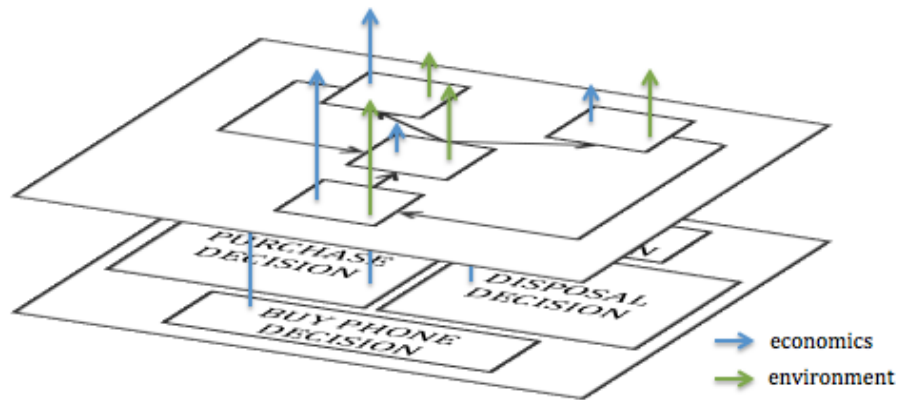


Figure 5.2: Two layer of the model: the process layer and the choices layer.



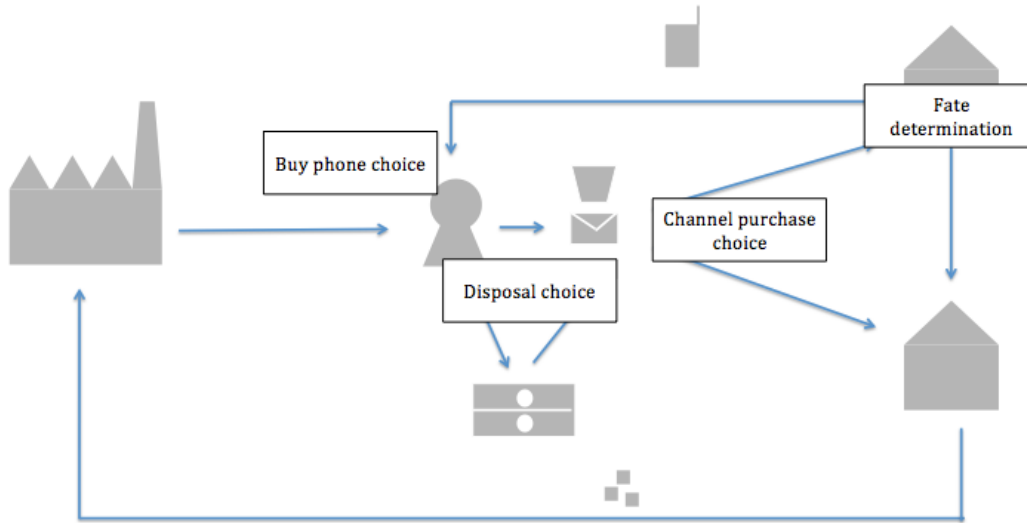


Figure 5.3: Key Choices

#### 5.1.4 Key Choices

Each phone follows its own route through the process and reaches its destiny based on a number of key decisions made by different agents. EPR and NRP will possibly influence these decisions, either direct or indirectly. Changes in decisions can change the flow of phones through the process, thus affecting the energy demand and economic impact of each individual phone over its lifetime. The four key decisions are:

**Fate-determination by refurbishers** For each phone a refurbisher receives, it needs to make a decision whether to refurbish the phone or send it to a recycler. This decision is made on a cost-benefit analysis, where the benefit is determined by the expected price a future consumer is willing to pay for the phone and the costs are the costs a refurbisher makes in refurbishing and transporting the phone. In the model refurbishers determine the fate of a phone by searching for consumers with a need for a phone, sufficient budget and a function threshold high enough so that they will use the phone for at least a number of months.

**Collection channel purchase decision by refurbishers and recyclers** Refurbishers and recyclers<sup>1</sup> have to buy collection channels in order to receive phones from the consumer. The

<sup>1</sup>Buying collection channels is not in all cases required for recyclers. Recyclers can also receive phones from refurbishers

purchase of a collection channel creates an option for a consumer to dispose its phone to. The consumer however makes an independent choice which collection channel it selects to dispose its phone.

The choice of refurbishers and recyclers which collection channel to purchase depends their profit expectation, based on the historic profits they have gained from using that channel.

EPR changes the collection channel purchase decision. EPR sets a collection target which overrides profit as the mode of decision making. The agent responsible for the collection of mobile phones (in case of EPR: refurbishers, in case of EPR/NRP: recyclers) will now strive towards collection maximization at lowest cost, until the collection target is reached. Hypothesis 1 states that these changes will influence the collection channel infrastructure, which in turn affects the collection channels available to consumers and therefore the disposal choices of consumers. This then affects the flow of phones through the system which affects economics and energy demand.

A complete overview of the factors influencing the collection channel purchase choice is shown in Figure 5.4

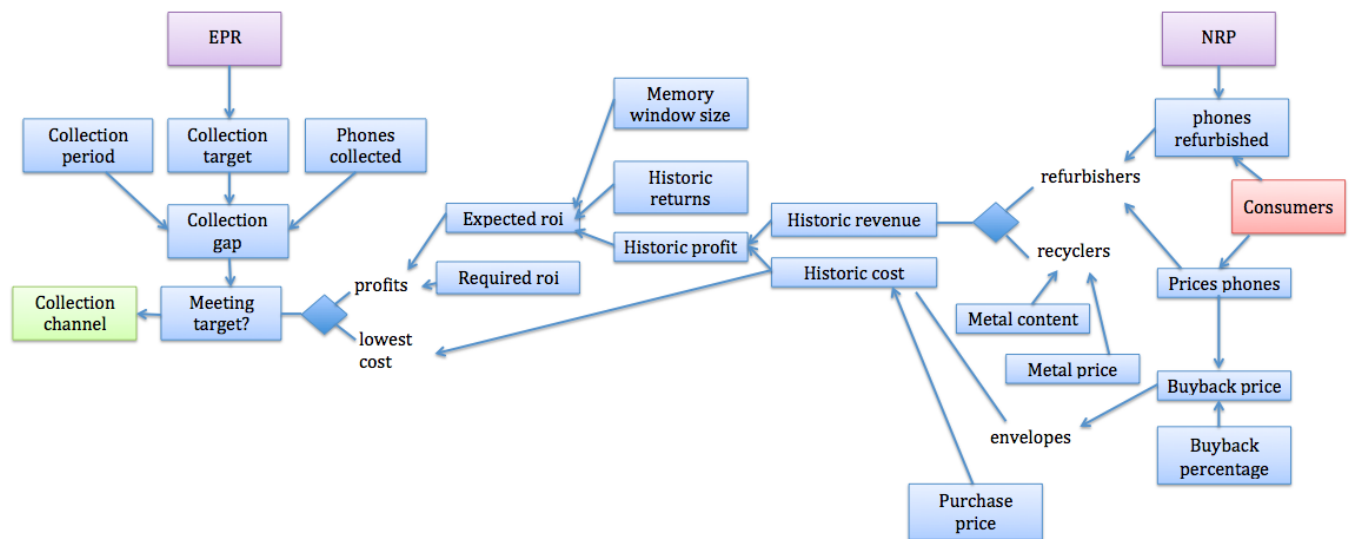


Figure 5.4: Factors influencing the collection channel purchase choice or refurbishers and recyclers. The diagram shows how EPR, NRP and the disposal choices of consumers indirectly affect the collection channel purchase choice.

**Phone disposal decision by consumers** Consumers make an independent decision which channel they use to dispose their phone. This choice is modeled as a utility maximization, based on

disposal ease and revenue of the channels that are available to a consumer. Consumers only receive revenue for their old phone by choosing envelopes. Availability of disposal channels is determined by refurbishers and recyclers. An overview of the factors influencing the disposal decisions of consumers is shown in Figure 5.5.

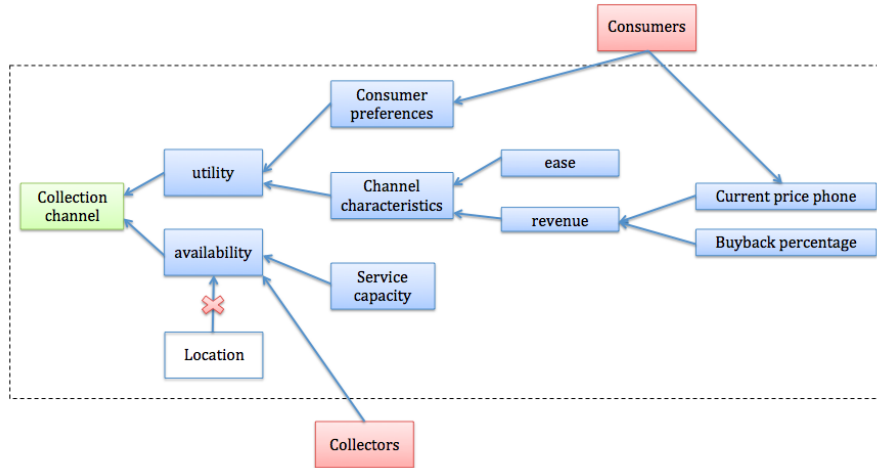


Figure 5.5: Factors influencing the choice through which collection channel (including drawers) a mobile phone is disposed

**Phone choice by consumers** Consumers have a choice to buy a new or refurbished phone. If a consumer who used to buy new phones now buys a refurbished phone, this is called *demand cannibalization*. Consumers are modeled to make a rational choice when buying a phone. First they scan the market for available phones that have a function higher than their function threshold and a price lower than their budget. If more than one phone fits these requirements, the consumers will buy the phone with the highest utility. Here utility consists of function that is maximized and price that is minimized. Two consumer segments with different preferences have been defined: one segment favors function over price. The other segment favors price over function.

## 5.2 Formalization

### 5.2.1 Model Pseudocode

This section presents the model in pseudocode. The idea of pseudocode is that it is code without being tied to one specific language. It is readable to every programmer, who can use the pseudocode

to implement the model in a programming language of choice. Pseudocode concentrates on *what is said* without having to worry about *how it is said*.

**Remarks:** At some points `item i` is used. This means that the parameter it refers to has more than one value. It indicates that the product or agent comes in different variations.

`make choice` indicates a multi criteria choice. See Section 5.2.2 for more information on this procedure.

**Main procedure** The main procedure calls the procedures of the agents. The procedures are called after each other. Within each agent procedure, the agents are called randomly. Setup procedures are not shown. The function `trend` represents the generations of phones with increasing functionality.

```
run every tick [  
  set function trend: function trend + 1  
  
  manufacturers  
  phones  
  consumers  
  refurbishers  
  recyclers  
  one day events  
]
```

**Manufacturers** The most important function of manufacturers is to manufacture phones. The `manufacture phones` procedure is called by a consumer when a new phone is bought. Because the `make_choice` procedure requires agents as input, every tick the manufacturer produces one phone of each phone type, so that consumers always have a newly manufactured phone to choose from. The energy demand of manufacturing of a phone is added if the new phone is actually bought.

```
manufacturers [  
  manufacture phones  
  if collection target percentage > 0 [  
    set target volume: sold phones * collection target percentage
```

```

    if EPR [set collection agent: refurbisher]
    if EPR/NRP [set collection agent: recycler]
]
ask collection agent [set collection target: target volume]
]

```

Notice that there is a parameter `sold phones`. This parameter denotes the sold phones over a specified period (`collection_target_period`). With every tick, this parameter is updated. We have implemented a database system with records to keep track of the number of sold phones.

```

manufacture phones [
  repeat for i [
    set function item i phone_function * function_trend
    set function_devaluation item i phone_function_devaluation
    set original_price maximum_price_phone - ((function_trend - function)
      * function_devaluation)
    set metal_content: item i start_metal_content
    add energy demand "manufacturing"
    set required new metal: required metal - available recycled metal
    add energy demand: energy demand of one-of technologies
      with type "mining" * required new metal
  ]
]

```

**Consumers** Currently there are two consumer segments defined. They differ in their preferences (see `make_choice` procedure).

```

consumers [
  if not have phone [ try to buy phone ]
  if have phone [ add energy demand "usage" ]
  phone suffices if function > function threshold
  if phone not suffices [dispose phone]
  set function threshold: function trend - trend lag
  set money: money + (start money / (trend lag + 1))
]

```

```
]
```

```
buy phone [  
  make shopping list of phones with  
    price < budget and function > function threshold  
  set best phone: make choice from shopping list  
  buy best phone  
  ask manufacturer [manufacture phone]  
]
```

```
disposal decision: [  
  set available disposal list:  
    all disposal options to which consumer is connected  
  if disposal option is envelope [  
    set revenue characteristic of envelope:  
      buyback percentage * current price of phone  
  ]  
  set best disposal option: make choice from available disposal list  
  dispose phone to best disposal option
```

**Refurbishers and Recyclers** Refurbishers and recyclers can both decide to purchase one collection channel per tick. They are conceptually the same except that refurbishers refurbish phones (after fate-determination) and recyclers smelt phones.

```
refurbishers [  
  determine fate of phones  
  
  make purchase decision  
  empty collection channels  
  update expectations  
  update records  
]
```

The fate is determined by assessing the costs and revenues. A function gap is defined to mitigate the occurrence of superfast transfers, which ramp up the energy demands due to transport.

```
determine fate: [  
  if current price of phone > refurbishing cost  
  and any consumers with budget > current price  
    and function threshold < function [  
  and function > function threshold of consumer + function reserve  
  and reuse allowance of phone is true [  
    set phone: on sale  
    add energy demand "refurbishing"  
  ]  
]
```

```
recyclers [  
  smelt phones  
  
  make purchase decision  
  empty collection channels  
  update expectations  
  update records  
]
```

it is assumed that 100% of the metal is recycled at 100% quality.

```
smelt phones: [  
  add metal content of phone to commodity market  
  set revenue: metal content * metal price  
  add energy demand "recycling"  
]
```

The next decision is the purchase decision. Notice that because the logic is that refurbishers and recyclers will base their expectation on historic profits, a form of memory is required. In the implementation of the current model, a database system consisting of records is constructed. It contains the revenues and costs per phone and from which channel the phone came. Using this database system, the expectations are updated.

```

make purchase decision: [
  if meeting collection target [set decision mode "profit"]
  if else [set decision mode "cost"]

  if decision mode = "profit" [
    set best channel: channel with highest expected profit
      based on historic profits
    set return on investment of best channel:
      expected profit based on historic profits / purchase costs
    if return on investment of best channel >
      required return on investment [
        purchase best channel [
          make connections to (service capacity)
          number of consumers
        ]
      ]
  ]
]
if decision mode = "cost" [
  set best channel: channel with lowest cost per phone
  purchase best channel [
    make connections to (service capacity) number of consumers
  ]
]
]

```

All the empty collection channel procedure does is empty a collection once if is full or it has been a certain specified time since it has been emptied. Envelopes are removed once they have been used.

```

empty collection channels: [
  if time since last emptied > maximum empty time
  or number of phones > capacity [
    send phones to owner of this collection channel
    if collection channel is "envelope" [

```



```

        remove this envelope
    ]
]
]

```

```

one day events [
  with probability X [
    if connected to consumers with drawers with phones [
      collect phones
    ]
  ]
]
]

```

**Phones** Every tick the age and price of the phone have to be updated. If the phone is too old, it breaks and has no function anymore.

```

phones: [
  set age: age + 1
  set new price: original_price - (function_trend - function) *
    function_devaluation
  if new price >= 0 [set current_price: new_price]
  else [set current_price: 1]
  if age > lifetime [set function 0]
]

```

### 5.2.2 General decision method: Multi-Criteria Choice

All agents have to make decisions. Often they have to make trade-offs, which means they have to balance conflicting criteria. In this model it is assumed that agents have the ability to balance these criteria by means of an internal Multi Criteria Analysis. This is based on the work of Chappin et al. (2007). It assumes that there is a set of possible options with a number of attributes which can be scored. This is called the *Attributes matrix*, which contains for each options (in the row) the values of its attributes (columns):

$$A_{m,n} = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m,1} & a_{m,2} & \cdots & a_{m,n} \end{bmatrix}$$

Each decision-maker has a predefined set of preferences. Agents are considered to be heterogeneous, thus these preferences can differ per agent. When requested every agent can construct a *Preferences matrix*:

$$P_{m,1} = \begin{bmatrix} p_{1,1} \\ p_{2,1} \\ \vdots \\ p_{m,1} \end{bmatrix}$$

Now matrix A is normalised, transformed and then multiplied with the matrix P (computing the dot products). A new  $[m, 1]$  matrix is obtained, called the *Score matrix*:

$$S_{m,1} = \begin{bmatrix} s_{1,1} \\ s_{2,1} \\ \vdots \\ s_{m,1} \end{bmatrix}$$

The best option, according the multiple criteria calculations, will now be the options that has the highest score in the score matrix. This option is returned. The procedure is summarised in pseudo-code:

```

let all options make a list of their attributes and attribute names
place these lists in the columns of a matrix
request the preferences of the decision maker
normalise the matrix
    determine min and max
    use the preferences for directions
multiply the options matrix with the preferences matrix
report the option with the highest score

```

### 5.2.3 Assumptions

The model is based on a large number of assumptions, which are listed in the table below. Appendix 11 contains explanations and discussions on the assumptions.

---

Assumption
1 No market mechanism implemented
2 Not all consumers have the same preferences
3 If refurbishers cannot refurbish a phone, they will pass it onto recyclers
4 Consumers always have a need for communication
5 In case of no policy, not all consumers have access to collection channels
6 Consumers do not distinguish between new phones and refurbished phones
7 Consumers have function threshold and a fixed budget
8 Consumers maximize utility
9 Consumers buy phones based on function and price
10 Consumers dispose phones based on access, revenue and ease
11 Phones hibernate in consumers drawers
12 Manufacturers are perfect market servers
13 Service providers only sell phones from manufacturers to consumers
14 Manufacturers do not take remanufacturing issues into account
15 Manufacturers always use recycled metals first
16 Recycled metal completely displaces new metals
17 Refurbishers and recyclers have a finite memory
18 Refurbishers and recyclers perform pilot programs for collection channels
19 One day events only target hibernating phones
20 If recyclers can afford it, they would perform the collection step
21 Under NP, refurbishers and recyclers base purchase decisions on highest expected profit
22 Under EPR, refurbishers and recyclers base purchase decisions on lowest cost
23 No landfilling or incineration of mobile phones

---

## 5.3 Requirements check

This section formally checks if the model fits requirements that were specified in Chapter 4:

- the most important requirement is that the model should be able to test the effect chain specified in section 4.4. **CHECK** This requirement leads to the specification of consumers, manufacturers, refurbishers and recyclers and their choices. Specifically, a mechanism/logic

has to be implemented that allows changes in the purchase decisions of refurbishers and recyclers. **CHECK**

- the dependencies between the agents, in particular between refurbishers and recyclers **CHECK**
- include (market) mechanisms that connect the sales of new phones to sales of refurbished phones and the mining of new metals with recycled metals. **CHECK. but no endogenous price mechanism**
- include the relevant steps from the process analysis and the agent described in the agent analysis. **CHECK** Here the choice has been made not to include Service Providers and phone/data plans. In addition, usage is confined to consumers and smelting process can be performed by the recyclers.
- make it possible to specify multiple segments in collection channels, consumers and phones. **CHECK**

## 5.4 Software Implementation

The formalized model has been implemented in Netlogo<sup>2</sup>. Netlogo is a specialized ABM programming language and software. The main advantage of using Netlogo is that it is a simple language which allows one to concentrate on the modeling. More details on the Netlogo code can be found in Appendix 18.

## 5.5 Scaling

It would be a waste of research and computing time to simulate the model with 6 billion mobile phones. Therefore, only a small number of phone agents will be created in the model. This is called scaling. If one is able to scale everything down proportionally, the conclusions can be extended to a larger system. In this thesis, it has been attempted to scale all characteristics in a similar manner. An example is the capacity of bins. In reality, bins with a capacity of 1000 phones exists. If one would insert these numbers into the model, than there would be only room for two or three collection bins, which would yield strange results. Therefore, the capacity of the bins is also scaled down. One problem arises: the capacity of envelopes cannot be made smaller than 1. If one does scale the prices, than this causes envelopes to be very cheap compared to collection bins. The

---

<sup>2</sup><http://ccl.northwestern.edu/netlogo/> created by Uri Wilensky

chosen input parameter ranges are expected to balance this scaling. This explains why some input parameters presented in Appendix 10 are not directly comparable to their real world counterparts.

## 5.6 Verification

Verification<sup>3</sup> means: "have you build the thing *right*?" (Dam et al., 2012) This means that this step verifies if the software implemented model is build according to the specifications in the formalized model. For this thesis, extensive verifications have been performed. The verification is documented in Appendix 16.

## 5.7 Optimization

In order to perform the EMA experiments explained in Section 6.4, a large number of simulation runs have been performed (over 40 runs). After initial runs with a previous version of the model, the model was found to be too slow to be used in EMA experiments. Therefore, the model has been optimized<sup>4</sup>, which resulted in an approximate five to ten-fold increase in speed. This means that an experiment which would have taken 3 full days, can now be performed in a time span of 7 hours. The optimization is documented in Appendix 15.

---

<sup>3</sup>Verification and validation are often named in one breath. Validation means: "have you build the *right* thing?"(Dam et al., 2012) Or in other words: is the model, for its specific purpose, a good enough representation of reality? Validation was not part of the scope of this thesis and is therefore not included.

<sup>4</sup>The author acknowledges Kasper Kisjes for his advise on Netlogo optimization. The optimization has been performed based on his recommendations.

## 6 | Simulation Results

The main research question this thesis investigates is : What are the environmental and economic effects of EPR and NRP in Mobile Phone End of Life Networks?

Based on existing knowledge from literature and expert opinion, four hypothesis have been formulated, comparing EPR and NRP cases to the NP case. (Hypothesis 1 has been formulated in Section 4.5).

**Hypothesis 2:** EPR leads to a higher collection rate, has positive environmental effects and increases the economic gains of refurbishers and recyclers. (H2)

**Hypothesis 3:** NRP leads to less refurbished phones, has negative environmental effects and increases the economic gains of manufacturers and recyclers. (H3)

**Hypothesis 4:** EPR/NRP leads to lower profits of refurbishers and has negative environmental effects compared to EPR. (H4)

**Hypothesis 5:** EPR and NRP will lead to changes in the types of collection channels that are purchased by refurbishers and recyclers and the amount of phones that consumers dispose in the different collection channels. (H5)

### 6.1 Experimental Design

In order to verify or falsify these hypotheses, a model of the EOL Mobile Phone system was constructed, which has been presented in Chapter 5. This means the conclusions that will be drawn in this analysis are only valid for the current version of the model under the specified input values. So the analyses have to be interpreted bearing these conditions in mind.

The EOL Model is by nature a simplified representation of reality. Therefore, the numbers cannot

be directly compared to reality. For instance, the economics of manufacturers are modeled using simplistic assumptions, simplifying the complications of the real world. This means the numbers are meant to be used for comparative analyses between policies and not as accurate calculations. So instead of representing *quantitative estimates* of economics, the indicators represent *qualitative estimates* of the consequential effects of policies. An exception is the energy demand. The parameters for absolute and relative energy demand are well supported by data, which mean that for the energy demands approximate quantitative interpretations are possible.

The experiments are designed using the classical intervention-control method. The simulations are run with exactly the same input parameter values, except for one parameter which is changed according to the policy setting. Thus the difference can be attributed to the policy parameter, as this was the only parameter that was changed.

As described in Chapter 3, ABMs are not deterministic but stochastic. This means that a run with exactly the same input values can produce different outcomes. To accommodate for this influence of randomness, the experiments are repeated a sufficient number of times. This is called the number of **repetitions**. These repetitions yield a *set of outcomes* per combination of input values, instead of one outcome per combination of input values. This results in a **spread** of outcomes.

In this case the best way to visualize this spread is the use of *boxplots*. The advantage of boxplots is that boxplots provide information about the mean and the spread of the set of outcomes. Here is some guidance on how to interpret the boxplots in this analysis part of the thesis (See Figure 6.1): the black horizontal line in the box indicates the **mean** of the runs. The entire box incorporates the 25th and 75th percentiles. These upper and lower limits of the box are called the upper and lower hinges. In other words, the box contains 50 percent of the values around the mean. The vertical lines extend to the highest value that lies within a range of 1.5 times the Inter Quartile Range (IQR). The IQR is the height of the box: the distance between the upper and lower hinges. Points that fall outside of this range are called **outliers** and are displayed by a point in the graph.

Figure 6.2 shows the boxplots for sets of individual data points.<sup>1</sup>

It should be noted though, that because a limited number of datapoints is used here (most of the time only 5 to 10 repetitions), the boxplots can sometimes give a false representation of the data. Sometimes one point in the graph is included in the box, but in another run has become an

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<sup>1</sup>The data is example data about cars in the United States from the mpg dataset contained in the ggplot2 package in R.

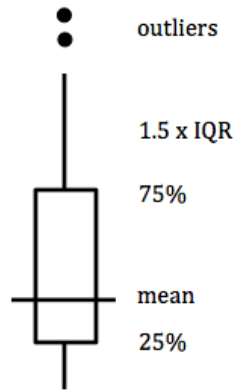


Figure 6.1: Explanation of boxplot visualization

outlier. This changes the visual appearance of the boxplot significantly, while in fact, the data has not changed that much. Because of this reason, one should remain cautious in the interpretation of the graphs.

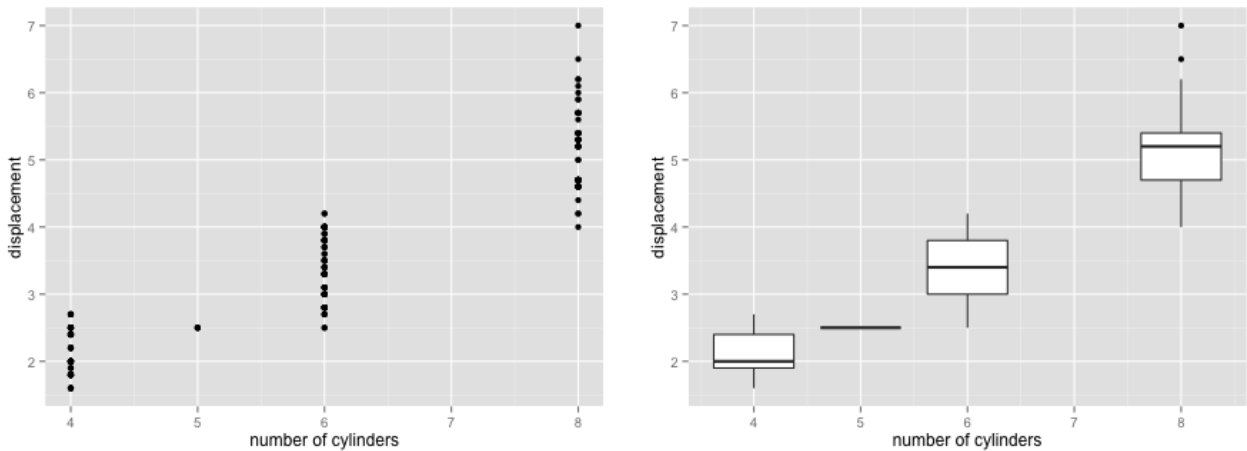


Figure 6.2: Example of boxplot visualization.

**Tests of Statistical Significance** Most times, the whiskers of the boxplots of different policies will overlap while their means are different. In order to check if the economic and environmental effects are really different under the different policies, one needs to make sure that the observed difference is not just a matter of coincidence. In the field of statistics, this is called a test of statistical



significance. If a difference is significant, it means that with a certain percentage of certainty (usually 95%) it can be stated that the difference is not due to chance. In this analysis, the differences in means of the output indicators for the different policies are tested for their statistical significance by using a non-parametric, two-tailed Mann-Whitney-Wilcoxon test<sup>2</sup>, comparing the means of the policies to NP. Results of significance tests are commonly reported in *p-values*. *p-values* lower than 0.05 indicate that the difference is **statistically significant** with a confidence of 95%. No statistical significant conclusions can be drawn from differences with a *p-value* higher than 0.05.

**Experiment Types** For this thesis, three sets of analyses have been performed:

1. **Base Scenario:** The first analysis computes the economic and environmental effects under different policies for *one combination of input values*.
2. **Uncertainty Exploration:** Next the conclusions from the base scenario are tested on their *sensitivity to changes in input values*.
3. **Scenario Discovery:** The third analysis, taking into account the uncertainty in input values, several *scenarios are explored* which lead to significantly different environmental and economic effects of NRP, EPR and EPR/NRP.

In displaying the results, the policy scenarios have been abbreviated. The numbers behind the policies indicate the values of the policy parameters. So EPR65 means that a collection target is set the 65%<sup>3</sup> of the phones sold over the past 24 months. NRP40 means that 40%<sup>4</sup> of the phones are not allowed to be refurbished.

---

<sup>2</sup>The Mann-Whitney-Wilcoxon test is a non-parametric test. This means that the distributions do not have to be similar and/or normally distributed (which is required for the student t-test). Mann-Whitney-Wilcoxon tests the null-hypothesis that the two means are from the same distribution versus the alternative hypothesis that the means are from different distributions. So:  $H_0 : \mu_1 = \mu_2$  versus  $H_1 : \mu_1 \neq \mu_2$ .  $H_0$  is rejected if  $p < 0.05$  (for 95% significance)

<sup>3</sup>65% collection target is assumed. Under the current EU WEEE directive, there are ten categories and mobile phones fall in the third category (IT and telecommunications equipment), which requires 75% of the weight should be recovered and 65% of the parts and materials. (Ponce-cueto et al., 2010)). If a producer sells only phones, then a collection target of 65% seems justifiable.

<sup>4</sup>NRP of 40% is assumed to be a realistic percentage. We have no data which suggests how many phones are not allowed to be reused

## 6.2 emaR Workbench

In order to prepare, run and analyse the experiments in this section, a set of experiment and analysis tools was required: a workbench. The possibility to use an existing workbench was explored. (the EMAworkbench: <http://simulation.tbm.tudelft.nl/ema-workbench/contents.html> ) Although there is no doubt that a connection between Netlogo and the EMAworkbench will be established in the near future. However, at the time of experimentation, the EMAworkbench was not compatible with the Netlogo output. This problem could not be solved in time.

Therefore an alternative workbench had to be developed specially for this thesis: the **emaR workbench**. It uses R to prepare and analyse the experiments, and uses the native Netlogo BehaviorSpace to run the experiments. A manual of the emaR workbench can be found in Appendix 17. The workbench is now open-source available and has already been tested by a group of students, both for their benefit and as a measure to test the tool for possible software bugs. Their reactions on the emaR workbench can be found in Appendix 17.

## 6.3 Model Analysis 1: Base Scenario

This section presents the analysis of the simulation results of the base scenario. The Base Scenario is one set of input parameter values that is considered a very plausible scenario. Where possible, parameter values have been chosen based on expert judgement by Dr. Vered Blass. In other cases, the parameters are more abstract and likely values were assumed. The Base column in Appendix 10 shows the chosen parameter values and the motivations supporting the choices.

### 6.3.1 Economic Results

First the economic results are investigated. Figure 6.3 shows the economic results.

The profit of the manufacturing agent is calculated as follows:

$$P_m = R_s - C_m - C_c \quad (6.1)$$

where  $P_m$  is the profit of manufacturers,  $R_s$  is the revenue from sales of new phones.  $C_m$  are the costs of manufacturing, which are assumed to be  $0.9 \times R_s$ .  $C_c$  are the collection compensation costs.

The profits of refurbishers and recyclers are:

$$P_r = R_s + R_c - C_t - C_b - C_r \quad (6.2)$$

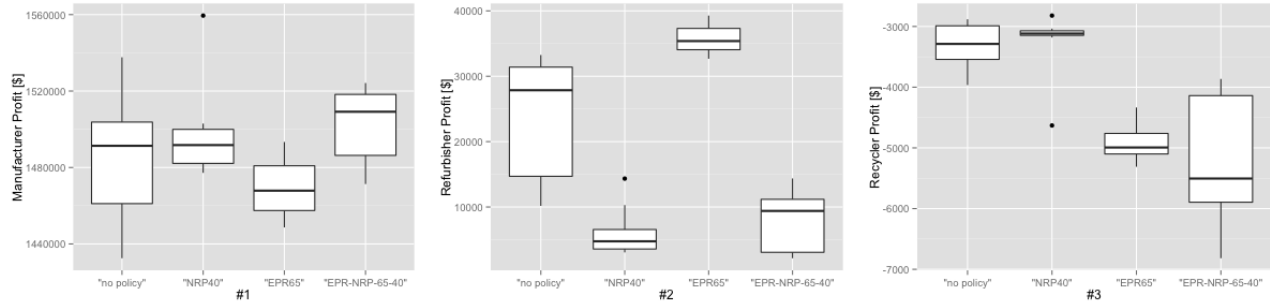


Figure 6.3: Economic Results from model under Base scenario

where  $P_r$  are the profits of respectively refurbishers and recyclers.  $R_s$  are the revenues from refurbishing or recycling. For refurbishers the revenue is the current price of the phone at the time of resale to a consumer. For recyclers, the revenue is the metal content  $\times$  the metal price per gram.  $R_c$  are the revenues from collection compensation from manufacturers.  $C_b$  are the costs for buyback, which only occur with envelopes.  $C_r$  are the costs for refurbishing and recycling.

**Observation O1:** No significant changes in manufacturer profits

Although graph #1 in Figure 6.3 seems to indicate that profits of manufacturers decrease a little, this decrease is not statistically significant ( $p=0.14$ ) That there are no significant changes in manufacturer profits might be due to the small collection compensation costs compared to the incoming revenue from new sales of phones. This also means that no evidence of significant demand cannibalization is observed.

**Observation O2:** NRP and EPR/NRP lead to significantly lower profits of refurbishers.

Refurbishers generate profit by refurbishing phones and selling them. Under NRP, they are not allowed to refurbish some phones, which leads to significantly lower profits for the refurbishers. EPR/NRP aggravates this effect, because then recyclers, paid by manufacturers, offer collection infrastructure as well. EPR/NRP decreases the number of phones that pass through the hands of the refurbisher and thus decreasing their chances of obtaining refurbishable phones.

**Observation O3:** EPR and EPR/NRP lead to significantly lower profits of recyclers.

Contrary to H4, EPR/NRP does not lead to higher profits for recyclers. This can be explained by the fact that recyclers now have to pay for the additional collection channels and transport. It is not profitable for recyclers if they have to pay for the collection of phones because their margins

on phones are too small. (Geyer and Doctori Blass, 2010) In the current model, the collection compensation per phone is a fixed value. O3 suggests the compensation per phone is too low for recyclers to benefit from the agreement. O3 suggests that EPR/NRP is not in the interest of manufacturers as they are financially responsible.

### 6.3.2 Environmental Results

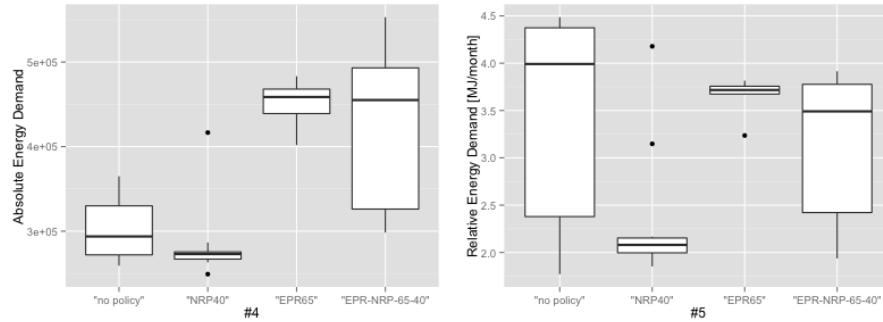


Figure 6.4: Environmental Results from model under Base scenario

**Observation O4:** EPR and EPR/NRP lead to higher absolute energy demands

Intuitively, one expects that EPR legislation would lead to lower energy demands instead of higher demands. However, accumulated energy demand is only registered when phones are recycled. So more recycled phones mean a higher absolute energy demand. In addition, if refurbished phones are sold to consumers who could otherwise not afford a phone, energy demand will also rise. Graph #4 shows that both EPR as EPR/NRP increase the total absolute energy consumption.

From an environmental perspective, it would be better if we would not use mobile phones at all. However, we cannot stop consumers from wanting access to communication. So as more consumers gain access to mobile communication, a relative measure, showing decreasing monthly energy demands per phone used, provides a more balanced indicator.

**Observation O5:** Large deviations in relative energy demand and no significant differences between policies.

The energy demand per (recycled) phone is defined as:

$$E_p = \frac{E}{m_{used}} \quad (6.3)$$

where  $E_p$  is the total energy demand and  $m_{used}$  is the total number of the months phones have been used. It has been decided to show the total energy demand per months, as it allows one to distinguish between active and hibernated phones, and means this indicator only has to be calculated at the end of each run.

Although it seems that there are large differences between the results in graph #5, the differences are not statistically significant (p=0.14 to p=0.31).

### 6.3.3 Collection Rate

In order to explain the results from the economic and environmental assessments, a deeper look into dynamics of the model is required. One indicator that conveys a lot of information is the collection rate. Figure 6.5 displays the collection rates under the different policies. The collection rate is calculated as follows:

$$CR = \frac{N_c}{N_c + N_h + N_t} \quad (6.4)$$

where  $CR$  is the collection rate,  $N_c$  denotes the number of collected phones,  $N_h$  the number of hibernated phones in drawers and  $N_t$  the number of trashed phones by consumers, which is set to 0 in the current model. The collection rate is calculated at every tick in the model. The reported collection rate is the mean of the last 10 ticks.

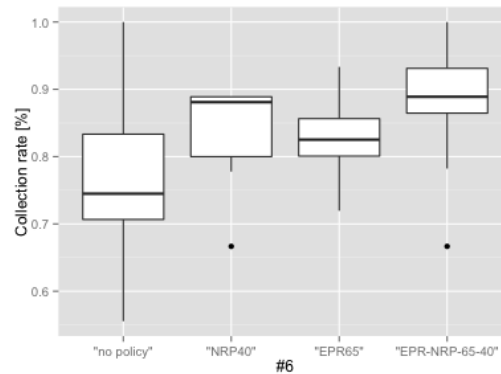


Figure 6.5: Collection rate from model under Base scenario

**Observation O6:** Collection rates very high with no significant differences as effect of policies

That EPR and EPR/NRP have no significant effects on the collection rate is not as expected. EPR sets collection targets so at least some increase is expected. This can be explained by the

observation that the collection rate is already very high (75%) under NP. Surely, at that level, not much increase is to be expected. The high collection rate contrast with observed collection rates in literature, which are between 5% and 35%.(Doctori Blass et al., 2006; Geyer and Doctori Blass, 2010) This means that the conclusions may well be skewed because of these unrealistic NP settings.

### 6.3.4 Significance tests

Table 6.1 contains the results of the significance tests.

	parameter	NRP	EPR	EPR-NRP
1	manufacturer_profit	0.58	0.14	0.11
2	refurbisher_profit	0.00	0.00	0.00
3	recycler_profit	0.39	0.00	0.00
4	absolute_energy_demand	0.17	0.00	0.01
5	relative_energy_demand	0.14	0.25	0.31
6	collection_rate	0.15	0.19	0.06

Table 6.1: Significance test of the differences in means of policies for the base scenario

### 6.3.5 Conclusion

The economic and environmental assessments point to the conclusion that EPR/NRP should be avoided as it has negative economic effects for both refurbishers and recyclers. O4 suggests that EPR and EPR/NRP both increase the number of recycled phones. Absolute energy demands increase under EPR and EPR/NRP, while no statistically significant conclusions can be made about the relative energy demands. One may be tempted to draw strong conclusions based on these results. However, O6 pointed out that the value of these conclusions is debatable due to the unrealistic high collection rate under the NP settings. Therefore, simulations with different, equally plausible, input values should be performed to check the sensitivity of these conclusions to changes in input values.

## 6.4 Model Analysis 2: Uncertainty Exploration

Section 6.3 presented the outcomes of the model under one combination of input parameter values. Analysing a base scenario is sufficient if one is confident about the *input values* and *model structure*. If there is a lot of uncertainty on one or both aspects, a base scenario can easily create a misrepre-

sentation of the model behavior. The classical approach to modeling, termed *consolidative modeling* (Bankes, 1993), is to decrease this uncertainty. This can be done by making the input values and model structure more and more accurate, using more field data and detailed assumptions.

However, "where there are uncertainties that make strong validation<sup>5</sup> impossible, the consolidative modeling paradigm will not lead to reliable results."(Bankes, 1993) This is termed *deep uncertainty*<sup>6</sup> Deep uncertainty requires a different approach: *Exploratory Modeling Analysis* (EMA) can be thought of as being the opposite of consolidative modeling. EMA takes uncertainty as point of departure. The EMA procedure is to first generate a large collection of models with alternative input values and alternative model structures (often called different models). Then the analyst looks whether patterns can be discovered in the set of generated outcomes. Data mining techniques are used to help the analyst in the exploration.

#### 6.4.1 Parameter Selection

The objective of this section is to investigate the **sensitivity** of the conclusions from the Base scenario to changes in input parameter values. This section will focus on input parameters which are most uncertain and are not supported by data (Appendix 10). A list of 18 parameters was drafted, which is displayed in Table 6.2.<sup>7</sup> Using these parameters, a large set (200 experiments) of combinations<sup>8</sup> of different values for the parameters was generated.

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<sup>5</sup>Actually, the fact that strong validation is often not possible for socio-technical systems, causes most modeling difficulties. It is the reason that models often become very large, because it is unknown whether a simple model would be a sufficient approximation.

<sup>6</sup>The definition by Bryant and Lempert (2010) is followed: deep uncertainty is the condition where parties to the decision do not know or do not agree on the system model relating actions to consequences

<sup>7</sup>parameters 8, 14 and 16 are included for comprehensiveness, but these parameter are not varied as their range includes only one fixed value. 8: Drawers do not have to be purchased so by definition purchase price is 0, 14: Ibid. 16: All consumers have access to drawers. So service capacity is by definition 1.

<sup>8</sup>There are different methods for generating a set of parameter values. *Full Factorial* combines all possible combinations. This quickly becomes computationally impossible. The next option is to draw samples from all possible combinations. Two well-known methods are: 1) *Monte Carlo Sampling/Simulation*, which draws random samples from the parameter space. 2) *Latin Hypercube Sampling* (LHS). LHS is a uniform sampling method. This ensures that all of the parameter space is equally covered.

parameters	
1	consumer_preferences_disposal_revenue_high
2	consumer_preferences_disposal_ease_high
3	consumer_preferences_disposal_revenue_low
4	consumer_preferences_disposal_ease_low
5	collection_channel_purchase_price_collection_bin
6	collection_channel_purchase_price_envelope
7	collection_channel_purchase_price_one_day_event
8	collection_channel_purchase_price_drawer
9	collection_channel_disposal_ease_envelope
10	collection_channel_disposal_ease_collection_bin
11	collection_channel_disposal_ease_one_day_event
12	collection_channel_disposal_ease_drawer
13	collection_channel_service_capacity_collection_bin
14	collection_channel_service_capacity_envelope
15	collection_channel_service_capacity_one_day_event
16	collection_channel_service_capacity_drawer
17	buyback_percentage
18	required_roi

Table 6.2: Parameters which have much uncertainty regarding their value and are varied in this analysis

#### 6.4.2 Selection of realistic experiments

As pointed out by O6, the results of the base scenario are debatable because they show high collection rates (75%) under NP, which contrast with the observed collection rates (15% - 35%) in reality. In this section only the simulation runs that have a collection rate lower than 40% (at some points in the text and figures presented as fraction: 0.4) under NP are used. These runs correspond to observations in reality. Based on those runs, conclusions regarding the effects of policies will be drawn. Although the high collection rates under NP are still possible, they have a much lower probability as they have not been observed. This procedure is a form of *model calibration*. The details on the procedure are described in Appendix 14. The selected runs will be called *realistic runs*. Figure 6.6 shows which selection of runs is used in the following analyses. Figure 6.7 shows



the distribution of collection rates within the selection of realistic experiments.

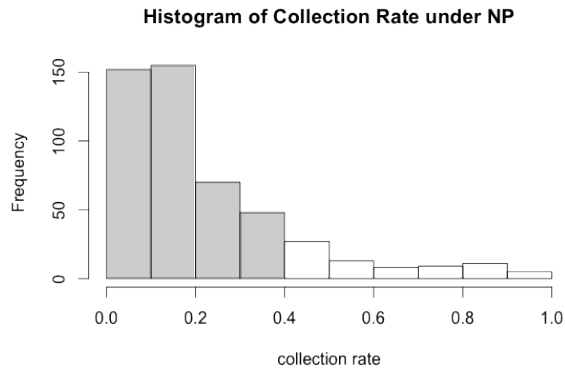


Figure 6.6: Histogram of Collection Rate under NP, showing the set of realistic experiments in dark color.

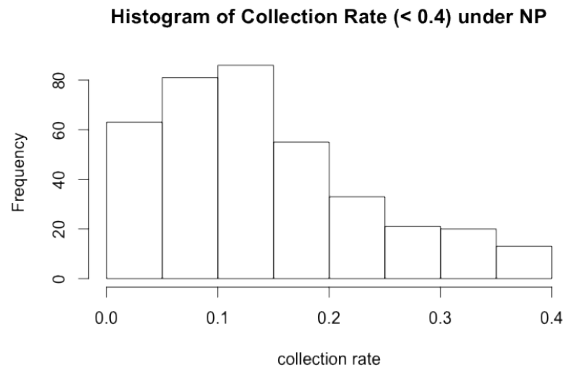


Figure 6.7: Histogram of Collection Rate for the subset of simulations under NP

### 6.4.3 Economic Results

See section 6.3.1 for the method of calculation for the profits of manufacturers, refurbishers and recyclers.

**Observation O8:** Spreads have increased and contain large amounts of outliers

Compared to the base scenario from Section 6.3, Figure 6.8 shows that the spreads and number of outliers have increased for all indicators. This indicates that most of the conclusions are strongly

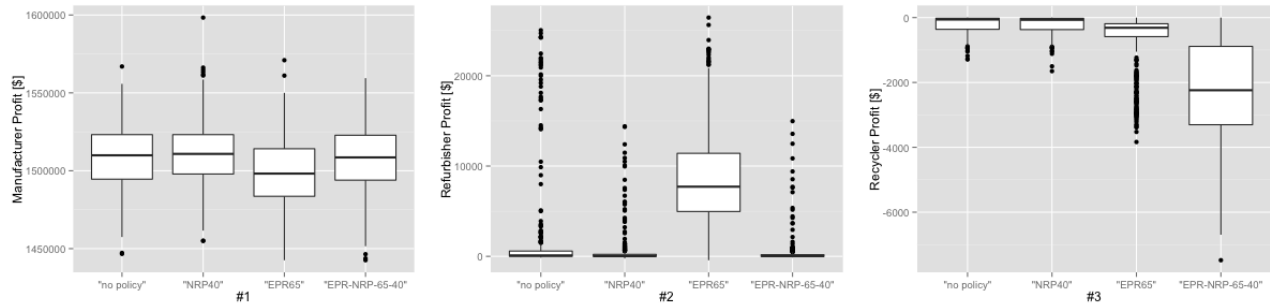


Figure 6.8: Economic Results from model under different scenarios

dependent on the input values.

**Observation O9:** Minor decrease in manufacturers profits under EPR

The profits remain mostly unaffected by the policies. There is a statistically significant but very minor decrease in the manufacturers profits. This can be due to collection compensation or decreased sales due to demand cannibalization. As this decrease does not show under EPR/NRP, it suggests a low percentage of demand cannibalization .

**Observation O10:** Refurbishers profit significantly higher under EPR

The high profits of refurbishers under NP reported in the Base case seem to be an outlier, as the majority of profits reported under NP are much lower. EPR causes a significant increase in refurbishers profits, likely due to higher sales of refurbished phones.

**Observation O11:** EPR/NRP negative impact on recyclers profit

Just as under the Base scenario, EPR/NRP has negative consequences for the profits of recyclers. There is a decrease in profits under EPR as well, but this decrease is in 75% of the scenarios very small.

### 6.4.4 Environmental Results

**Observation O12:** EPR and EPR/NRP decrease relative energy demand

Absolute energy demand of EPR and EPR/NRP increases in all scenarios. This seems to indicate that EPR and EPR/NRP are not environmentally beneficial compared to NP (which is logical as in those cases, phones are mostly just hibernated, and their accumulated energy demand is released

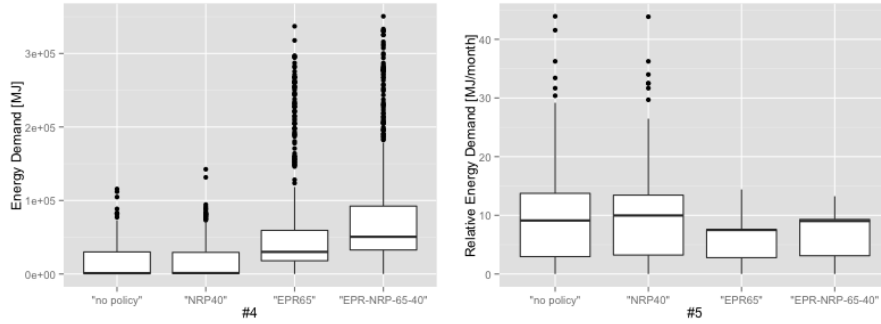


Figure 6.9: Environmental results from model under different scenarios

yet). However, the relative energy demand decreases. So EPR and EPR/NRP are actually beneficial for the environment, as the relative energy demand per individual phone decreases.

#### 6.4.5 Collection Rate

**Observation O13:** Mean collection rates of EPR and EPR/NRP suggest that collection targets increase the collection rate. However, only in approximately 35% of the scenarios under EPR, the 65% targets are reached.

The model rules regarding collection targets state that refurbishers and recyclers will keep purchasing collection channels until the collection rate reaches the specified 65%. Figure 6.10 and Figure 6.11 show that approximately 35% of the scenarios, these collection target are reached. However, both figures also show the large spread from 10% to 100%. In 25% of the scenarios, the collection rate does not reach 45%. This indicates that the effectiveness of EPR legislation strongly depends on the specific values of the input parameters.

#### 6.4.6 Significance tests

Table 6.3 contains the results of the significance tests.

**Observation O14:** No significant effects of NRP.

With the exception of a minor decrease in profits for refurbishers, NRP shows no statistically significant effects. This does not support H2, which suggested that NRP does have significant effects. However, NRP in combination with EPR does have (large) significant effects. But because in EPR/NRP manufacturers hire recyclers, these effects cannot be attributed to NRP alone. Therefore the observation is that NRP, under collections rates lower than 40%, do not have any effects.

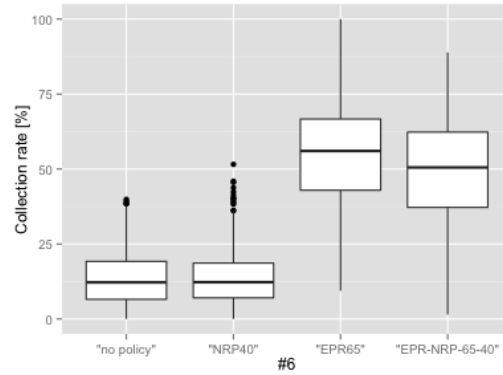


Figure 6.10: Collection rate from model under different scenarios

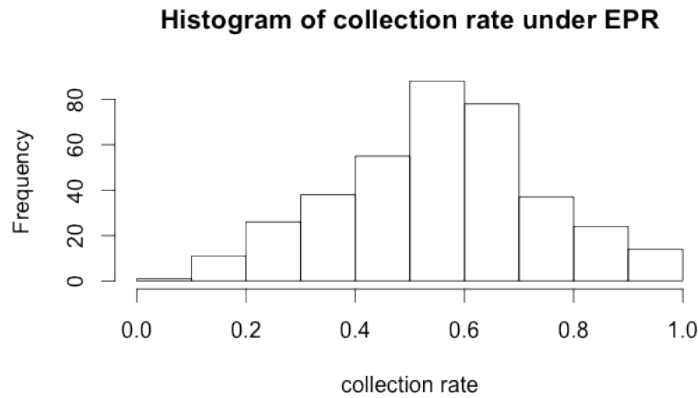


Figure 6.11: Histogram of collection rate under EPR

#### 6.4.7 Channel availability

An important question is whether the model simulations support the hypothesized effect chain (H1). Graphs #7, #8 and #9 in Figure 6.12 display the total amount of collection bins, envelopes and one day events at the end of each run.

**Observation O15:** EPR increases the amount of collection channels across all types

As stated in the effect chain, refurbishers are expected to buy more collection channels in order to reach the collection target specified under EPR. As the graphs #7-#9 show, the simulations generate the expected increases in collection channel amounts. Interesting is that all collection

	parameter	NRP	EPR	EPR-NRP
1	manufacturer_profit	0.27	0.00	0.68
2	refurbisher_profit	0.00	0.00	0.00
3	recycler_profit	0.76	0.00	0.00
4	absolute_energy_demand	0.19	0.00	0.00
5	relative_energy_demand	0.52	0.00	0.00
6	collection_rate	0.89	0.00	0.00

Table 6.3: Significance test of the differences in means of policies for the set of realistic scenarios

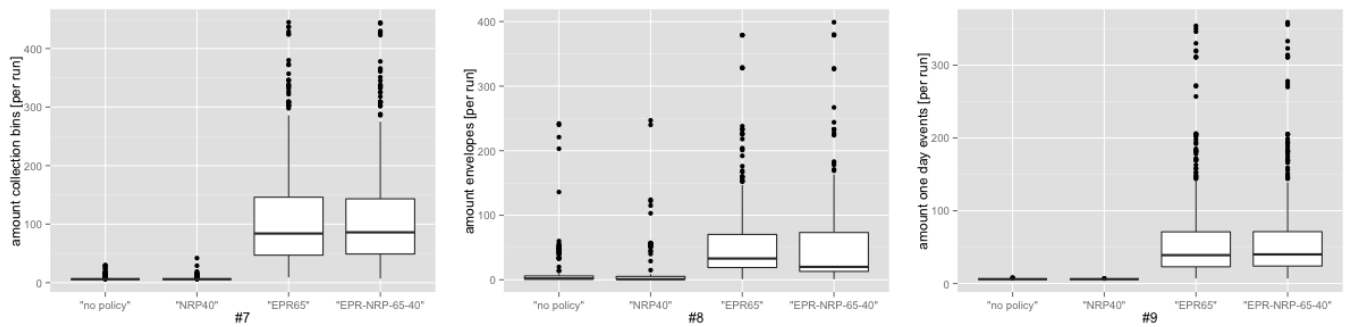


Figure 6.12: Channel availability under different policies

channel types increase. Whether this occurs every run cannot be stated based given the available data.

**Observation O16:** Under NP, envelopes are the most prevalent type of collection channel

As expected, refurbishers use envelopes as their main type of collection channel. This can be explained by the notion that envelopes allow for targeted buybacks, thus providing consumers an additional incentive. As this incentive is bigger for newer, more expensive phones, refurbishers in this way attract the phones that are most profitable for them.

#### 6.4.8 Channel usage

The next question is whether consumers respond to this increase in collection channel infrastructure. Graphs #10,#11 and #12 in Figure 6.13 show the number of phones that consumers dispose at the last tick to the available collection channels.

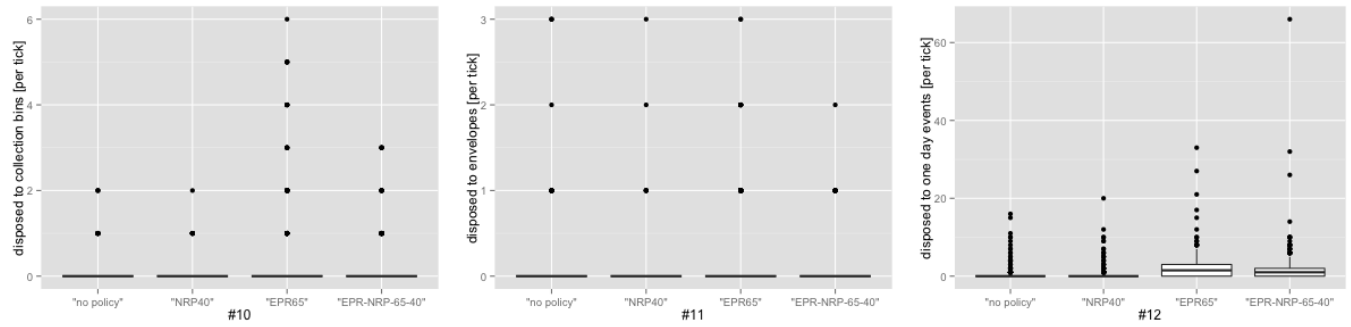


Figure 6.13: Channel usage by consumers under different policies

**Observation O17:** Channel usage of collection bins and one day events increases

Graphs #10 and especially graph #12 show that EPR increases the number of phones that consumers dispose to collection bins and one day events. The larger increase in one day events can be explained by the fact that, in the model, one day events also target hibernated phones. In that case, we have modeled that, if consumers have access to one day events, there is a fixed probability that consumers will return all their phones. If there are more one day events, more consumers have access and thus the number of disposed phones to one day events will increase.

**Observation O18:** Channel usage seems to increase less than channel availability.

When comparing #10-#12 to graphs #7-#9, it seems that the increases in channel usage are lower than the increases in collection infrastructure. (The increases in channel availability under EPR are 3-100 times larger compared to NP. Channel usage only 2 - 30 times). However, channel availability is calculated for the entire run and channel usage per tick, so the two indicators should be compared more methodical and precisely to confirm this hypothesis). If it turns out to be that a lot of channels are not used, then there is form of "over supply" of collection infrastructure, which would mean that EPR leads to high collection inefficiencies.

### 6.4.9 Conclusion

Based on the results from this analysis, it is concluded that 1) NRP has no significant effects under collection rates lower than 40% (O14), 2) EPR has positive environmental effects when measured in relative energy demand (O12), is not detrimental for the economics of manufacturers and positive for the economics of refurbishers 3) EPR/NRP also has positive environmental effects when measured in relative energy demand, but negative economic effects for refurbishers and recyclers. This suggests

EPR/NRP should be avoided.

In addition, a preliminary comparison of channel availability and channel usage suggests that EPR could lead to high inefficiencies in collection operations (O18), due an oversupply of collection channels.

These conclusions, especially the economic effects, depend strongly on the specific input values: the attitudes of consumers towards the disposal and disposal channels and the costs of the collection channels.

## 6.5 Model Analysis 3: Scenario Discovery

The objective of this section is to find out whether there are certain sets of scenarios that lead to high or low values of the indicators presented in the previous sections. These are essentially *scenario discovery* questions. This section will use one (data-mining) technique from the set of EMA tools: PRIM. (To make sure the tool works, it has first been tested on a simpler ABM. See Appendix 17, Exploring Agent Based Models using PRIM: Analysis of Predator-Prey model)

### 6.5.1 PRIM for Scenario Discovery

Bryant and Lempert (2010) have described how to use a statistical technique called Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999) to look for interesting scenarios. In this thesis scenarios are defined as being specific combinations of input values.<sup>9</sup> PRIM is a statistical bump-hunting technique. It is a algorithm that tries to find regions in the parameter space<sup>10</sup> with a high density of *interesting* outcomes. What is interesting is specified by the modeler and depends on the analysis objective. The PRIM procedure consists of the following steps:

1. **Classification:** this step classifies a number of points as *interesting* and the rest of the points as *non-interesting*. The classification depends on the analysis objective and context. It can be anything as long as the classification is *binary*, meaning that a point is either interesting or not. Practically, this often means classifying values. For example: very high values of an output indicator. The values can then be visualized by means of a *histogram*. By specifying a *threshold level* a point is either classified as interesting or not.

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<sup>9</sup>This definition is different from the definition used by Bryant and Lempert (2010). They define scenarios as a set of future states of the world that represent vulnerabilities of proposed policies.

<sup>10</sup>combinations of input values. In other words: the full set of scenarios

2. **Form Boxes:** PRIM will form boxes by decreasing the size of the box such that the *density* is increased. This is called *peeling*. When it has identified a box that cannot be made smaller without increasing the density, the box can optionally be made bigger to include more interesting points. This is called *pasting*. A simple example of the peeling procedure is visualized in Figure 6.14. The type of plots in Figure 6.14 are called *scatterplots*.

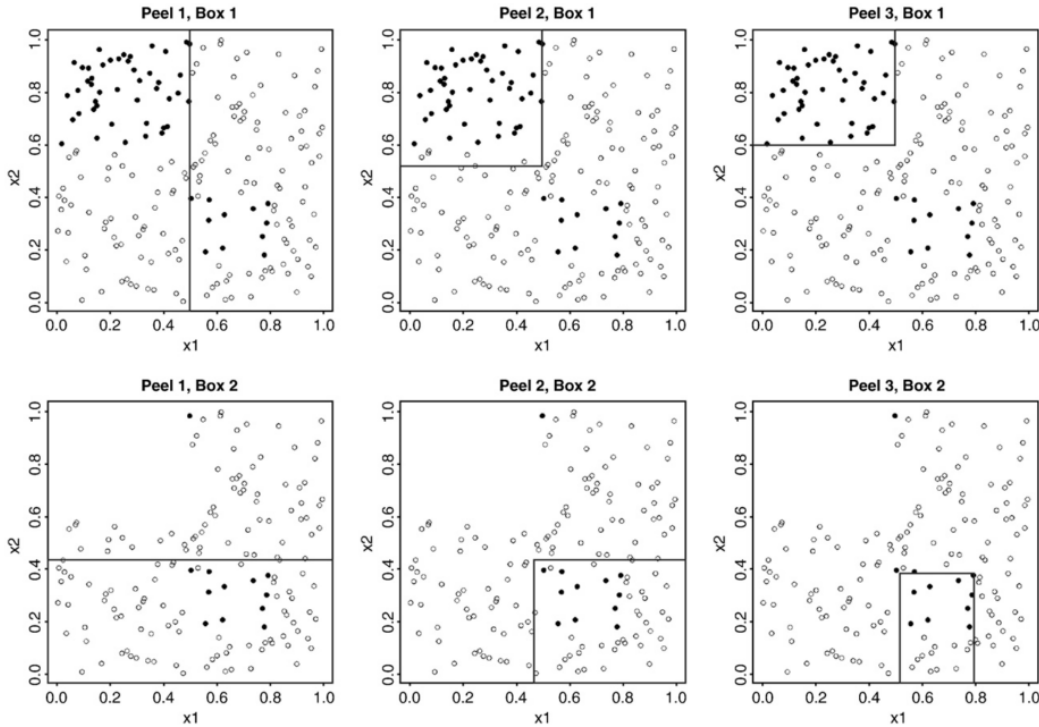


Figure 6.14: Example: Visualization of PRIM peeling procedure to form boxes. Source: Bryant and Lempert (2010)

This thesis uses an implementation of PRIM in an interactive algorithm created by Bryant and Lempert (2010), which allows the analyst to choose between multiple boxes. The choice for a suitable box is often a trade-off between *density* and *coverage*. Density is defined as:

$$D = \frac{\sum p_{b1}}{\sum p_{b1} + \sum p_{b0}} \quad (6.5)$$

where  $D$  stands for Density,  $\sum p_{b1}$  as the number of interesting points in the box,  $\sum p_{b0}$  as the number of non-interesting points in the box. Coverage is defined as:

$$C = \frac{\sum p_{b1}}{\sum p_1} \quad (6.6)$$



where  $C$  stands for Coverage,  $\sum p_{b1}$  for the number interesting points within the box and  $\sum p_1$  for the total number of interesting points.

**Visualization: Dimension plots** In the analysis of the parameter space, parameters are called *dimensions*. For two or three dimensions, scatterplots can be used to visualize the boxes. Because we humans cannot see more than three spatial dimensions, no spatial visualizations can be used for more than three dimensions. Figure 6.15 show how more than three dimensions can be visualized using *dimension plots*, or the shorthand *dimplots*.

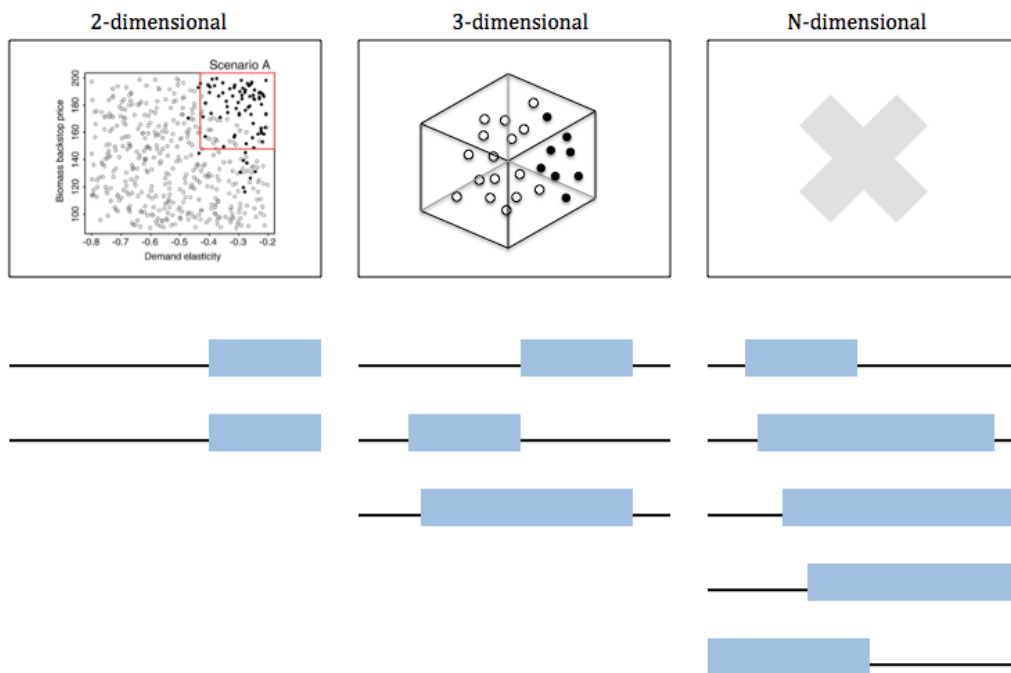


Figure 6.15: Visualization of how dimplots represent N-dimensional boxes

**Overfitting** Just as with other data mining techniques, the largest risk of PRIM is to blindly trust the results the algorithm presents. The algorithm will always be able to form a box. Random fluctuations will always cause some regions to have higher density of interesting points. A robust box will yield in every run the same region of the parameter space, with a similar density of interesting points. Now if the analyst accepts a box that only contains a higher concentration of interesting points due to chance, a new run will not yield the same

concentration of interesting points (as it was only due to chance). This is called *overfitting* and the analyst must be really careful not to identify patterns that are caused only by chance. Appendix 13.1 contains a demonstration of overfitting with random data.

To summarise: it is up to the judgement of the analyst whether a PRIM box contains a useful subset of points. Analysing the peeling plots and visual inspections of scatterplots are key in mitigating the risk of overfitting.

### 6.5.2 Energy Demand

The results in the previous section showed large spreads in environmental impact. The question is whether there are patterns, specific combinations of input values, that lead to very high or low environmental effects. This PRIM analysis (details of this analysis can be found in Appendix 13.4) explores whether there are circumstances that lead high environmental effects of EPR. Figure 6.16 shows the dimension plot. This plot shows that the absolute energy demands are higher when a refurbisher has only bought a low number of collection bins, while the price and ease for collection bins is high.

These results do not lead to an insight into why these input parameters lead to scenarios of high energy demands. Without an explanation, one risks communicating a pattern due to overfitting. Therefore, it was decided not to use this observation in drawing conclusions.

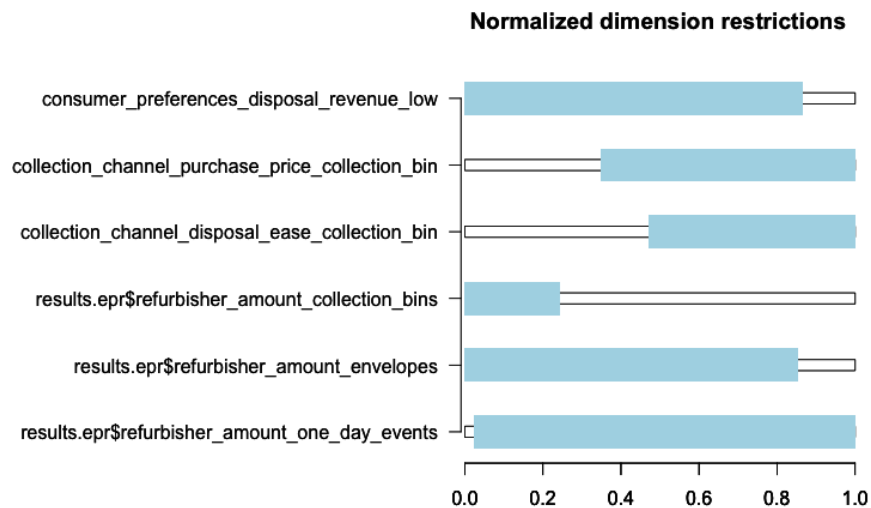


Figure 6.16: dimplot env

### 6.5.3 Refurbisher Profit

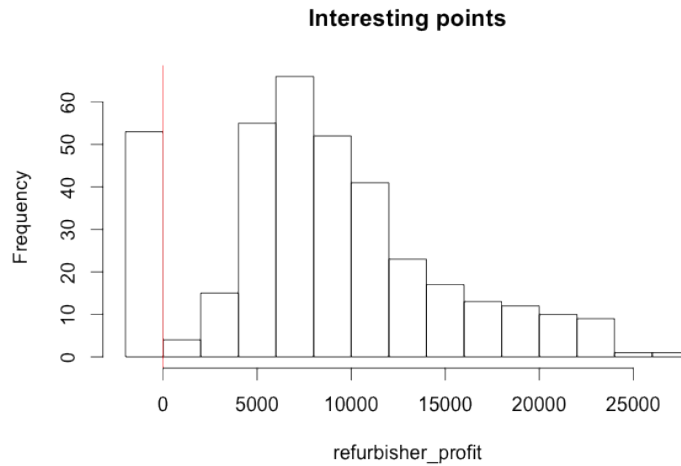


Figure 6.17: Refurbishers profit under EPR. The red line represents the classification ( $< 0$ : interesting)

Figure 6.8 showed that the profits of refurbishers under EPR were mostly positive. It also showed a large spread which stretched to below 0, meaning that in some cases, EPR leads to a negative situation for refurbishers. Figure 6.17 displays the distribution, which clearly shows a number of simulation runs with a negative profit. These negative profit runs reverse the conclusion. The question whether there is a pattern, one set of scenarios, that leads to the negative refurbisher economics under EPR. Using PRIM, cases were investigated for common patterns. All 52 cases that lead to a negative refurbishers profit have one thing in common: the refurbisher has bought more than 11 one day events. This suggests that if refurbishers use a lot of one day events as collection infrastructure, this is bad for their balance sheet.

This result can be explained by the fact that one day events mostly target hibernated phones. These phones are older and therefore not suitable for refurbishment. This means that refurbishers will make a considerable amount of costs for collecting the phones while they cannot gain profits from refurbishing and selling them.

#### **6.5.4 Conclusions**

The PRIM analysis on the negative profits of refurbishers provides preliminary generative evidence for the effect chain specified in hypothesis H1. In particular that the type of collection channel matters for the economics of refurbishers.



# 7 | Conclusions

This section presents the final conclusions of this thesis, which are based on insights from the problem analysis, model design and model analysis chapters. First the main conclusions will be stated, then the subquestions will be answered one by one. Finally, the implications for policy makers are described.

## 7.1 Main conclusions

Based on the economic and environmental assessment of EPR and NRP, using the agent-based model presented in Chapter 5, this thesis concludes that:

- EPR, in 35% of the scenarios, is effective in ensuring higher collection rates. EPR has positive effects on economics of refurbishers while the profits of manufacturers and recyclers show minor decreases. Compared to leaving the phones in hibernation, the absolute energy demand rises. But the relative energy demand decreases, thus leading to positive environmental effects.
- The results provide no evidence that the effects of NRP (without EPR) are significant, countering H3.
- The combination EPR/NRP should be avoided, in case manufacturers hire recyclers to perform the collection. In this case, it is detrimental for the economics of both refurbishers and recyclers, as well as the relative energy demand compared to EPR.

In addition, the PRIM analysis in thesis provides preliminary generative evidence for Hypothesis 1, which states that the type of collection channels affect the economic and environmental effects of EPR and NRP.

## 7.2 Answers to subquestions

These conclusions were reached by a structured answering of six subquestions:

**SQ1:** *How can EPR and NRP, in theory, affect economics and the environment?*

The Effect Chain: Economics and energy demand depend on the flows of phones passing different steps in the process. Through which processes phones flow is determined by agent choices. EPR and NRP change the fate-determination and purchase choices of refurbishers and recyclers. This can, in theory, change the collection infrastructure. One of the factors that determines the disposal choices of consumers is the available collection infrastructure. Therefore, the disposal choices of consumers are influenced. These changes in choices can affect the flows of phones which change the economics and energy demands.

**SQ2:** *What are the requirements for modeling the environmental and economic effects of EPR and NRP in Mobile Phone End of Life Networks?*

A model should include: 1) the effect chain specified in SQ1. 2) dependencies between the agents, in particular between refurbishers and recyclers. 3) include (market) mechanisms that connect the sales of new phones to sales of refurbished phones and the mining of new metals with recycled metals. 4) make it possible to specify multiple segments in collection channels, consumers and phones.

**SQ3:** *How does an Agent Based Model look like that fits the requirements specified in SQ2?*

The model has been presented in Chapter 5. It specifies four agents: manufacturers, consumers, refurbishers and recyclers. These agents interact through two objects: phones and collection channels. There are four key choices: the phone buy choices of consumers, phone disposal choices of consumers, fate-determination choice of refurbishers and the purchase choice of refurbishers and recyclers. Economics and energy demand are determined by the summation of the accumulated impacts per individual phone. By changing collection targets (EPR) or the percentage of phones that are not allowed to be reused (NRP), the differences in economics and energy demand are measured, which are attributed to the policy.

**SQ4a:** *What are the economic effects of EPR in the model specified in SQ3?*

EPR leads to a minor decrease in profit for manufacturers (O9), likely due to some demand can-

nibalization of refurbished phones. EPR is very positive for refurbishers (O10) and leads to small decreases in the profits of recyclers.

**SQ4b:** *What are the economic effects of NRP in the model specified in SQ3?*

The economic effects of NRP are not significant.

**SQ4c:** *What are the economic effects of EPR/NRP in the model specified in SQ3?*

EPR/NRP has negative effects for the profits of recyclers, likely due to high collection costs under low profit margins.

**SQ5a:** *What are the environmental effects of EPR in the model specified in SQ3?*

EPR increases the absolute energy demand. However, the relative energy demand decreases under EPR.

**SQ5b:** *What are the environmental effects of NRP in the model specified in SQ3?*

The environmental effects of NRP are not significant

**SQ5c:** *What are the environmental effects of EPR/NRP*

The absolute energy demand increases. Compared to NP, the relative energy demand decreases, yet less than EPR.

## 7.3 Implications for policy makers and industry

The results from the model simulations have the following implications:

- For policy makers: Do not focus on minimizing NRP. Under collection rates lower than 40%, the economic and environmental effects of NRP are negligible.
- For policy makers: Concentrate much more on the disposal choices of consumers. There are two motivations: 1) EPR only reached the specified collection targets in 35% of the scenarios. 2) EPR collection targets may lead to high inefficiencies due to an over supply of collection channels
- For industry: Refurbishers are best positioned to perform the collection activities. The combination of EPR with NRP and hiring recycling firms is not in the interest of any of the agents. In addition, the environmental benefits are smaller than under EPR.





## 8 | Recommendations for Future Research

### 8.1 Add empiric data on Key Choices

#### 8.1.1 Consumer phone choices

The first recommendation is to replace the phone purchase choices of consumers in the model by the utilities obtained in the behavioral study on consumer phone purchases, performed by Ovchinnikov et al. (2013). This entails 1) replacing the two consumer segments by the four identified segments, 2) adding phone plans in the purchase decision 3) replacing the parameterized utilities by the table presented in Table 8.1. If furthermore prices are determined indogeneously in the model, the possibility arises to repeat the study performed by Ovchinnikov et al. (2013). It is strongly recommended to first repeat their study using the ABM presented in this thesis, to verify if their results can be repeated using a different modeling approach.

#### 8.1.2 Consumer disposal choices

The uncertainty exploration in Section 6.4 showed that the effects of EPR and NRP are strongly dependent on the disposal choices of consumers. However, there is a lack of data on the disposal choices of consumers. In particular, there is a lack of data on which channels they prefer to use, how they make this choice and which factors they take into account in their choice. The recommendation is to use Discrete Choice Models to obtain partworth utilities for the disposal decisions of consumers. This is similar to the behavioral study on the purchase choices of consumers, performed by Ovchinnikov et al. (2013). After obtaining the results of the behavioral study on consumer disposal choices, it is recommended to first model, simulate and analyse these choices separately before including them into the current model.

**Table 1 Partworth Utilities for the Case with and without the Remanufactured Product**

	Without Remanufacturing			With Remanufacturing			
	Segment 1	Segment 2	Segment 3	Segment 1	Segment 2	Segment 3	Segment 4
Size (%)	40.5	22.5	37.0	30.6	15.8	25.2	28.4
Product = <i>NH</i>	1.005	-0.793	3.089	0.688	-0.972	3.427	1.4
Product = <i>RH</i>				-0.027	0.255	1.031	1.061
Product = <i>NL</i>	-1.005	0.793	-3.089	-0.661	0.717	-4.458	-2.461
Price = 0	7.557	9.635	3.076	8.244	4.214	6.33	1.431
Price = 50	6.487	8.602	2.473	7.427	3.072	4.639	1.501
Price = 100	4.481	8.567	2.213	6.147	4.309	3.787	1.098
Price = 150	4.702	-0.078	1.931	-4.654	2.838	2.89	0.643
Price = 200	4.070	-1.350	1.130	-5.879	0.82	1.328	0.216
Price = 250	3.367	-2.200	0.135	-5.261	1.885	0.869	-0.063
Price = 300	-14.503	-2.576	-1.539	-6.253	1.644	-0.515	-0.964
Price = 350	-1.806	-3.094	-2.427	3.482	-0.364	-1.238	-0.957
Price = 400	1.225	-4.176	-3.368	3.618	-9.095	-8.245	-1.245
Price = 450	-15.580	-13.329	-3.623	-6.871	-9.323	-9.844	-1.66
Plan = <i>L</i>				0.84	1.194	-0.241	0.203
Plan = <i>H</i>				-0.84	-1.194	0.241	-0.203
None	6.484	-1.25	-0.413	8.093	-1.071	3.983	-1.931

Figure 8.1: Partworth utilities in phone purchase decisions for different consumer segments. Source: Ovchinnikov et al. (2013)

### 8.1.3 Refurbishers and Recyclers behavior under EPR

The model presented in Chapter 6 is based on strong assumptions on the purchase choices of refurbishers and recyclers. It is recommended to investigate if there is evidence that supports the assumptions made on purchase choices of refurbishers and recyclers.

## 8.2 Perform additional analyses

The analyses on economic and environmental impact show some results, which cannot be explained using the current available data. In order to explain these results, the model should be analyzed more elaborate. The proposed order of investigation is: a) effects of EPR and NRP on collection channel purchase choices, b) the consequent effect on collection infrastructure. c) Effect of collection infrastructure on disposal choices of consumers. d) Effect of collection infrastructure on flows and types of mobile phones through the EOL network. e) Consequential effects on environment and economics.

### **8.3 Analyse current and potential role of Service-Providers**

The model presented in Chapter 6 does not include Service Providers. However, their role could be more important than assumed in this thesis. Research should not only focus on the current role, but also on the future role of Service Providers, which may change significantly as an effect of increased servicizing of mobile communication.



# 9 | Reflection

## 9.1 On the project

### 9.1.1 Switch to White-box testing

For this thesis the choice was made to concentrate directly on economic and environmental effects. Due to the scope of the project, this meant other analyses could not be performed. In the interpretation of the results we want to know: what caused this. Without further analyses, this is a sort of black-box testing. It requires us to reason what may have caused the results. I think a switch should be made to white-box testing. I believe it is wise to, before proceeding with extensions of the current model, analyse the model more extensively. It is recommended to start at the start of the effect chain. First analyse the effects in the chain separately. Then extending the analysis. One can think of this approach as a pyramid. First the effects are investigated on the first link in the chain. There is only a small amount of parameters involved, which allow for quick interpretations. Step by step the effects are extended. This widens the pyramid. It allows for more interesting conclusions, but also increases the parameters involved. By following the pyramid step by step, results can be explained using knowledge from earlier analyses.

## 9.2 On Agent Based Modeling and Exploratory Modeling Analysis

### 9.2.1 PRIM methodologically preferred, practically difficult

From a methodological perspective, combining ABM with EMA tools such as PRIM is definitely preferred. PRIM allows one to find the most important parameters that lead to interesting outcomes. As these parameters are sometimes not the parameters that one expected, it really uses the computer as a tool to help one understand the model and modeled problem. Due to the stochastic nature of ABMs, there is less certainty captured in the discovered scenarios using PRIM. With this note on

decreased certainty in mind, PRIM can be used with good results with ABMs. (See PRIM analysis of PredatorPrey model in Appendix 17.3) However, there are two disadvantages to the combination of EMA with ABMs instead of System Dynamics (SD), where it has been used more often:

1. the high computing requirements make EMA experiments very expensive or sometimes even practically impossible. The modeler then needs to make choices on which parameters to include and limit the experiments to such an extent that the stated benefits of EMA are not exploited anymore.
2. with ABMs it is harder than SDs to find the causal structures that caused an outcome. If there are multiple choices between the input parameters and the output parameters, understanding why PRIM returned certain ranges can be quite a challenge.

Thus on the one hand, the combination of EMA with ABMs is methodologically preferred. On the other hand, its practically difficult because of the computing requirements and the inability to immediately explore the causal structure that lead to an outcome. Therefore, I think we should explore solutions that use a different kind of EMA for ABMs.

### 9.2.2 Explore and analyse at the same time

The current EMA practices all follow the same two steps: 1) generate a large set of outcomes using different combinations of input parameters. 2) analyse the large set of outcomes using data-mining tools. The computing requirements form a big practical problem for the generation of the large set of outcomes. One solution is to stop generating and analysing concurrently, and instead generate and analyse at the same time, where the next generation step depends on the results of the analysis. An example of this novel approach is described by Stonedahl (2011), a student of Uri Wilensky who programmed Netlogo. Stonedahl (2011) uses **Genetic Algorithms** to explore the parameter space of ABMs and quickly converge to interesting regions. The disadvantage is that not the entire parameter space is sampled which makes the conclusions less valid. On the other hand, the fact that not the entire sample space is sampled is also the big advantage of this technique. I think this is a novel, state-of-the-art idea that is worth exploring further at Delft.

## 9.3 On simulation at TPM

### 9.3.1 Stimulate more codesharing

I have spend a lot of time in this thesis writing general code such as the workbench in R and the multi criteria choices in Netlogo. These codes can now be reused by others, which can save them a lot of time, allowing for more time to spend on doing the actual analyses. With a large number of students working on ABM related projects every year, it would be great if more code sharing is supported. The Wiki probably was created in part for this goal and I think it should be used more often to share code.

### 9.3.2 Decide whether to additionally support an R-based workbench such as emaR

First of all, I think the emaWorkbench should be supported more extensively. With support I mean that it should be possible for a student at TPM to setup and use the emaWorkbench without the help of faculty researchers. The use of the emaWorkbench is quite well documented. The installation and setup was not. Therefore I have created a Setup Manual for the emaWorkbench. This can save others the time and frustration I invested in this project. One group of TPM students has used this manual and succesfully installed the emaWorkbench.

The question is whether there is value in offering support for an R-based workbench, such as emaR, in addition to the emaWorkbench. The choice should be made by the simulation departments of TPM. emaR has already been used by other students (their reaction is included in Appendix X). Also, Appendix Y contains a manual regarding the installation and usage of emaR. Arguments in favor of offering support for an R workbench, such as emaR, are:

- the installation procedure of emaR is shorter
- emaR is easier to use for students and researchers with a background in R
- emaR already works with Netlogo

The disadvantages of emaR compared to the emaWorkbench are:

- in the current version there is no direct control over Netlogo. The hack through text files and the Netlogo BehaviorSpace can be cumbersome at times.
- a connection can be established through RNetlogo. However, this connection is quite slow according according to Jan Kwakkel.



- the emaWorkbench already offers an extensive set of tools. emaR contains just what is necessary for this thesis. (although this can be extended by using existing R packages)

If the choice is made to support emaR in addition to the emaWorkbench, then it is recommended to offer emaR as an official R package. This requires that the functions are partially rewritten and additional documentation is prepared.

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# Appendices

Pim Bernard Bellinga

Faculty of Technology, Policy and Management  
Section Energy & Industry

Master of Science Thesis

# 10 | Appendix: Input Parameters

## 10.1 Values

ID	Parameter	Unit	Lower	Upper	Base	Support
1	phone_function_high		1	1	1	
2	phone_function_low		0.1	0.5	0.25	
3	phone_lifetime_high	months	12	144	48	
4	phone_lifetime_low	months	12	144	72	
5	maximum_price_phone	\$/phone	300	700	500	
6	phone_function_devaluation_high	\$/month	10	30	20	
7	phone_function_devaluation_low	\$/month	1	10	5	
8	metal_content_high	gram/phone	30	60	12	<sup>1</sup>
9	metal_content_low	gram/phone	5	25	9	<sup>1</sup>
10	process_impact_mining	MJ/gram	1	4	2.5	<sup>2</sup>
11	process_impact_manufacturing	MJ/phone	100	250	150	<sup>3</sup>
12	process_impact_usage	MJ/month	2	10	3	<sup>3</sup>
13	process_impact_transport	MJ/trip	0	5	2.5	<sup>2</sup>
14	process_impact_recycling	MJ/phone	0.5	2.5	1.5	<sup>3</sup>
15	process_impact_refurbishing	MJ/phone	0.5	2.5	1.5	<sup>3</sup>
16	process_operating_costs_mining <sup>4</sup>	\$/phone	0	0	0	
17	process_operating_costs_manufacturing <sup>5</sup>	\$/phone	0	0	0	
18	process_operating_costs_usage	\$/month	0	0	0	
19	process_operating_costs_transport	\$/trip	0	5	1.9	<sup>1</sup>

<sup>1</sup> (Geyer and Doctori Blass, 2010)

<sup>2</sup> Vered Blass

<sup>3</sup>(Ovchinnikov et al., 2013)

<sup>4</sup>Mining costs are included in total manufacturing costs

<sup>5</sup>It is assumed that the costs of production are 90% of the revenue

20	process_operating_costs_recycling	\$/phone	0	1	0.18	<sup>1</sup>
21	process_operating_costs_refurbishing	\$/phone	0	5	2.1	<sup>1</sup>
22	preferences_relative_function_high		50	100	80	
23	preferences_relative_function_low		10	50	20	
24	preferences_relative_price_high		10	50	20	
25	preferences_relative_price_low		50	100	80	
26	consumer_trend_lag_high	months	1	24	12	
27	consumer_trend_lag_low	months	12	48	36	
28	consumer_start_money_high	\$	300	700	500	
29	consumer_start_money_low	\$	10	300	160	
30	preferences_disposal_revenue_high		0	100	80	
31	disposal_ease_high		0	100	60	
32	preferences_disposal_revenue_low		0	100	80	
33	preferences_disposal_ease_low		0	100	60	
34	capacity_collection_bin	phones	3	20	10	
35	capacity_envelope	phones	1	1	1	
36	capacity_one_day_event	phones	999	999	999	
37	capacity_drawers	phones	999	999	999	
38	purchase_price_collection_bin	\$/channel	1	20	5	
39	purchase_price_envelope	\$/channel	1	50	2	
40	purchase_price_one_day_event	\$/channel	1	50	25	
41	purchase_price_drawer	\$/channel	0	0	0	
42	disposal_ease_envelope		50	80	60	
43	disposal_ease_collection_bin		50	80	65	
44	disposal_ease_one_day_event		60	70	60	
45	disposal_ease_drawer		60	70	60	
46	disposal_ease_trash <sup>6</sup>		50	100	100	
47	service_capacity_collection_bin	consumers/channel	2	5	6	
48	service_capacity_envelope	consumers/channel	1	1	1	
49	service_capacity_one_day_event	consumers/channel	3	10	6	
50	service_capacity_drawer	consumers/channel	1	1	1	
51	buyback_percentage	%	0	0.3	0.1	
52	commodity_metal_price	cents/gram	5	200	10	<sup>1</sup>
53	refurbisher_function_gap	months	0	18	6	
54	number_consumers		50	200	200	
55	required_ROI		1	10	3	

---

<sup>6</sup>trash is not implemented in the current model



56	collection_target_period	months	24	24	24
57	memory_window_size	months	1	200	100
58	damping_percentage_meeting_target	%	0	100	100
59	max_empty_time	months	3	18	10
60	collection_compensation	\$/phone	0	5	3
61	bounded_information_buy_phones	phones	1	10	3
62	one_day_event_return_rate	1/n %	1	1000	20

---

## 10.2 Descriptions

**phone function** Phone function is a value from 0 to 1. When a new phone is manufactured, its function is set to the global trend \* phone function. The differences between [high] and [low] constitute the differences between smart phones and feature phones. The bounds are based on strong assumptions on the inherent function of a phone. A feature phone is believed to have 10 to 2 times less functionality (newest camera, internet, apps etcetera) as the smart phones.

**phone lifetime** Phone lifetime is the time until the phone breaks down. This is done by setting the function to 0 in the model. This means it will for sure be below the consumer's threshold and the consumer will dispose the phone.

It is assumed that the phones can be used for at least one year. The ticks are in months, so 12 ticks is one year. The limit for the lifetime of a phone is set to 10 years (Nokia, 2005), or 120 ticks.

**maximum price phone** The maximum phone price is the price set for a phone with the highest function. This means that phones with phone function 1 always are priced with the maximum price. This price makes it impossible for some consumers to buy the phone, if the phone is more expensive than their budget.

What matters here is not the exact value of the maximum price, but its relation to the budget of consumers. The prices reflect real-life prices. A high end smart phone such as an iPhone is priced around \$700. (Apple, iPhone 5, 32 GB, \$749, July 2013)

**phone function devaluation** The price of a phone drops as phones get older. Because there is no market to establish prices, the current price is a parametrized function of age \* phone function devaluation.

It has been observed that most smart phones drop in price quite rapid, although some smart phones

such as the iPhone seem to keep their value for almost a year. In reality, this devaluation is non-linear, but rather negative exponential. In this model a linear devaluation is chosen, such that the phone will have no value after around three years.

**metal content** The metal content is the aggregate grams of precious metals contained within a phone. Even with legislation, it is the precious metals that deliver both the most value, as well as having the largest impact on the environment, so the studied metals are limited to precious metals. Reported values in Geyer and Doctri Blass (2010) are 12 grams of recoverable metals for a high-end phone and 9 for a low-end phone. This data is from 2007 though, which is before the smart phone era. Therefore, the bounds have been stretched to be robust against uncertainty.

**process impact** If a phone passes a process, the process adds its environmental impact to the phone. When the phone finally leaves the system, the collected impact of the phone is added to the environment.

- Mining: First it is important to remark that the mining impact is calculated in the model by multiplying the mining process impact by the amount of new metals contained in the phone. The energy demand per gram of precious metal is calculated by dividing the impact of mining as reported by Vered Blass, by the average precious metal content (Geyer and Doctri Blass, 2010).

$$\text{Mining impact[upper bound] [MJ/gram]} = 43.4 / 9 = 4.8$$

$$\text{Mining impact[lower bound] [MJ/gram]} = 11.6 / 12 = 0.96$$

For the base case, the average of the two is taken.

- Manufacturing: Total manufacturing impact, including mining, is reported in Neto and Bloemhof (2009) and Doctri Blass et al. (2006) as 200-250 [MJ/phone]. Ovchinnikov et al. (2013) report 222 for a smart phone and 105 [MJ/phone] for a feature phone. For the base case an average of 150 [MJ/phone] is taken.
- Usage: Ovchinnikov et al. (2013) report the environmental impact of usage to be 53 MJ. However, they do not state over what period this impact is calculated. To convert this total number into a usage impact per tick, a time period of 18 months (Wilhelm et al., 2011) over which the total impact is accumulated is assumed.

$$\text{Usage impact per tick} = 53 / 18 = 3 \text{ [MJ/tick]}$$

Intuitively, this seems quite high, so the lower bounds have been stretched to make the analysis robust against such a claim.

- Transport: The current model is not spatial yet so an aggregate number is taken. Vered Blass reports 5 MJ. This number is divided by two as it takes two trips in the model to collect and deliver a phone.
- Recycling and Refurbishing: The following values are reported in Doctori Blass et al. (2006). Refurbishing: 1.25 MJ, Recycling: 1.5 MJ. For both 1.5 MJ is taken (Vered Blass).

**process operating costs** For the transport, refurbishing and recycling, the numbers are taken from (Geyer and Doctori Blass, 2010). The figures are from the US, from the year 2006.

**consumer preferences relative function** When consumers need a phone, they will look for phones with a function higher than their threshold. The utility they attach to a phone with a certain function is determined as such:

```
relative_function = phone_function - threshold  
utility = relative_function * relative_function_preference
```

Qualitative, the bounds are determined by the consumer segments. One of the segments, [high], has a strong preference for phones with a high function, the other segment, [low], does not have a strong preference. The exact difference between these two is determined by the values. By definition, the relative function preference of [low] will never be higher than [high].

**consumer preferences relative price** When consumers need a phone, they will look for phones with a function higher than their threshold. The utility they attach to a phone with a certain function is determined as such:

```
relative_price = phone_current_price - threshold  
utility = relative_price * relative_price_preference
```

Qualitative, the bounds are determined by the consumer segments. One of the segments, [low], has a strong preference for phones with a low, the other segment, [high], does not have a strong preference. The exact difference between these two is determined by the values. By definition, the relative price preference of [high] will never be higher than [low].

**consumer trend lag** Every tick, a variable called global trend is increased by 1. The trend lag is the amount a consumer is behind the global trend. The function threshold of the consumer is set to global trend - trend lag. The bounds are set quite arbitrarily. It is assumed that consumer in segments with a preference for high function phones are zero to two years behind the global trend. Consumers with a low preference one year to four years behind the global trend. As this will affect their function threshold, it will also affect their possibility to accept refurbisher phones, which naturally have a lower function than new phones.

**consumer start money** The consumer start money is the budget it which a consumer starts with at the beginning of the run. Every tick it receives a salary as well, which is added to its budget. This salary is set by the following rule:

```
money = money + ( start_money / (trend_lag + 1) )
```

The idea behind this formula is that consumers who have a low function threshold also have lower budgets. Note that this is not necessarily true, as there could also be wealthy consumers who just don't need a phone with a lot of function.

The values are chosen to match the value of phones. At the lower limit, this will not be possible and they will first have to save money. It is unknown how this will affect the outcomes. The lower bound of the consumer start money[low] is supposed to indicate consumers in emerging markets, who at this moment do not yet have a lot of money to spend. Perhaps that refurbished phones provide access to these consumers.

**consumer disposal preferences** When consumers dispose their phones they make a rational multi criteria decision and choose the alternative with the highest utility. The preferences are the criteria on which this analysis is based. The disposal cost is the cost consumers would have to pay. The preferences are all normalized to a scale from 0 to 100. There is much uncertainty regarding the weights the consumers attach to cost, revenue and ease. Thus no assumptions are made and the sensitivity of the model to different combinations of values is explored.

**collection channel capacity** The capacity of a collection channels is the amount of phones that can be stored in a collection channels before it is emptied. The capacity of a collection channel can determine the time it takes before phones reach a refurbisher or recycler. In case of refurbishers, the time it takes for a phone to reach the refurbisher determines the price and the profit a refurbisher can make. Therefore, the capacity (and maximum empty time) are relevant for the profits of refurbishers

and with it the rest of the system.

Envelopes can only hold one phone, therefore its capacity is 1. Drawers and one day events are assumed to have infinite capacity, taking 999 as a very large number in the model. The capacity of collection bins is very loosely based on the capacities of collection bins in reality: small bins with a capacity of 100 phones, large bins with a capacity of several thousand phones.

**collection channel purchase price** This is the price refurbishing and recycling agents have to pay when they purchase a new collection channel.

The base scenario values are based on the assumptions that envelopes are more expensive than collection bins and one day events. The prices per phone depend on the capacity and number of phones that are collected.

**collection channel disposal ease** The disposal ease indicates how easy a disposal alternative is viewed by consumers.

There is no proof on which to base the values for the disposal ease parameters. Therefore, they are inspected along the full range. In the base case they are set to favor collection bins and make no distinction between the other disposal options.

**collection channel service capacity** Because the current version of the model is not spatial, this parameter has been established as a proxy. It determines the amount of consumers who have access to the collection channel.

Every consumer has one drawer and always has access to it. Envelopes can serve just one consumer. The service capacities for collection bins and one day events are determined arbitrarily, with the assumption that one day events, when organized, can provide access to a large number of consumers.

**buyback percentage** The buyback percentage is the percentage of the current price of the phone that is about to be disposed that consumers would receive if they dispose the phone in an envelope. The collector buy back the phone from the consumer, which explains the name of the parameter. It is assumed that consumers are paid between 5 and 30% of the current value of the phone. For feature phones this will likely be one or two dollars, for new smartphones this can be up to 100 dollars, of course depending on the function values, devaluation values and disposal time. This corresponds loosely to observed data.

**commodity metal price** The commodity metal price is the price in cents per gram of metal that the commodity market pays a recycler for the recycled metals.

The values are based on data from Geyer and Doctori Blass (2010). The aggregate price for all recoverable metals is used. Note that only the metals printed in *italic* are currently recycled. However, since the significance of input numbers is qualitative instead of quantitative, the exact value is of less importance and it seemed more robust to take the aggregate price.

$$\text{Commodity price} = 0.7 - 0.9 \text{ [$/phone]} / 9 - 12 \text{ [gram/phone]} \approx 10 \text{ [cents/gram]}$$

**refurbisher function gap** This is the gap that has to exist between the function of a phone and the function threshold of a consumer, when the refurbishing agent determines its fate. This parameter basically acts as a form of transaction cost.

If the function gap is set to 0, consumers will buy a phone and use it for one tick and dispose it again, because they follow their need to have a phone if they can afford it. This does not correspond to our intuition about consumer behavior. The maximum value is 18, meaning that a consumer can use the phone for at least 18 months.

**number consumers** This is the number of consumer agents in the model.

This number has no relationship at all to reality. The value matters as it is the main driver of computation time.

**required roi** The required ROI is the Return On Investment the purchase of a new collection channel has to yield.

The numbers are set in such a way that at some finite point in time, the refurbishers stop purchasing collection channels because they are not profitable enough anymore. Since this strongly depends on the prices, functions of phones and preferences of consumers the right value is unknown and depends on the simulation.

**collection target period** The time in ticks over which the collection target is determined.

A fixed amount of 24 ticks has been chosen, which corresponds to collection periods in reality.

**memory window time** In determining the expected profit based on historic profits per collection channel, there is a risk of strong path dependence. This is mitigated by only taking the profits into account.

Arbitrarily set to 100.

**damping percentage meeting target** This parameter dampens the effect of volatile collection rates. The parameter specifies the percentage of ticks the collection target has to be reached from the specified collection target period.

**maximum empty time** This is the number in ticks that may pass between the current tick and the last time a collection channel was emptied. This parameter has been installed to, in case of collection targets, mitigate the continuous purchasing of more collection channels because the last channels did not return any phones, and with it just spreading out all the phones over the increasing number of collection channels.

Arbitrarily set.

**collection compensation** This is the money the hired collection agent is paid by the manufacturer, in the case of EPR legislation. It is a fixed amount of money per collected phone. Set based on real life collection compensation values, which depend very much per individual agreement between collectors and producers.

**bounded information buy phones** The number of phones a consumer takes into account when performing its multi criteria analysis choice to buy a phone. It is a technical variable to limit computation time.

Arbitrarily set.

**one day event return rate** This parameter specifies the occurrence of one day events. If the event occurs, all consumers who have access to the event will hand in all the phones that are hibernating in their drawers. To be more precise, the parameter specifies a random number:

```
pick random number from range [0 - one day event return rate]
if lucky number = 1 [
    organize one day event
]
```

The smaller the one day event return rate, the higher the chance an one day event is organized.

Arbitrarily set.





# 11 | Appendix: Model Assumptions

The explanations of assumptions in this section are structured into three parts:

- What is the assumption?
- What is the situation in reality?
- What is the implication of changing the assumption on answering the research question ?

## 11.0.0.1 No market mechanism implemented

The assumption is that prices are determined outside of the model. This is not the same as normally occurs, where prices are determined by the market, based on the supply and demand of consumers, manufacturers and refurbishers.

A change in this assumption can have effects on the answer on the research question. Since the price of phones determines a lot of the choices being made in the model, by consumers, refurbishers and recyclers, letting prices determine by the market can change their behavior. However, this would come with a more complicated model, as well as more assumptions on which factors determine the preferences and willingness to pay of consumers. Therefore the choice has been made not to implement a market mechanism.

## 11.0.0.2 Not all consumers have the same preferences

The assumption is that not all consumers have the same preferences. Although the models allows for complete heterogeneous preferences (as long as they are constant and additive), the consumers have categorized into two segments.

This is based on (Ovchinnikov et al., 2013). There are four consumers segments that can be identified in the mobile phone market, when taking remanufacturing options into account. The authors conducted a web-based, choice-based behavioral study with North-American university employees

Segment	Description
1	I dont really need a phone
2	I want a feature phone (with no data)
3	I want a new smartphone with data
4	I want a smartphone, OK with refurbished and with or without data

Table 11.1: Consumer segments in choices for mobile phones and cellular plans. Source: (Ovchinnikov et al., 2013)

(N=102). The subjects were asked to choose their best alternative from different combinations of mobile phones and cellular plans. The mobile phones ranges from low priced feature phones with no data, to high-priced new smartphones with data. By comparing the choices between these alternatives, utilities for each option are calculated. Finally, using a latent multi-nomial logit model, four segments showed the best fit:

The model can be extended to exactly fit the consumer segments identified in (Ovchinnikov et al., 2013).

#### **11.0.0.3 If refurbishers cannot refurbish a phone, they will pass it onto recyclers**

In the process of fate determination, the refurbisher checks whether a phone is viable to refurbish. If not, it passes the phone to a recycler without charging money.

This assumption is based on empiric evidence from Geyer and Doctori Blass (2010). It states that refurbishers are the ones who perform the collection step in case of no policy and that they hand phones which are not fit for refurbishing to recyclers. In practice several agreements are involved about who pays for the collection.

If the price for recyclers would be more than 0, this would of course affect their profits and the profits of refurbishers. However, this estimated to be a small effect.

#### **11.0.0.4 Consumers always have a need for communication**

In the model it is now assumed that all consumers always want to have a phone. If they do not have a phone, they will immediately try to buy one. Given the penetration percentage of mobile phones, almost everyone has a mobile phone nowadays, this seems a fair assumption. In reality this might differ if the price of mobile phones would skyrocket. Since prices for mobile phones are assumed to

stay within bounds, these boundary effects are not expected. Note that consumers no longer have a need for a phone when they already have one that suffices. This assumes consumers only need one mobile phone to call and need no backups. This latter assumption might be challenged in reality as it is known that often consumers want to have at least one backup phone. This has no major implications for the workings of the model though.

#### **11.0.0.5 In case of no policy, not all consumers have access to all types of collection channels**

It is assumed that in case of no policy, it is mainly the refurbishing agent who buys collection channels to increase their profit. It will do this until the expected profit drops below a threshold, called the required return on investment. This will occur before all consumers have access to all types of collection channels. In the current version of the model, access to consumers is modeled by a fixed number of links (determined by the collection channel service capacity value) to random consumers. In case of EPR legislation, either the refurbisher or recycler will keep purchasing collection channels until all consumers have access to all types of collection channels. It is hypothesized, and investigated in this model, whether the provision of access to collection channels to more consumers will increase the collection rate.

This last assumption, that consumers do not have access, or are unaware of the possibilities, to collection channels is supported by empiric evidence. In a survey study by Nokia, the recycling behaviour of consumers has been investigated. Their report contains, among other findings, seven main motivations for not recycling. Please see Table 11.2. Although the numbers add up to more than 100%, indicating that multiple choices were possible, 44% of the consumers responded that they did not know where to recycle, that there were no collection points near by or that they did not know that they could recycle.

If other empiric evidence suggests that consumers actually always have access to collection points and that their reasons for not handing in their phone is based on other reasons (such as data security concerns as mentioned in Table 11.2, this assumption would be unjustified. This would have large implications for the mechanisms of the EPR legislation that are currently modeled and should lead to a rethinking of the model.

I prefer to keep my old phone as back up	33%
It didn't occur to me to recycle my mobile phone	20%
I don't know where to recycle my mobile phone	17%
There are no mobile phone recycling facilities near me	15%
My old mobile phone was worth good money so I didn't want to give it away for nothing	15%
I didn't know that I could recycle old mobile phones	12%
I was concerned about the security of my personal data that was stored on my phone	10%

Table 11.2: Reasons for consumers not to recycle, according to Nokia Survey (N=3693). Source: Tanskanen (2009)

**11.0.0.6 Consumers have a function threshold and a fixed budget for a phone**

The assumption is that consumers have a certain threshold value which their phone needs to pass. If the function of their phone is lower than what they require, it no longer suffices. I believe this is a reasonable assumption: often consumers want a new phone even though their old phone still works. The major reason for this is that the phone no longer has the functions they require (cite research). We also assume that consumers have a fixed budget for a phone. If the price of a phone exceeds their budget, they will not buy it. In reality this might not be completely true. If all phones get more expensive, consumers will probably start spending more on phones, prioritizing the need for communication above other goods and needs. In the model, this boundary effect is not assumed to take place.

**11.0.0.7 Consumers buy phones based on function and price**

The assumption is that consumers judge the utility of phones only on function and price. This assumption is based on a study into consumer choice behavior regarding mobile phone selection. Mokhlis and Yaakop (2012) have performed a study with Malaysian university students (N=376) on the factors that drive consumer choices regarding buying a new mobile phone. Their principal component factor analysis yielded seven independent dimensions: (1) innovative features, (2) image, (3) price, (4) personal recommendation, (5) durability and portable aspects, (6) media influence, and (7) post-sales service. Their research showed that the top three most important factors influencing consumer choice of mobile phones are: innovative features, recommendation and price.

One must heed though to jump to conclusions based on these results. The authors note that

<b>Three most important factors influencing consumer choice</b>
Innovative features
Recommendation
Price

Table 11.3: Factors influencing consumer choice for mobile phones. Source: (Mokhlis and Yaakop, 2012)

due to the small sample size and homogeneity of the subjects, these findings can only be generalized to university students with an age of 21 to 26.

In the model, innovative features are translated to one value on a nominal scale. Price is also a value on a nominal scale. What is omitted are the recommendations from other consumers. If one believes this could make a large difference in the behavior of consumers, recommendations could be implemented in the future though by creating social networks between consumers, passing on recommendations on good phones. The translation of innovative features and price to a nominal value on a linear scale implies that the function of a phone can be made explicit in a number and that the price utility is constant over the range of prices and constant for all consumers. In reality, this is not likely to be true. We know that a phone can be more valuable to consumer A than to consumer B, because both have different preferences and/or needs at that moment. This behavior could be accommodated by implementing the different factors of the mobile phone and let consumers calculate the price they are willing to pay for the phone. Then they could compare their utility with the price the sellers wants for it and calculate the most optimal utility-for-price phone and buy that one.

#### **11.0.0.8 Consumers dispose phones based on revenue, cost, ease and availability**

The assumption is that consumers dispose their based on a multiple criteria decision where the criteria are revenue, cost and ease. This is not based on any empiric evidence. For this thesis a review of the literature on disposal has been performed though. A summary of this review, which relate to this assumption, are presented below:

**Willingness to pay for disposal of E-Waste** Nixon and Saphores (2007), Nixon et al. (2008) have collected consumer preferences regarding the disposal electric waste from Californian households. Their findings are that: a) Most people in their sample are willing to pay a 1% Advanced

Recycling Fee (ARF). They also provide the factors that determine their willingness-to-pay. (Nixon and Saphores, 2007) b) Their sample prefers dropping the electronic waste at recycling centres with curbside drop off as a close second. Most of them are willing to pay \$ 0.13 per mile per month to increase recycling convenience. (Nixon et al., 2008)

The authors themselves provide a note of caution on that this sample might not be generalizable. We should also note that they investigated these aspects for electronic waste as a whole. Question is whether people treat computers, fridges and mobile phones the same way.

#### **11.0.0.9 Phones hibernate in consumers' drawers**

In the disposal choice of consumers, they can also dispose their phone into their own drawer. This choice is assumed to be mostly driven by the high ease factor of drawers.

This assumption is supported by a consumer survey. It shows that 62% hibernate their disposed phone. Wilhelm et al. (2011) have performed survey studies with North American college students (N=254) to explore mobile phone disposition behaviour. Table 11.4 contains an overview of their results.

#### **11.0.0.10 Manufacturers are perfect market-servers**

The assumption is that manufacturers manufacture exactly as many phones as are required by consumers. This means they have no stock. This assumption enables the manufacturers to operate without making any decisions on how many phones they should produce. In reality manufacturers do make choices on how many phones they make. However, producing more phones than consumers want doesn't make too much sense, since they would be losing money. This situation changes if consumers do not have enough options to choose. But following economic principles and the fact that the mobile phone market is a global market, the assumption that sufficient demand will call for its own supply seems fair.

#### **11.0.0.11 Manufacturers do not take remanufacturing issues into account**

In this version of the model, manufacturers do not make choices. They manufacture phones, where function and metal content are set to pre-specified values. In reality, manufacturers do make choices about what type of phones they manufacture. Actually, this was one of the main reasons to adopt EPR legislation: to provide incentives to manufacturers to redesign their phones so that they are more easily recycled or reused, as this would cost them less money.

Number of mobile phones owned	1-2	11%
	3-6	74%
	more than 6	15%
Replacement frequency	less than 1 year	2%
	every 1-2 years	62%
	every 3-4 years	31%
Fate of 'old' phone	keep it as backup	62%
	recycle it	12%
	sell it or give it away	9%
	throw it away	4%
Expected product lifetime	1 year	7%
	2 years	54%
	3-4 years	32%
Desirable product lifetime	2 years	12%
	3-4 years	56%
	5 years	13%
	6 years or more	15%

Table 11.4: Phone ownership profiles Source: (Wilhelm et al., 2011)

#### **11.0.0.12 Refurbishers and recyclers have a finite memory**

This assumption is made based on a quite technical reason: as the refurbishers and recyclers make their purchasing decision based on historic profits, they are affected heavily by *path dependence*. Once one of the collection types would generate a little bit more profit, that collection point will be purchased more often, making it likelier for consumers to use that channel, thus further increasing the profit expectation. By assuming finite memory, only the most recent records are taken into account. This will mitigate, though not completely, the strong path dependency effects.

In reality path dependency also plays a significant role. Especially in conservative companies this can be an issue. In reality this is sometimes mitigated by trying different pilot programs. (see next section)

It is unknown what for an effect changes to this assumption will have on the outcome of the model. This should be investigated further.

#### **11.0.0.13 Refurbishers and recyclers get experience with different collection channels by doing pilot programs**

In the beginning refurbishers and recyclers have no clue which collection channel will yield higher profits. There are two options: let them choose one type. Because of the path dependency described in the previous paragraph, this will mean that the first choice determines the outcome of the model. This would mean it is equal to a random choice and repeat the run a number of times. The second option is slightly more advanced: it assumes an *incubation period*. In this period the refurbishers and recycler just purchase a number of different collection channel types. Later in the model these channels will yield their own profits and the refurbishers and recyclers can start choosing based on their expectations.

As explained in the previous paragraph, this incubation can be compared to trying different pilot programs and evaluating the outcomes after a certain period.

It is unknown how long the incubation period should be to mitigate strong path dependency. This should be tested.

#### **11.0.0.14 If recyclers could afford it, they would also perform collection step**

It is assumed that recyclers, just like refurbishers, could and would perform the collection process, given that it is profitable for them.

In reality, there are (almost) no recyclers, who operate only based on profits, who perform these



collection steps. According to Geyer and Doctori Blass (2010) this is because the recycling currently does not yield high enough profits, so recyclers are dependent on refurbishers. But perhaps this would change if collection volumes increase.

This assumption certainly has an impact on the outcomes of the model. It is therefore wise to investigate this impact, by comparing allowing the recycler to collect and not allowing them.

#### **11.0.0.15 No landfilling or incineration of mobile phones**

It is assumed that phones will only leave the system through recycling. The other EOL alternatives are refurbishing or hibernation, where in both cases the phone does not leave the system.

In reality, phones also leave the system through landfilling and incineration. Although in most western countries landfill bans are in place, the bans are often difficult to enforce. If a consumer throws a phone in a trash can, it is difficult and very costly to sort the trash to find the phone and prevent it. In the emerging markets, phones are more often landfilled and incinerated.

The question is whether this assumption is justified. Given that consumers often keep their phone and given that landfill bans are in place, the assumption seems justified. A more practical argument is that there is no information yet on when consumers or companies would throw away/incinerate a phone. Adding incineration would only add more uncertainty to the model.

In conclusion, the assumption has some support that justifies it. However, more research should be performed to see what effects adding incineration to the model would have.



## 12 | Appendix: Output Indicators Overview

This appendix contains an overview of the indicators that are measured every simulation run. First a table with all the indicators and brief descriptions is presented. Then a set of diagrams is presented which show why these indicators are measured, which quantities they measure and at which point in the model.

## Measurements Overview

The two main performance indicators have been translated into concrete measurements. The environmental impact is calculate per phone and computed for each step of the process. To gain more insight in the behavior of the model, the flows of phones and metals are measured at each step of the process as well. The economics are calculated per agent: manufacturers, refurbishers and recyclers. The profits are the main indicator, which is made up of costs and revenue. These are calculated per segment. A key interest apart from the economics and environmental performance is which collection channels are used. Therefore, the amount of collection channels that are bought by refurbishers and recyclers is also measured. For verification purposes, some control parameters have been added. This brings the total of measurements to 58.

ID	Parameter	Description
	<b>Environmental impact</b>	
1	environmental_impact_phone	Total_environmental_impact / number_phones
2	Total_environmental_impact	Energy leaving system (now only via recycling)
3	energy_manufacturing	Manufacturing + mining energy
4	energy_transport_recycler	
5	energy_transport_refurbisher	
6	energy_hibernation	Energy of phones that are hibernating in drawers
7	energy_usage	
8	energy_incineration	= 0. No trash/disposal of phones
9	energy_refurbishing	
10	energy_recycling	Energy leaving system to environment via recycling
11	energy_added_recycling	
	<b>Phone flows</b>	
12	number_manufactured	
13	number_sales	New phones sold to consumers
14	number_sales_refurbished	Refurbished phones sold to consumers
15	number_recycled	
16	number_hibernated	Phones in drawers
17	collection_rate	Collected_phones / collected_phones +

		hibernated_phones
	<b>Metal flows</b>	
18	amount_metals_new	
19	amount_metals_sold	
20	amount_metals_recycled	
21	metals_hibernated	
22	amount_metals_disposed	
	<b>Economics</b>	
23	manufacturer_revenue	
24	manufacturer_costs	
25	manufacturer_profit	
26	refurbisher_profit	
27	recycler_profit	
28	refurbisher_revenue_collection_compensation	
29	recycler_revenue_collection_compensation	
30	manufacturer_costs_collection_compensation	
31	refurbisher_costs	
32	refurbisher_revenue	
33	recycler_revenue	
34	refurbisher_costs_channels	
35	recycler_costs_channels	
36	refurbisher_revenue_sales	
37	recycler_revenue_sales	
38	manufacturer_revenue_sales	
39	refurbisher_costs_transport	
40	recycler_costs_transport	
41	refurbisher_costs_buyback	Costs paid to buy phones from consumers (via envelopes)
42	recycler_costs_buyback	
43	system_profit	Added profits of manufacturers, refurbishers and recyclers
	<b>Number and use of phones</b>	
44	refurbisher_collected_phones	
45	recycler_collected_phones	
46	refurbisher_amount_collection_bins	
47	refurbisher_amount_envelopes	
48	refurbisher_amount_one_day_events	
49	recycler_amount_collection_bins	
50	recycler_amount_envelopes	
51	recycler_amount_one_day_events	
	<b>Control parameters</b>	

52	current_policy	
53	access_communication	
54	collection_gap_ref	
55	collection_gap_rec	
56	timer	
57	no_reuse_percentage	
58	collection_target_percentage	

# 13 | Appendix: Analyses

This appendix contains more details on the analyses that have been performed for this thesis. Section 13.1 starts with a demonstration on overfitting with the PRIM algorithm. Section 13.2 and 13.3 contain large verification exercises with the entire model. Using these verifications an error was discovered, in the last phase of the project. The error was then corrected and new results were generated. To show how these verifications have been performed, these analyses have been included here. Finally, section 13.4 contains the details from the scenario discovery analyses. Chapter 6 presented one of these results.

## 13.1 Overfitting demonstration

Figure 13.1 shows the histogram of a random generated variable with uniformly distributed values between 0 and 1. The input values are three variables that are also randomly generated variables with uniform distributions. Therefore, there can be no pattern that leads to interesting points  $> 0.8$ . A visual inspection of the scatterplot in Figure 13.3 shows that the box that PRIM delivers is a clear example of overfitting.

## 13.2 Limits on collection rate

After the initial verification had been performed, some analyses returned questionable results. It turned out that there was indeed an error, hidden deep in the model. This section shows the analysis that lead to the discovery of the error.

### 13.2.1 Objective

The purpose of this analysis is to find out why the collection rate is not higher than approximately 25%. In theory, with the right settings, we should be able to drive the collection rate to 100%.

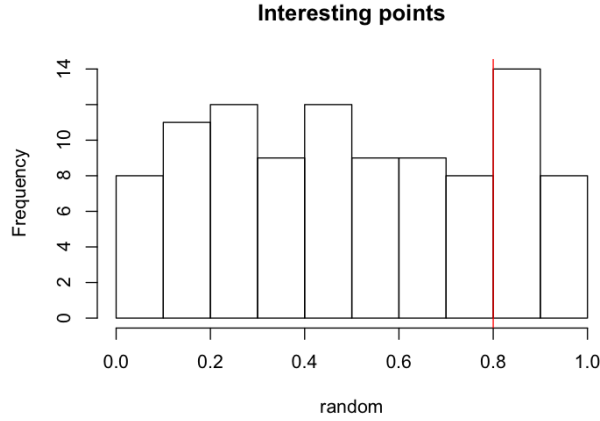


Figure 13.1: Classification histogram of random variable.

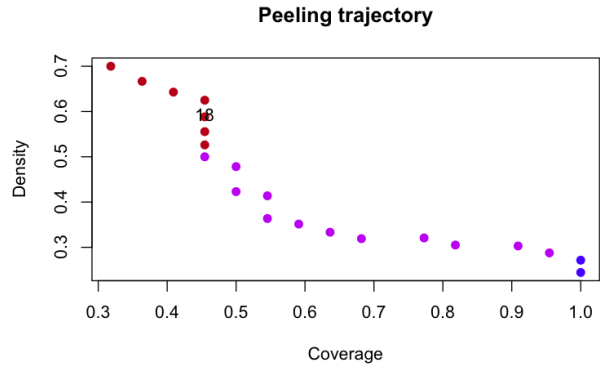


Figure 13.2: Peeling plot of random variables. Note that PRIM will still form boxes.

### 13.2.2 Hypothesis

The working hypothesis is that the collection rate is low because of the way the collection rate is calculated.

$$CR = \frac{\sum p_c}{\sum p_d} \quad (13.1)$$

Where  $CR$  denotes the collection rate,  $\sum p_c$  the number of collected phones and  $\sum p_d$  the total number of disposed phones. This equation is calculated at the end of the entire run. The hypothesis is that in the beginning the consumers do not have access to collection channels. Therefore they dispose their phones in drawers. Slowly more consumers will get access but the large number of



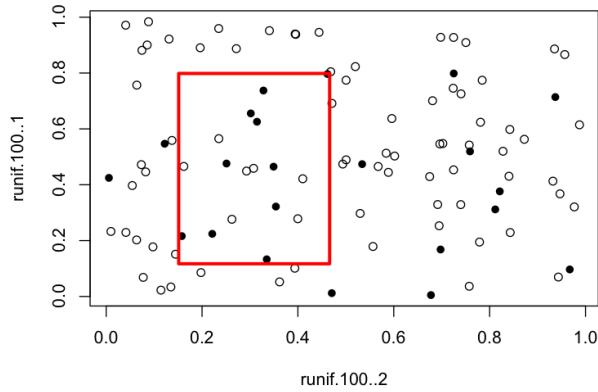


Figure 13.3: Scatterplot of random variables. A visual inspection helps to verify if the scenario is really a scenario or just a random increase in density

hibernated phones is still in the equation. Therefore, the average collection rate of the entire run can be much lower than the collection rate at the end of the run.

The parameter input values of the collection channels have been set in such way that collection bins are always superior to drawers. So if consumers have access, they should choose collection bins.

The expected graphs should show a line of decreasing slope for the number of hibernated phones, as less and less consumers will dispose their phone to drawers. The number of collected phone should be an a line with an increasing slope. (i.e: the time derivative should be higher than 0).

Second hypothesis that will be checked is whether the time scale is long enough. The hypothesis is that the time is too short for all consumers to get access to collection channels and dispose their phones, therefore the collection rate is lower than it could be.

Experiment Type	Repetitions	Experiments	Runs	Ticks	Input values	Output indicators
Scenario	10	1	20	1000		

Table 13.1: Experiment Design Base Scenario. Run: EOL\_0712\_1.csv

### 13.2.3 Results

The results in Figure 13.4 point that the model is not working as it should, or that the output is not registered correctly. The lines are straight while according to the conceptual model, they should

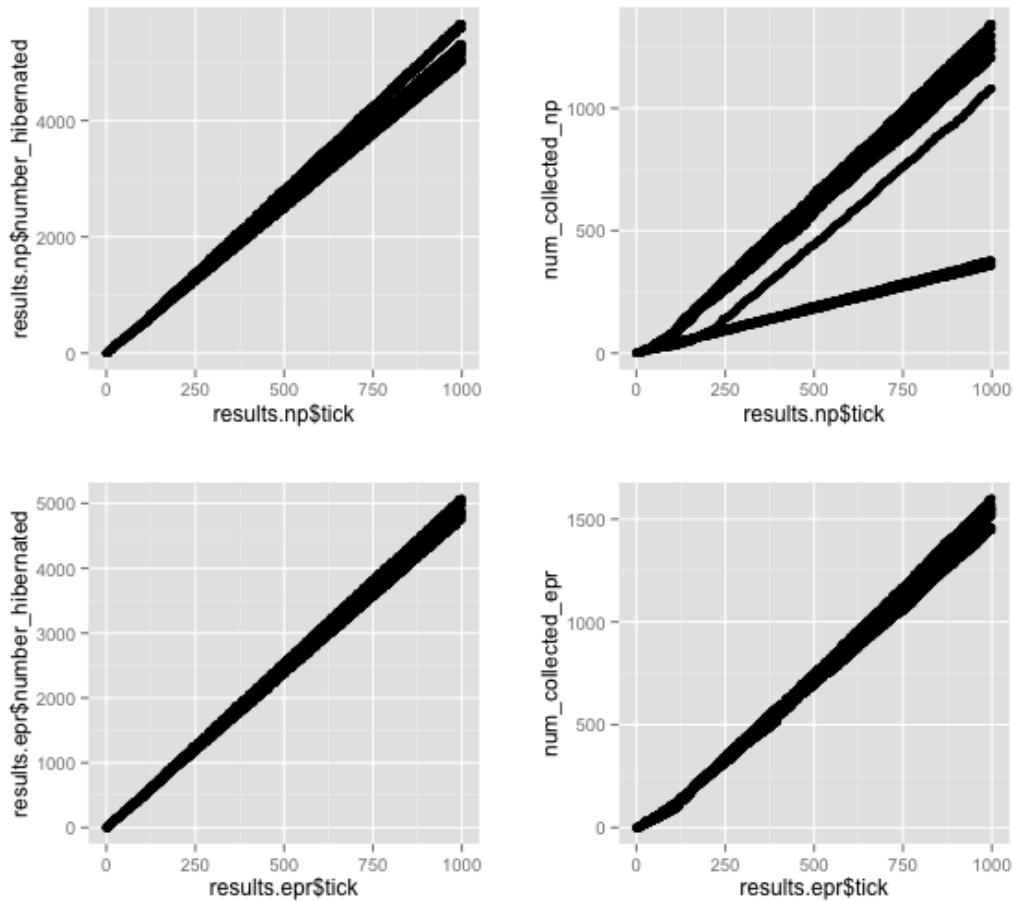


Figure 13.4: Number of phones disposed in drawers and number of collected phones, under NP and EPR

be curved.

In addition, the number of hibernated phones also rises under EPR, which is unexpected. Further analyses have to be done to understand this artifact.

### 13.3 Limits on collection rate with revised model

The results of the first analysis on collection rate in Appendix 13.2 showed that there might still be a bug in the model. The full model verification in Appendix 16.3 confirmed this hypothesis and identified a bug in the implemented model. The purpose of this section is to perform the same simulation as specified in 13.2 to verify if this time the model does behave like we expect it to, based

Model	Output file	LHS input file
EOL_0719_2	EOL_FMV_0718_2.csv	-

Parameter	Value
collection channel service capacity collection bin	200
target purchase price	0
collection channel disposal ease collection bin	65
collection channel disposal ease all others	60
number consumers	200

Table 13.2: Changes in input parameter values

on knowledge of the conceptual model.

The changes made to the input values are:

Experiment Type	Repetitions	Experiments	Runs	Ticks	Input values	Output indicators
Scenario	2	1	40	1000	Appendix X.1	Appendix Y.1

Table 13.3: Experiment Design Base Scenario.

Further experiments and test lead to the following insight:

**Insight: collection channel decisions change but effects are quite chaotic.** What is meant is that the mechanism works, but not in all cases. Even with the same input parameters, it does not always lead to the same outcomes. Whether this should be called chaotic or just stochastic can be matter of discussion. The conclusion is that these analyses suggest the model works as specified in the formalization. Figure 13.7 shows how the used collection channels change when the collection infrastructure changes. The expected increase in disposals to collection bins and decrease in disposal to drawers is now observed.<sup>1</sup>

As a last check the collection rate is calculated again. This time taking the disposed phone volumes **per tick**. Figure 13.8 shows the results. The collection rate is much higher than observed

<sup>1</sup>The disposal numbers have now been changed to disposed *per tick*. This explains the differences with figure 13.6.

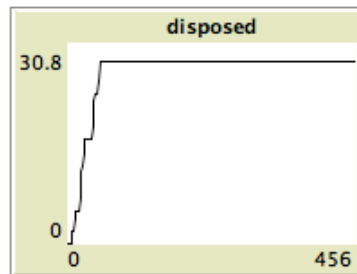
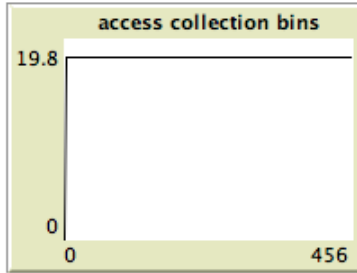


Figure 13.5: collection bin service capacity 3

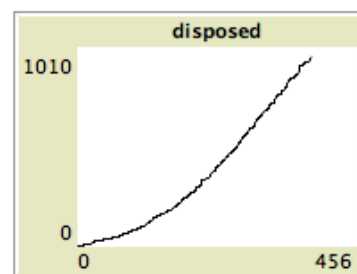
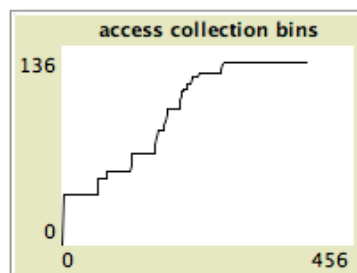


Figure 13.6: Collection bin service capacity 6

in reality, but that is understandable given the input values.

The changes made to the input values are:

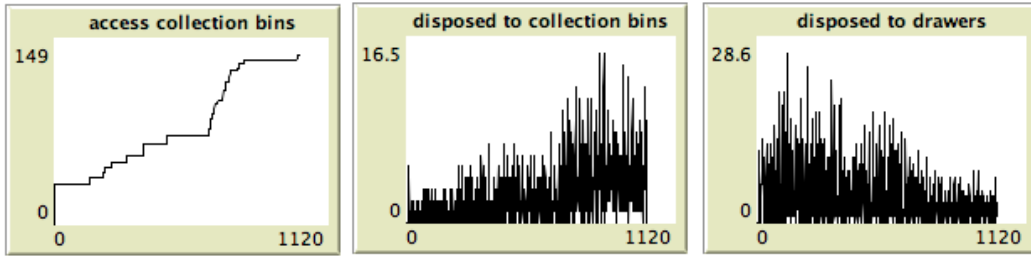


Figure 13.7: Disposed phones to collection bins and drawers as a function of time

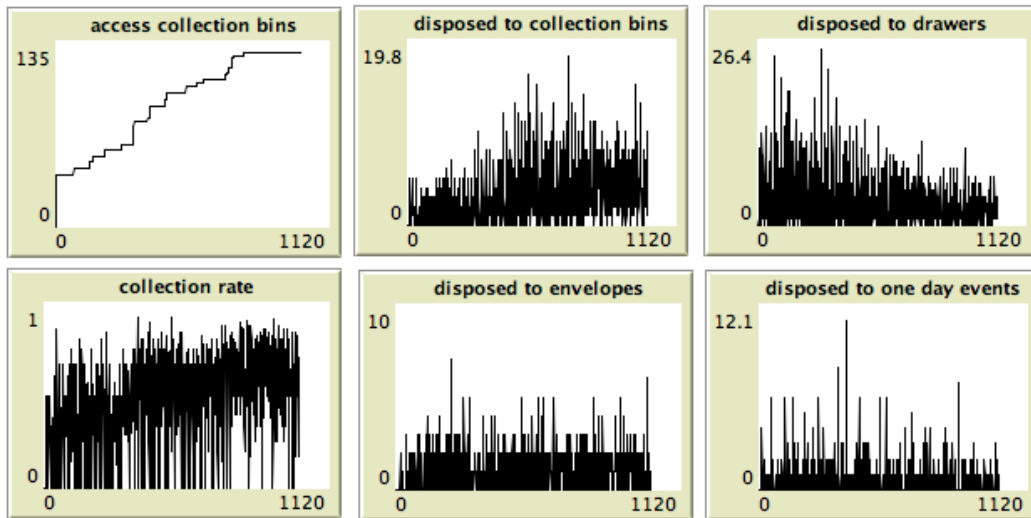


Figure 13.8: Collection rate and disposed phones per channel as a function of time

## 13.4 PRIM Scenario Discovery

### 13.4.1 Collection Rate under EPR

Figure 13.9, Figure 13.10 and Figure 13.11 show the results of the PRIM analysis for the collection rate under EPR.

### 13.4.2 Environmental Impact under EPR

Figure 13.12, Figure 13.13 and Figure 13.15 show the results of the PRIM analysis on the relative energy demands under EPR.

Parameter	Value
collection channel service capacity collection bin	6
collectio channel purchase price	1
required roi	3

Table 13.4: Changes in input parameter values

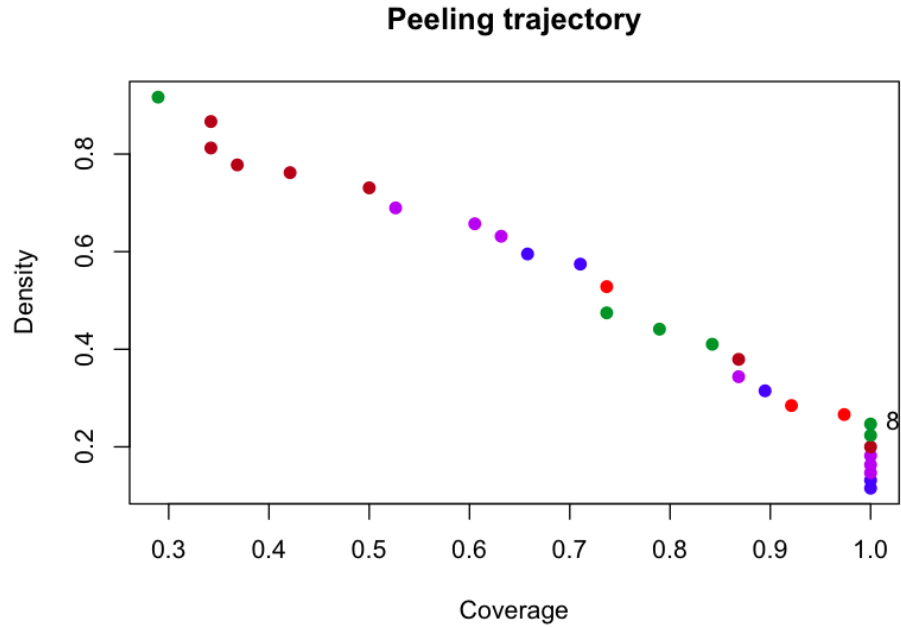


Figure 13.9: Peeling plot of collection rate under EPR

### 13.4.3 Refurbisher profit under EPR

Figure 13.16 shows the peeling plot of the PRIM analysis of the profits of refurbishers under EPR.

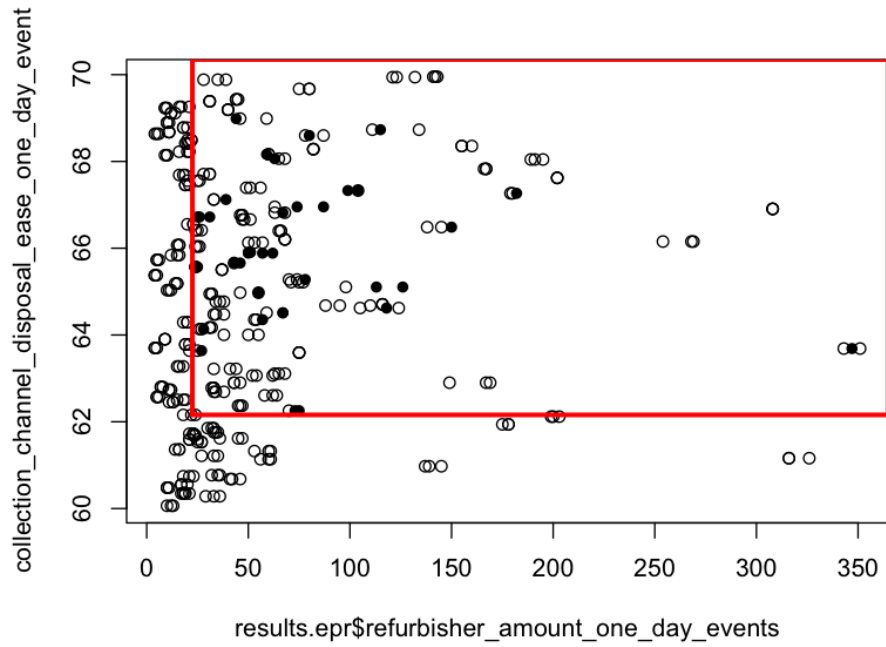


Figure 13.10: Scatterplot of collection rate under EPR

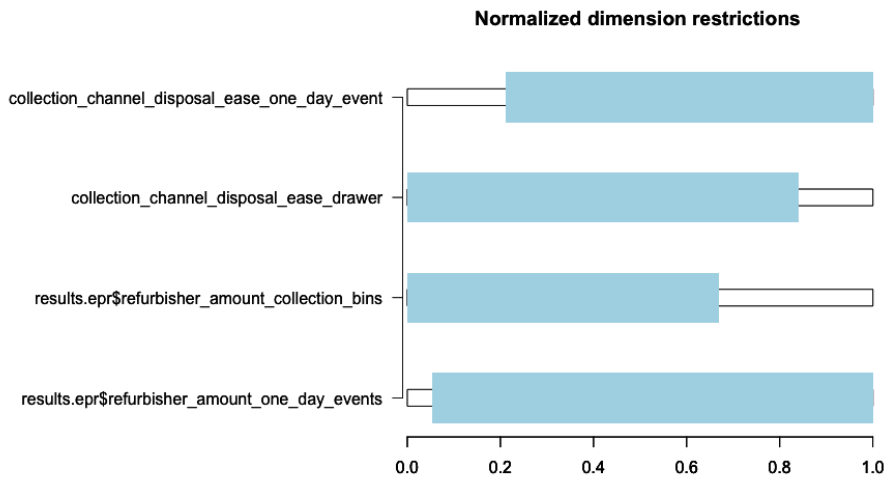


Figure 13.11: Dimplot of collection rate under EPR

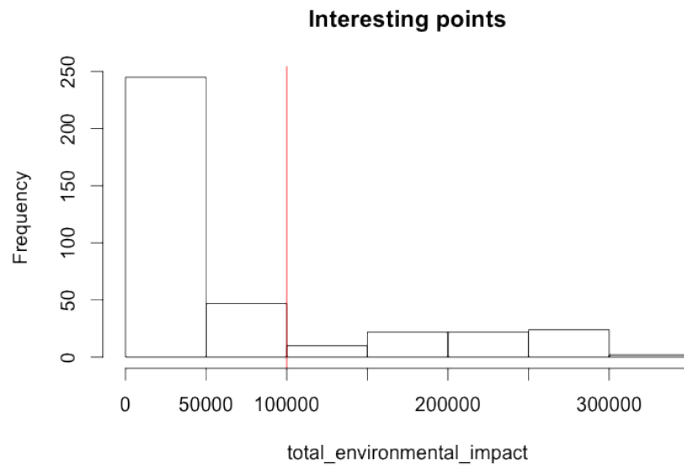


Figure 13.12: Histogram of relative energy demand under EPR. Runs higher than the red line have classified as interesting

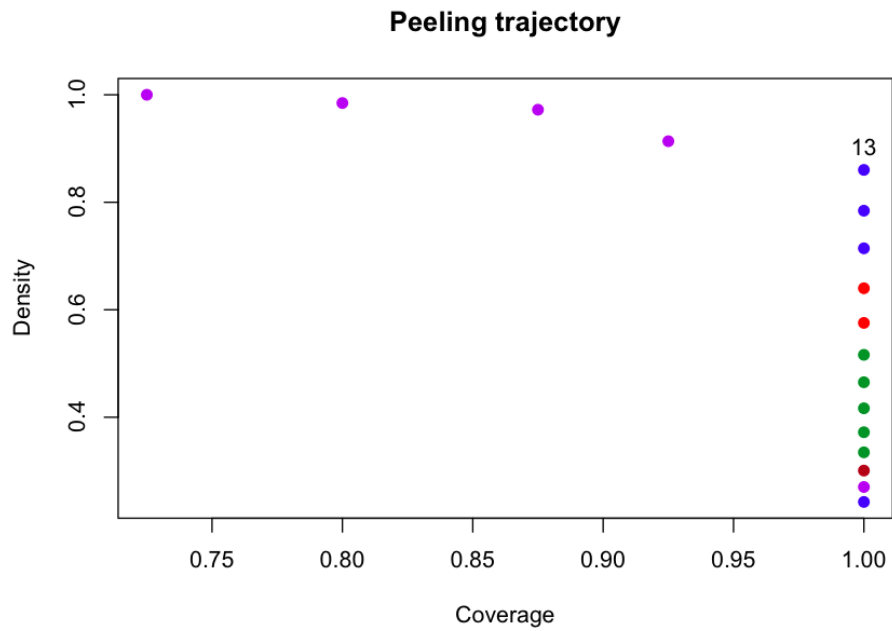


Figure 13.13: Peeling plot Relative Energy Demand under EPR



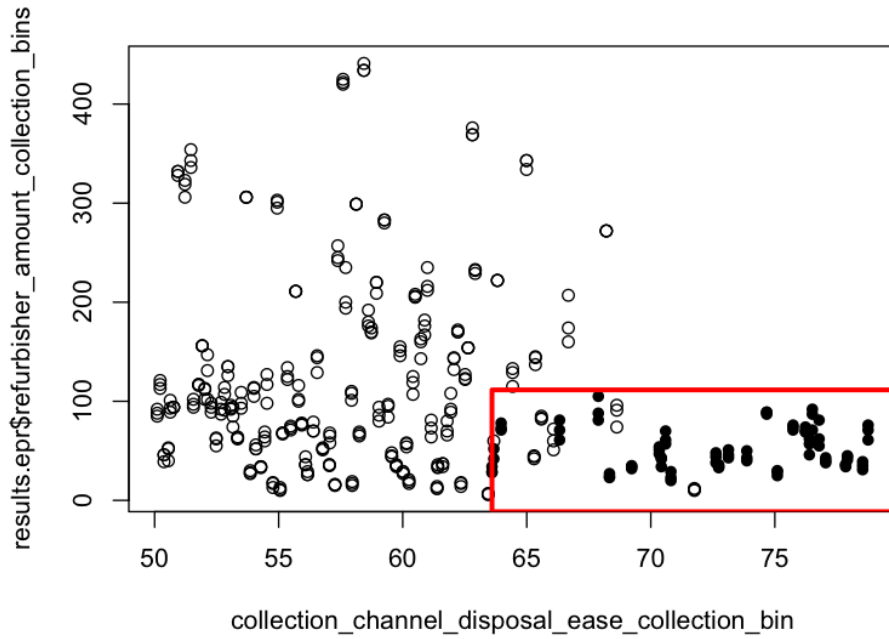


Figure 13.14: Scatterplot Relative Energy Demand under EPR

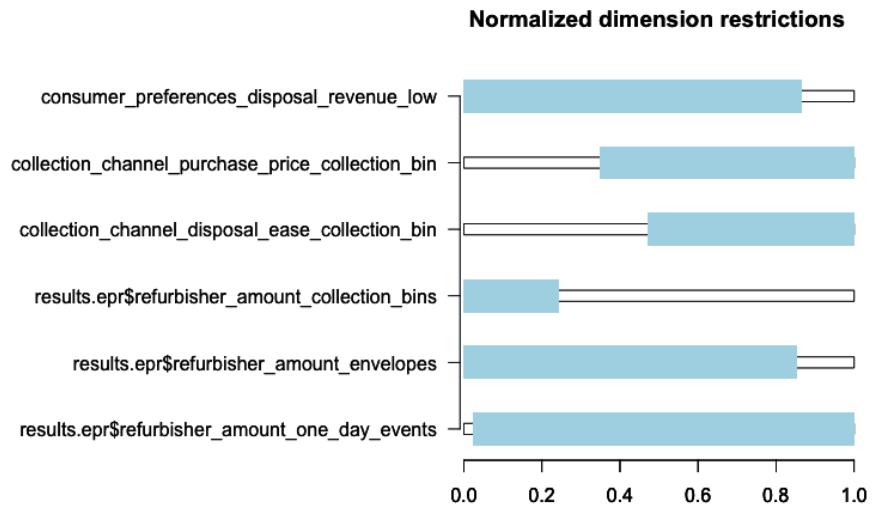


Figure 13.15: Dimplot Relative Energy Demand under EPR

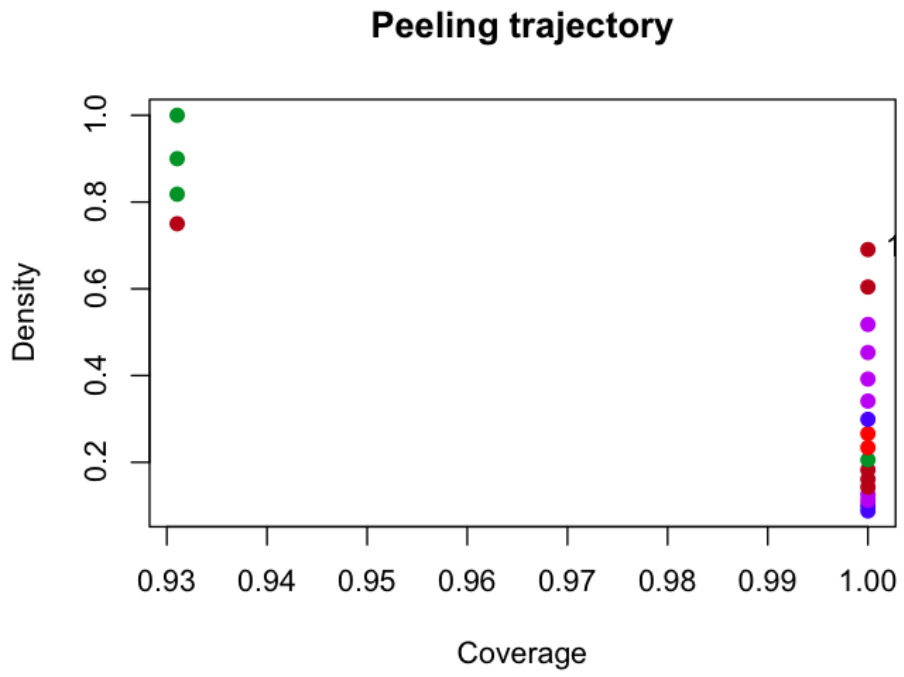


Figure 13.16: Peeling plot profits of refurbishers

# 14 | Appendix: Base Scenario Calibration

## 14.1 Complications in choosing the Base Scenario

The Base Scenario is a specific combination of input values that, by expert judgement, is considered plausible and realistic. For most of the parameters, there is data to support the chosen input parameter values. For other parameters there is no data available yet. This forces the modeler to make a choice for one value from a range of plausible values. These choices can have big effects on the workings and outcomes of the model. Figure 14.1 shows the results from one plausible base scenario. Graph #6 in that figure displays the collection rates under different policies. It is observed that the collection rates are very low: 5% for the NP case, compared to observed collection rates of 25% to 35% in reality. (Geyer and Doctori Blass, 2010). The low collection rates in Figure 14.1 form a complication. EPR and NRP are expected to have very different economic and environmental effects under certain input values that lead to a low collection rate of 5%, compared to input values that lead to a higher collection rate of 25 to 35%.

## 14.2 Empirical Calibration - Procedure

One method of choosing a base case from a range of plausible cases, is to use empirical calibration. The procedure that was developed for this thesis bears strong similarities with the Indirect and Werker-Brenner Calibration approaches described by Fagiolo et al. (2007). The procedure consists of 5 steps:

1. **Define Stylized Facts:** The first step is to define one or more stylized facts that the model should simulate under the no policy case. These effects have to be emergent in the sense that

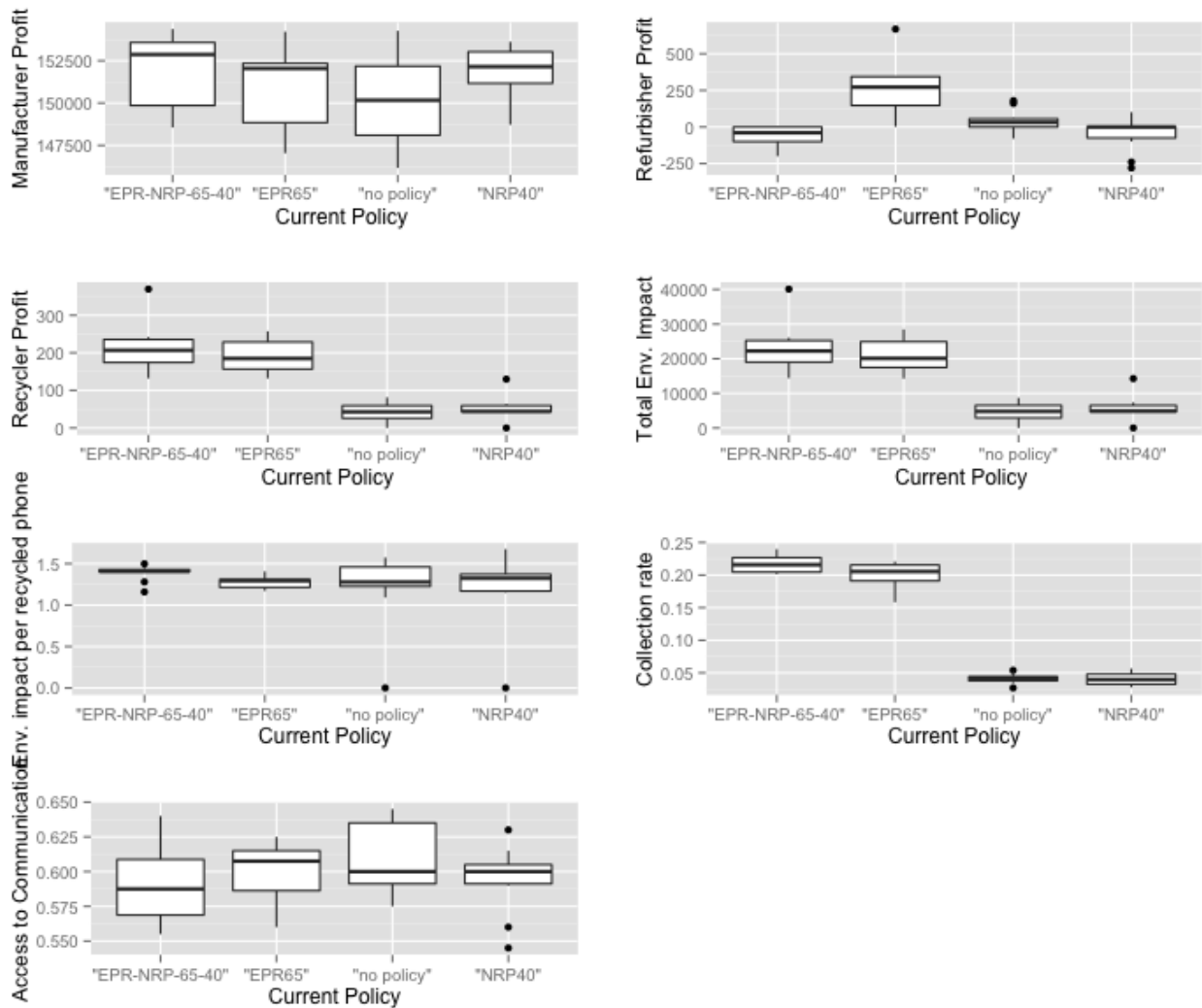


Figure 14.1: Overview of Performance Indicators of Base run

they should not be inserted in the model by programming them in the algorithms, but emerge as a consequence of the behaviors and interactions of agents.

2. **Define the Parameter Space:** In the next step the values for the input parameters have to be specified. Wherever there is uncertainty about the values, ranges should be specified, containing all plausible values.
3. **Simulate and Observe Stylized Facts:** Now simulations have to be performed with the model, sampling from the entire parameter space. The specified stylized facts should be observed in each run.

4. **Confine Parameter Space:** Now the parameter space can be confined to the combinations of input values that lead to the correct value of the specified stylized fact(s).
5. **Choose Base Scenario** From set of scenarios in (4), select one Base Scenario.

### 14.3 Empirical Calibration - EOL Model

A simple version of the procedure outlined in the previous section has been used to specify a base scenario for the EOL model. In this case, conceptual knowledge about the model was used instead of simulations in the entire parameter space. The execution is stated below:

1. First one stylized fact was specified: the collection rate under NP should be 25% - 35%.
2. Simulations were run, yielding much lower collection rates as displayed in Figure 14.1.
3. Hypothesis: low collection rates are caused by low consumer disposal behavior, caused by their disposal preferences. Therefore, the disposal preferences were changed from 50 for `consumer_preferences_disposal_revenue` and 90 for `consumer_preferences_disposal_ease`, to 80 for `consumer_preferences_disposal_revenue` and 40 for `consumer_preferences_disposal_ease`.
4. Using these input values, the collection rate increased to 17-18%.
5. The number of collection channels was then analysed. This showed that the refurbishers only buy envelopes and a higher amount of envelopes than the number of consumers in the model. This suggests that the purchasing mechanism might not work the same as in reality. In reality, the collection channel mix of refurbishers might be more balanced over the different channel types. In the current model, the purchasing mechanism is discrete. The new hypothesis (H5) is that with envelopes the collection rate in the model cannot get higher than 18% because there are not enough collection bins and envelopes or that these are not used enough by consumers. This hypothesis is not investigated further and the model is calibrated using the new input values.

Note: This section presented results from a previous version of the model, which contained an error. The calibration procedure has been performed with the new model as well and the results are to be found in Chapter 6.



# 15 | Appendix: Model Optimization

In this Appendix the performance of the model is investigated and optimized by changing the most computational demanding procedures.<sup>1</sup>

**Situation before optimization** The first step in the optimization process is to know the current performance. Using the Netlogo Profiler the three most computational demanding procedures are identified:

Name	Calls	Incl(ms)	Excl(ms)	Excl/calls
SELL_PHONE	40833	264476.694	187768.497	4.598
BUY_PHONE	71047	438071.152	174515.732	2.456
SUFFICING_PHONES_PROC	71047	93048.18	93048.18	1.31
GENERATE_MCA_MATRIX	20935	86071.629	85483.327	4.083
MAKE_CHOICE	20935	192181.884	85252.684	4.072
UPDATE_RECORDS	17533	76378.935	76352.042	4.355

Table 15.1: Profiler output of initial Netlogo model sorted by exclusive time. The total runtime was 895 seconds for 1000 ticks and 200 consumers.

```
total run time: 895 seconds
```

**Improvement 1: seperate active from hibernated phones** The first improvement is to add a breed called `hibernated_phones`. In the process of querying phones, the hibernated phones are no longer taken into account, resulting in an increase in speed:

<sup>1</sup>Kasper Kisjes is acknowledged here for his advise on how to change Netlogo procedures to increase the model performance. The adaptions in this appendix are based on his recommendations.

```
total run time: 487 seconds
```

**Improvement 2: no display** All visuals are not displayed. Result: two-fold increase in speed:

```
total run time: 257 seconds
```

**Improvement 3: remove unused records** Records outside of the memory windows size are not used anymore. The implementation before was that only the records within the memory window size were queried. The new implementation is that all records outside of the window are deleted. This is repeated for target records and sales records, using the collection target period instead of the memory windows size. Result: run time cut in half again

```
total run time: 164 seconds
```

The new, most expensive procedures are:

Name	Calls	Incl T(ms)	Excl T(ms)	Excl/calls
MAKE_CHOICE	21788	73076.591	47022.364	2.158
SUFFICING_PHONES_PROC	68531	36472.858	36472.858	0.532
GENERATE_MCA_MATRIX	21788	17568.122	17132.450	0.786



## 16 | Appendix: Verification

This section verifies whether the software model works as specified by the conceptual model. In the process of modeling, many of these verification steps are performed in an iterative manner: write a procedure, check whether it works, rewrite, check, try again. This section does not include all the intermediate checks, but the most relevant verification checks that have been performed when the model seemed to work correctly. These verification checks have been structured by what are perhaps the most important procedures in an agent based model: the choices that agents need to make.

### 16.1 Multi Criteria Choices

The buy, purchase and disposal choices have all been implemented as multi criteria choices. Therefore first the multi criteria choice procedure will be tested to verify if it works correctly.

The input parameters for the test procedures are:

```
to setup_test
  clear-all
  create-test:agents 1 [
    set my_preferences no-turtles
    create_preference "feata" 100 "max"
    create_preference "featb" 50 "min"
    create_preference "featc" 0 "max"
  ]

  create-test:products 1 [
    set feata 1
    set featb 10
```

```

    set featc 0
    print self
]
create-test:products 1 [
    set feata 10
    set featb 1
    set featc 100
    print self
]
end

```

**Normalize matrix** In order to compare multiple products correctly, their values have to be normalized. Test procedure:

```

to test:normalize_matrix
  create-test:agents 1 []
  ask one-of test:agents [
    let test_matrix matrix:from-row-list [[10 5 1] [1 5 11] [10 10 0]]
    print matrix:pretty-print-text test_matrix
    let test_directions ["max" "min" "max"]
    normalize_matrix test_matrix test_directions
    print matrix:pretty-print-text test_matrix
  ]
end

```

A calculation by hand shows what the results should be:

row 1 : max = 10, min = 1, 5:  $\frac{5-1}{10-1} = 0.44$ , with direction = high value is better

row 2 : max = 0, min = 1, 5:  $\frac{5-1}{11-1} = 0.4$ , with direction = low value is better

row 3 : max = 10, min = 0, 10:  $\frac{10-0}{10-0} = 1$ , with direction = high value is better

Output is:

```

Output:
[[ 1 0.44 0 ]
 [ 1 0.6 0 ]

```

```
[ 1 1 0 ]]
```

**status: Confirmed**

**Generate MCA Matrix** This procedure should create a list of lists from the attributes of a product. The attributes that are used are specified in the first two procedures.

```
to generate_attributes_value_list
  if is-test:agent? self [
    set attribute_list (list feata featb featc)
  ]
end

to generate_attributes_name_list
  if is-test:agent? self [
    set name_list (list "feata" "featb" "featc")
  ]
end

to test:generate_mca_matrix
  setup_test
  ask one-of test:agents [
    let test_choices []
    ask test:products [ set test_choices lput self test_choices ]
    print test_choices
    let options_and_pointer_lists generate_mca_matrix test_choices
    print options_and_pointer_lists
  ]
end
```

Output:

```
[[[10 1 100] [1 10 0]] [(test:product 5) (test:product 4)]]
```

**status: confirmed**

**Generate Preferences List** This procedure should take a list of options and generate a list of preferences of the consumer that match the features of the products.

Output:

```
[[[] []]]
```

**status: error!** Bug discovered. Wrong agents in attribute name list procedure.

```
to test:generate_preferences_list
  setup_test
  ask one-of test:agents [
    let test_choices []
    ask test:products [ set test_choices lput self test_choices ]
    let preferences_list generate_preferences_list test_choices
    print preferences_list
  ]
end
```

This should now yield the preferences and directions.

Output:

```
[[[100 50 0] [max min max]]]
```

**status: confirmed**

**Make Choice** The combination of the test preferences should present the second product (product 5) as the best choice.

```
to test:make_choice
  setup_test
  ask one-of test:agents [
    let test_choices []
    ask test:products [ set test_choices lput self test_choices ]
    print test_choices
    let my_choice make_choice test_choices
    print my_choice
  ]
end
```

```
end
```

The results of the test is:

```
Output:
```

```
(test:product 5)
```

**status: confirmed**

This means the make choice procedure is verified. All choices that are correctly given to the make choice procedure will return the optimal choice, based on the multiple criteria that are the options can be evaluated on.

## 16.2 Agent choices

**choose collection channel highest profits** The expectation (about a collection channel) with the highest profit should be selected.

```
input:
```

```
channel a: profit = 1000, channel b: profit = 100, channel c: profit = 10
```

```
output:
```

```
channel a
```

**status: confirmed** What will happen if two channels have the same profit? Equal inputs should not lead to errors.

```
input:
```

```
channel a: profit = 1000, channel b: profit = 1000, channel c: profit = 10
```

```
output:
```

```
channel a (first time)
```

```
channel b (second time)
```

If the inputs are equal, the procedure will randomly select of the two expectations with equal profits.

**randomly select choice from best options. status: confirmed.**

**Determine Fate** First test: if no reuse percentage is 0, how many phones are refurbished after 1000 ticks?

```
set no reuse percentage 0
output:
881
```

If the no reuse percentage is set 100, no mobile phones should be refurbished.

```
set no reuse percentage 100
output:
0
```

**status: confirmed**

**manufacture phones** The manufacture phones procedure contains the specifications for all the parameters of the phone. In the setup these parameters should be specified correctly.

```
to test:manufacture_phones
  setup
  ask one-of manufacturers [manufacture_phones ]
  inspect one-of phones
end
```

The results of the inspection are that the parameter settings are correct.

**status: confirmed**

**price phones** Phones should always be priced positive or 0. Otherwise the sell procedure will not work correctly.

An inspection shows that this is not always the case

```
inspect phone
original_price: -575.
```

**status: error!** This turns out to be caused by a function much lower than the global function trend.

Changed the devaluation rates.

**status: confirmed**

**required return on investment** The required roi specifies that there is a certain level of required a collection channel has to generate. If the expected profit is lower than this value, no collection channels should be bought. In reality a value of 15% may be standard. However, in the model there is no connection with reality for the roi value. What is required though, is that there is a certain point at which refurbishers and recyclers stop purchasing.

The expected outcome of this test is that the number of collection channels will decrease as the required roi rises.

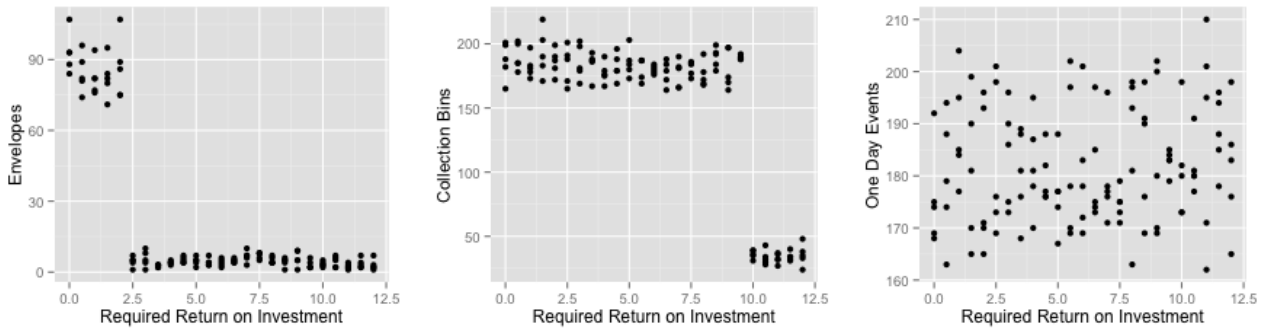


Figure 16.1: collection channels as function of required return on investment

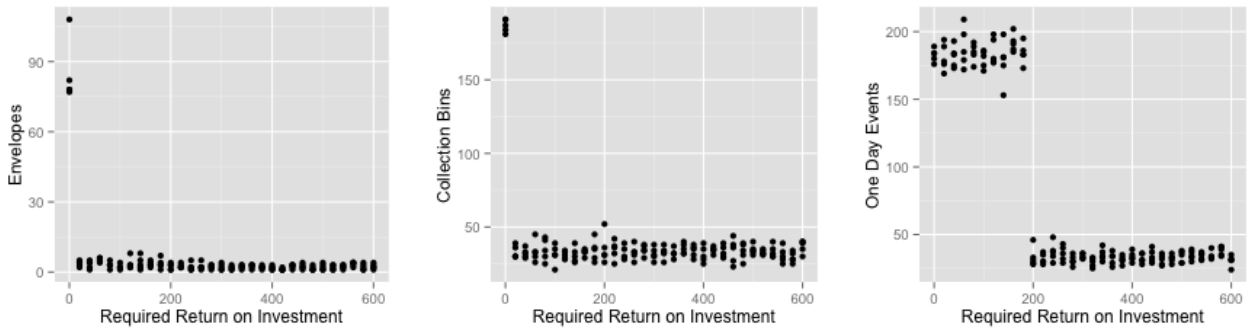


Figure 16.2: collection channels as function of required return on investment

### 16.3 Full Model Verification

The purpose of this section is to conduct a full-model verification. The separate components have already been verified in the previous sections, the question is now whether the full model behaves

Model	Output file	LHS input file
EOL_0718_1	EOL_FMV_0718_1.csv	-

Parameter	Value
collection channel service capacity collection bin	200
target purchase price	0
collection channel disposal ease collection bin	65
collection channel disposal ease all others	60
number consumers	200

Table 16.1: Changes in input parameter values

as specified in the formalized model.

This section starts by checking the hypothesis formulated in Appendix 13.2. The hypothesis is that something does not work correctly in the model because the collection rate is low and the slope of the number of collected phones does not increase as more consumers get access to collection channels.

The hypothesis is checked by the following procedure: Based on knowledge about the formalized model, input parameters are set in such way that collection bins are favored by all consumers and all consumers have access to the collection bins. This should lead to a collection rate of 100%. If a collection rate lower than 100% is observed, the model contains an error.

The results of this run should lead to collection rate of 100%. The collection rate of the simulation runs are:

```
collection rate:
...
0.092957746
0.051282051
0.092696629
...
```

This is not 100%! **Status: ERROR!**

Now the cause of this error needs to be identified. A first test is to plot the number of consumers



that have access to collection bins. If this is lower than 200, there is an error.

```
count consumers with my_disposal_option-neighbors
  with [channel_type = "collection_bin"]:
6
```

**status: ERROR!**

So it seems that something is going wrong in connecting consumers to the channels. Therefore I took a closer look at the `purchase_channel` procedure which connects the purchased channels to consumers. And there the culprit was hiding:

```
set service_capacity [service_capacity] of one-of templates
  with [product_type = collection_channel_choice]
let my_consumer one-of consumers
ask my_consumer [create-my_disposal_option-to this_product [set hidden? true]]
```

The bug is that the service capacity is requested the correct way but then only one connection is made to a random consumer.

**Status: Bug discovered** The code is changed to:

```
ask n-of service_capacity consumers [
  let my_consumer self
  ask my_consumer [create-my_disposal_option-to this_product [set hidden? true]]
]
```

The number of consumers with access to collection bins is now:

```
count consumers with my_disposal_option-neighbors
  with [channel_type = "collection_bin"]:
200
```

The new collection rates are:

```
...
0.99378882
0.991150442
0.994117647
...
```

Why is the collection rate not exactly 1? The formula is:

```
report (collected_phones / (collected_phones + disposed_drawers + 1))
```

The +1 is added to mitigate division by 0 errors. So the collection rate will never be exactly 1.

**status: Resolved**

# 17 | Appendix: emaR workbench

## 17.1 Manual

The model contains a brief explanation of how the emaR workbench works. It explains how R interacts with the Netlogo BehaviorSpace and provides an overview of the functions that have been included.

## 17.2 User reactions

Three students have used the emaR workbench for their project in the Advanced Agent Based Modeling course at TPM. This document contains a questionnaire with their reactions.

A few comments require explanation: the interviewed student is under the impression that emaR consists mainly of the PRIM algorithm. However, this is only one part and the PRIM algorithm is drawn from an existing package called `sdtoolkit`. It is the `sdtoolkit` that currently fails under the Windows operation system.

## 17.3 Exploring Agent Based Models using PRIM: Analysis of Predator-Prey model

To make sure the tools work and to discover possible complications of using PRIM on ABMs, the scripts have first been tested on the well-known Predator-Prey model. This document contains an explanation of the analysis.

## 17.4 emaR Code

The R code of the emaR workbench and the R code that has been used in this project are included. The code is located in the second map of appendices. One remark: The emaR workbench uses `sdtoolkit` package created by Bryant and Lempert (2010). This package however does not work on the Windows computer we have tested it on. Therefore, I have tested it as well on Macs. I had to make some changes in the source code of the package, and now it works well on Macs.

# Manual for the emaR experiment toolkit

Pim Bellinga

July 22, 2013

## 1 Purpose of this manual

The purpose of this manual is to guide you through the setup of the emaR workbench. The emaR workbench can be used to analyse and explore your Netlogo model in a relatively easy and quick way. The emaR workbench was created during a master thesis for personal use, and thus provides no additional help.

This manual does not provide any tutorials for R or Netlogo. If you want to learn more about R or Netlogo, here are some useful links:

- Quick-R: <http://www.statmethods.net/index.html> Useful overview of R functions and uses.
- Stackoverflow: <http://stackoverflow.com/> This is forum where programming questions are posted. I mainly use it by typing my question in Google in combination with "R" and often the answer already pops up.

or search the web, there is a huge amount of tutorials out there.

If you require more advanced exploration functions, it is recommended to take a look at the Explorative Modeling Analysis Workbench of Jan Kwakkel: <http://simulation.tbm.tudelft.nl/ema-workbench/contents.html>.

One important issue: PRIM is currently only supported on Macs, because the `sdt toolkit` package does not seem to work on PCs. In order for PRIM to work on a Mac, a adopted version needs to be manually installed. See section 3.2.

Finally, the emaR workbench is not an R package. It is just a combination of useful scripts and Netlogo BehaviorSpace setups. The next section will explain you exactly what this means.

## 2 emaR experiment setup

The experimentation setup can be divided into three phases:

- Preperation
- Simulation
- Analysis

In the emaR setup, the first and third step are performed using R. The second step is performed using Netlogo's BehaviorSpace.

## 2.1 Preparation

There are three type of experiments the emaR can generate:

- Fixed value runs
- Uniform Monte Carlo simulations (randomLHS)
- Latin Hypercube Sampling (optimumLHS)

## 2.2 Simulation

## 2.3 Analysis

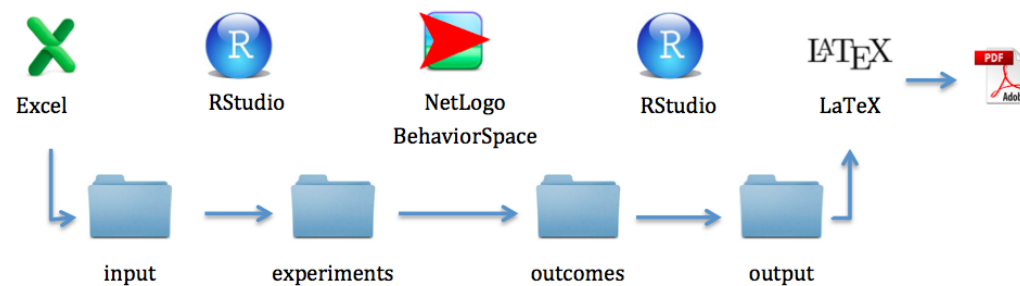


Figure 1: Visual overview of emaR experiment setup

## 3 Installation

This installation assumes you have a working version of Microsoft Excel or any other program capable of handling comma-separated value ( .csv ) files.

### 3.1 Create map structure

- Unzip **emaR.zip** in a location of choice. This creates the default map structure so all your files are always organized.

### 3.2 RStudio

Although you are free to use any other program that can handle .r files, RStudio is recommended as it has a very intuitive user interface.

- Download and install RStudio. It can be downloaded from <http://www.rstudio.com>. Rstudio is a development environment for the statistical analysis language R. RStudio automatically installs the language R.

- We will also need some additional **packages**. Packages are set of functions that can be downloaded from RStudio itself. The emaR setup requires the following packages:
  - ggplot2
  - reshape
  - lhs

These packages can be easily installed by typing:

```
install.packages("ggplot2")
```

- Install adapted **sdtoolkit** package. This adapted package currently only works on Macs. It requires Quartz. Download it from <http://xquartz.macosforge.org/landing/> and install it. Then manually install the package in R by typing in the following code (change the path to your path where the package is located):

```
install.packages("/Users/pimbellinga/Dropbox/Graduation/Rtests/sdtoolkit_2.31.tar.gz", repo="http://xquartz.macosforge.org/landing/")
```

### 3.3 Netlogo

- If you have not done this yet, first download and install Netlogo. It can be downloaded from <http://ccl.northwestern.edu/netlogo/>.
- Assuming you already have a model you want to analyze, place the .nlogo file of the model in the **models** map in the emaR map.
- Next, open emaR.nlogo, located in the **models** map. Copy all the code of your own model to emaR.nlogo (make sure not to overwrite the code which is already present!) and save the model under different name. The code in emaR.nlogo tells you exactly where to paste the parts of your code. Pay attention that you will need to make your `clear_all` procedure, which sets all relevant parameters to 0. Tip: use `ask agents [die]` to reset all agents. You now have all the necessary Netlogo procedures to analyse your model.

### 3.4 optional: Install LaTeX

The emaR toolkit doesn't require you to use LaTeX. All it does is save your plots in one map with a standard naming convention. You can use these images in whatever way you want, for example by importing them into your Word document or Powerpoint presentation. LaTeX however has one (huge) advantage over these methods: LaTeX uses code and imports the files every time the document is compiled. This means that if your plots change, the images will automatically change in your LaTeX document, which creates a .pdf file. This is an incredible advantage when you are facing a deadline, your document is ready, but you spot a calculation mistake. This would normally mean a sleepless night, creating new plots, then manually replacing them in your Word document. Horrible! But with R and LaTeX, it simply means running the .r script, compile your .tex document and you're done! Thus, using LaTeX is highly recommended! It does have a steep learning curve, so reserve some time to learn it. When you got it though, it certainly pays off.

- Mac users can download a full TeX distribution at <http://tug.org/mactex/>

- There is an abundance of TeX editors out there: [http://en.wikipedia.org/wiki/Comparison\\_of\\_TeX\\_editors](http://en.wikipedia.org/wiki/Comparison_of_TeX_editors) Choose the one you like. For Mac users TexPad is an option worth considering. (<https://www.texpadapp.com/>) It is not free (price: 16 dollars), but it works like a charm. TeXShop is also a good editor. (<http://pages.uoregon.edu/koch/texshop/>)

## 4 Conventions

All parameters need to be specified in `model_input_data.xlsx`. The names of the parameters need to be exactly the same as in the Netlogo model. The names are case sensitive.

## 5 Detailed experiment process overview

1. What is required to prepare an experiments is that you type in all the variables the model uses as input in an `.csv` file called **model\_input\_values.csv**. Using this file the fixed run, monte carlo and LHS experiments are generated.
2. Use **ema.convert** to first generate the fixed value run. This will be used by other types of runs as well. For a LHS experiment, use **ema.lhs** Specify the number of affordable runs and the parameters you want to use for the experiments. Default is that it uses all the parameters specified in `model_input_values.csv`.
3. Start the Netlogo Behavior Space and open [**lhs experiments**]. Fill the right number of columns (the number of parameters in the lhs set), the number of experiments and the filename of the lhs dataset. Click run and save the file as a **table** file in the **outcomes** map. The number of parallel experiments your computer can handle differs per computer. Try what works best for you.

## 6 emaR functions

- `ema.convert` (converts `model_input_data.xlsx` to `.data` file.)
- `ema.lhs` (creates LHS set in `.data` format)
- `ema.monte` (creates a monte carlo set around a given scenario)
- `ema.sweep` (creates a parameter sweep set)
- `ema.load` (combines simulation outcomes with experiment values)
- `ema.boxplot` (boxplot, automatically saves graphs to specified folder)
- `ema.lineplot` (lineplot, idem)
- `ema.prim` (contains wrapper code for `sdtoolkit` package)
- `ema.classify` (interactive classification for `ema.prim`)
- `ema.sign` (significance tests)



## **emaR - User Reactions - Survey**

**Name:** Alexander Oei

**Profession:** Master Student (SEPAM)

### **For what type of project have you used the emaR workbench?**

Agent Based Modelling project. Topic: Resilience of critical infrastructures

### **What was your intended use?**

In our project we built a model capable of representing existing infrastructures that modern society uses every day in an abstract way. Electricity and gas infrastructures (transmission plus distribution), road networks, cyber networks etc. To setup those networks many parameters had to be defined, the infrastructure characteristics. With PRIM we hoped to find how the infrastructure characteristics determined how well the networks would perform. The most important reason to choose for PRIM was that our study was an exploratory study. PRIM provided us with a means to find whether or not the infrastructure characteristics had an influence on reaching interesting behavior. Furthermore with PRIM, through the normalized dimensions restriction plots, it was possible to compare the influence of the different infrastructure characteristics on reaching interesting behaviour.

### **Usability:**

#### **Did you have previous experience with R?**

Yes, but only limited.

#### **Is it required to have previous experience with R to use the emaR workbench?**

I don't think it is necessary, but it is certainly very helpful. Using the emaR workbench was quite straightforward once you get to know it and you don't need to know so much of coding in R. However it's a huge pity that it's only possible to use the emaR workbench on a Mac.

#### **What did you think of the installation of the workbench? Was it easy or difficult?**

The manual that comes along with the workbench makes it very much doable. However if you don't have any experience on a Mac it will take some time to get used to it. For instance you need to download and install Quartz which allows you to use windows specific functions on the Mac.

#### **What is your opinion on the use of the workbench?**

I liked the fact that it is interactive and step by step takes you through the analysis. What I didn't like is that there are a few bugs in it, for instance when you have chosen a few points from the peeling trajectory you need to pick a box. But if you have only chosen one point you cannot type done, but you need to really type the number of the box, otherwise the workbench crashes (at least when I was running it). This was time consuming because you then had to run the analysis all over again.

**Is the workbench useable out of the box or does it have a steep learning curve?**

In my opinion it's quickly useable.

**Does the workbench report clear errors?**

Yes it does, except in the case mentioned above about picking the box.

**What have been your biggest problems with/questions about the emaR workbench?**

I could not get it to work on windows PC and therefore I had to borrow a Mac which is of course a huge problem. Furthermore when classifying which points you would like to define as 'interesting', only the greater than operator worked with me. When I used another operator, like smaller than, it just gave me the same dataset as with the greater than operator.

**Documentation:**

**Is there a manual? If so, does it contain a clear explanation on how to use the emaR workbench?**

There is a manual, written by Pim Bellinga.

**Is the code clearly documented?**

Yes I believe so.

**Are the functions clearly documented? What their function is, which conditions apply to the input?**

I looked at all the functions from the workbench, except the abm.monte function. From the functions I looked at I think they are clearly documented.

**Are there release notes available which state which issues have been resolved and which issues are not resolved yet?**

I don't think so, but that might be very useful.

**Do you have suggestions for improvement? Are these must-haves or nice-to-haves?**

Must-haves: Finishing the manual. Adding there a piece about installing quartz, that for now it only runs on a Mac, and that there are a few problems which have not been solved yet (the list of issues).

Issues:

- Classifying → Only the greater than operator seemed to work with me
- Picking a box → Make sure you type the number of the box and do not type done as the workbench asks you to.

Nice-to-haves: Make it usable for windows PC's as well.

**Which hardware and software environment did you use? Have you encountered problems with compatibility?**

MacBook Pro (an old one I don't know which one exactly, but I think it had a dual core with a 2.8 Ghz processor with multithreading)

Mac OS latest version on 7/20/2013.

**Would you recommend other students to use the emaR workbench? If yes, why? If no, why not?**

Yes I would, definitely. Because the emaR workbench is relatively easy to use it offers you a great way of exploring your data in a very robust way with little time investment.

Tip: Maybe it would be nice to ask Igor Nikolic if the workbench and manual could be uploaded to the TU Delft Wiki. There, many people can use it and the manual will hopefully be improved and edited by many people so it will get more and more elaborate. Furthermore the Wiki would also be a great place for a list of issues that are solved, and still have to be solved.

# Exploring Agent Based Models using PRIM: analysis of Predator-Prey model

Pim Bellinga

June 12, 2013

## 1 Purpose

The purpose of this small article is to demonstrate that the technical implementation of the Patient Rule Induction Method (PRIM) is working correctly. It is necessary to show that the technique works, to mitigate arguments that, in case of unclear results from an analysis, the cause might be an error in the technical setup. This paper shows the technical setup works correctly and that, if there exist regions with a high density of interesting points, this implementation of prim will find them and confine a box containing the points of interest.

## 2 Predator Prey model

The Predator Prey model is a model about two species, one predator and one prey species. The models demonstrate that possible includes instable behavior as well as behavior that displays strong fluctuations in population, while being stable in the long-term. There are many versions of Predator Prey models, of which the Lotka-Volterra equation-based versions is probably the most well-known. In this paper, an agent-based version created by Uri Wilensky is used. In this case the predators are wolves, the sheep the prey. Sheep need to eat grass, otherwise they will die. Wolves need to eat sheep, otherwise they will die. Under certain circumstances, this can lead to a stable relation between the grass, the sheep and the wolves. In other cases one of the populations dominates and the other perishes. In this paper PRIM is used to explore under what circumstances the behavior is stable.

## 3 Classification: exceptional cases

In order for PRIM to work, interesting points have to be classified. Most of the runs from the Predator Prey model result in instable behavior. The exceptional behavior in this case are runs with stable behavior. Stable behavior is indicated here by runs where the sheep nor the wolves have become extinct. In other words, were at least one member of the species exists at the end of the simulation run. The simulations end after 500 ticks. This classification can be formalized by:

$$c(n) = \begin{cases} 1 & \text{if sheep}(n) = 0 \text{ and wolves}(n) = 0 \\ 0 & \text{all other } n \end{cases}$$

## 4 Tool: sdtoolkit

PRIM is implemented by using the sdtoolkit package for R. This is a package written by ? and used to generate their results for their paper: *Thinking inside the box: A participatory, computer-assisted approach to scenario discovery*

## 5 Choosing boxes

A box is in this a multi-dimensional subspace of the parameter space. Choosing the size of a box often is a trade-off between a high density and a high coverage. Ideally, this box should have a maximum coverage, with a maximum density. **Coverage** is defined as the number of interesting points in the box as part of the total number of interesting points in the parameter space. **Density** is defined as the inclusion of interesting points as part of the total number of points in the box.

The PRIM algorithm tries to form this ideal box, by peeling of parts of the parameter space, if this increases the density. However, this often decreases the coverage. It therefore forms different boxes. This is shown in Figure 1. It is now up to the user to choose a box that fits the purpose of the analysis. In this case, this is one box with a high coverage and, given the coverage, a high density. The box that is chosen has a coverage of 0.85 and a density of 0.7.

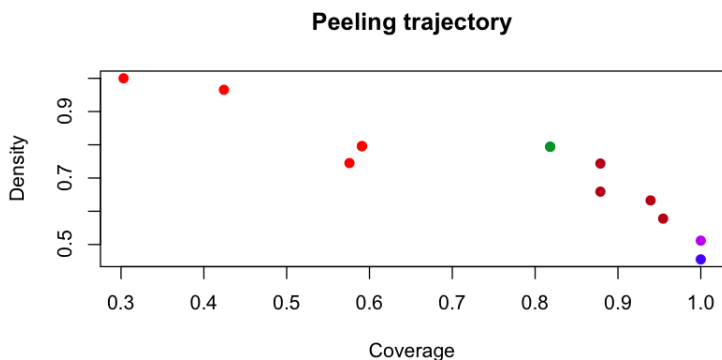


Figure 1: Peeling trajectory.

Figure 2 displays a visualization of the chosen box. Although only two dimensions are shown in this figure, the box actually spans across more than two dimensions.

## 6 Results: ranges of parameter values

Figure 3 shows the ranges of the input parameters that lead to stable behavior. This means that 80% of the cases of interest are contained in the blue ranges. From this plot the following insights can be drawn: the values of some parameters, such as `wolf.gain.from.food`, have little effect on leading to stable behavior. For other parameters such as `wolf.reproduce`, the values of the parameters do matter a lot.

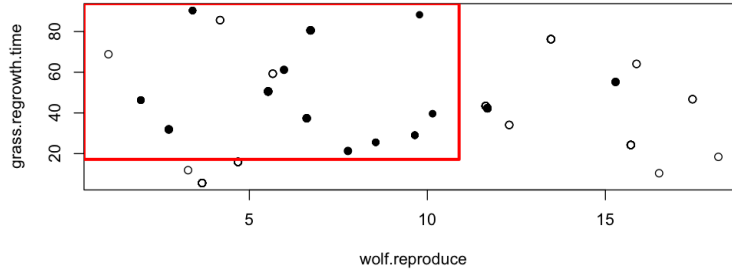


Figure 2: Visualization of box in two dimensions

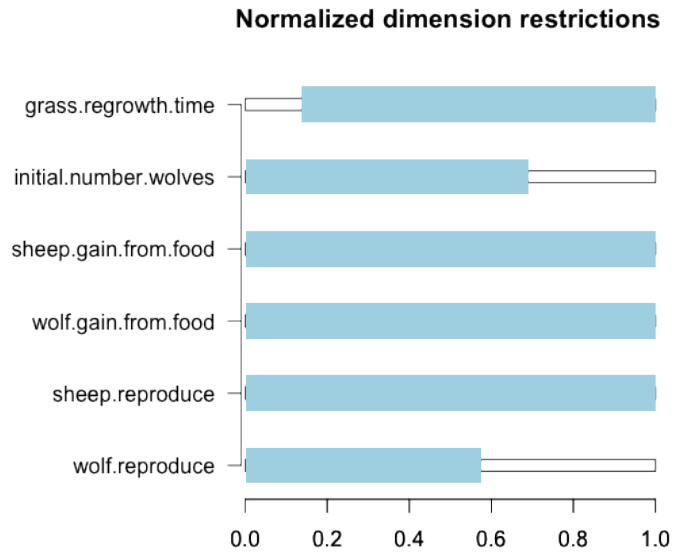


Figure 3: Visualization of ranges of input values that lead to stable behavior of predator prey model

## 7 Verification

Runs of agent based models with exactly the same input values do not necessarily yield the same output. In addition, the purpose of this paper was to demonstrate the working and usefulness of using PRIM. Therefore the ranges of the input parameters have been changed according to the information from the PRIM analysis.

It can be seen that after using the new ranges, simulation runs with values that are inside the box indeed still yield stable behavior. Not as many as with the full ranges, but this is understandable as the coverage of the box was not 1. (The math does not work out completely though:  $0.85 * 67 = 56$ . It is unknown why the results of the Inside Box run is lower than the expected result). However, these runs do not add that much confidence about the correctness of the approach. Performing the

	Full Range	Inside Box	Outside Box
Before	67	-	-
After	-	49	0

Table 1: Verification results

inverse, only sampling values outside of the ranges, should in theory not yield any stable behavior. The results in Table 1 confirms this: no runs with stable behavior have been observed after sampling from outside of the ranges. These results demonstrate the capabilities of using prim to identify sensitive parameters and show that this method has been implemented correctly.

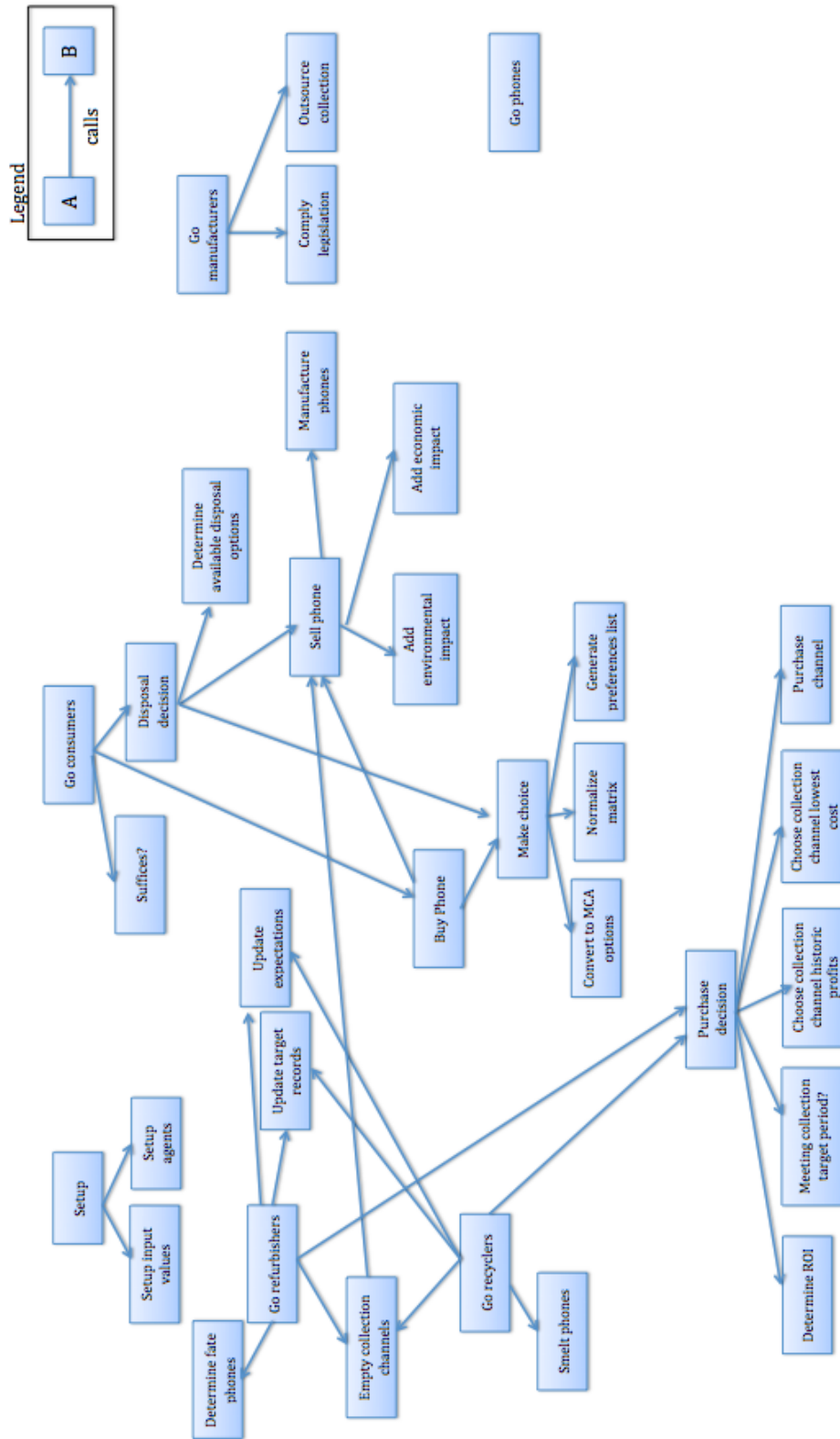
## 18 | Appendix: Netlogo Code

The code appendix contains the full Netlogo code. To aid the reader in getting an overview of the code, a UML package diagram has been added. This diagram visualizes which procedures are called by which other procedures. Two large workhorse procedures are:

- `sell_phone`: this procedure handles all the sales and movements of phones between agents. It is used for registering the sales and adding environmental impacts.
- `make_choice`: this is a general procedure which is able to make multi-criteria choices. It requires preferences and options and then makes the choice with the highest utility.

One note about the code: this latest version of the model has mainly been used in large experiments. Therefore, it can only be run from the Netlogo BehaviorSpace. Adjustments in runs require the emaR workbench to generate experiments and analyse the outcomes. See Appendix 17 for more information on this setup.





# 19 | Appendix: EMAworkbench Setup Manual

The EMAworkbench is a great workbench, filled with an extensive set of tools. However, without guidance, the setup of the workbench can be quite a challenge. To save other interested students and researchers time and frustration, I have documented the setup procedure in a manual. I have checked whether all necessary information is contained in the manual: one student has used only this manual and successfully installed the EMAworkbench.

# EMA Workbench Setup Manual

July 22, 2013

## 1 Purpose of this manual

Great! You are considering to explore your simulation model using structured methods. The EMA workbench is a great environment to do this and offers a lot of useful functions to assist you in your exploration. The workbench does not work right out of the box. Even for those who are technically experienced, the setup of the workbench and its requirements is not straightforward. The purpose of this manual<sup>1</sup> is to help you setup the workbench so you can concentrate your efforts on exploring your model. Note that this manual does not contain a tutorial on how to use the EMA workbench after you have it all set up. Tutorials and explanations on the functions of the workbench are available at <http://simulation.tbm.tudelft.nl/ema-workbench/contents.html>.

## 2 Structure

In order to use the EMA workbench to explore your model, there are three to four steps you will need to take:

1. Setup Python: Python is the programming language that the workbench uses
2. Download EMA workbench: the EMA workbench is a set of functions and scripts for the analysis of simulation models
3. (optional) Setup Eclipse: Eclipse is an Integrated Development Environment (IDE). It is the program in which you will write your code.
4. Prepare experiments.

## 3 Setup Python

Python is open-source software. Open-source software is fantastic since a lot of people are able to use it and a lot of users contribute to the advancement of the language. However, it's not so nice if you expect an easy installation. But it is less weird if you know what is going on: python is a programming language. Programs written in python, need this language to be installed on your computer. Most programmes also use packages; code written by other python programmers. This enables programmers to build on the work of others. For the scientific use of Python, the two most

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<sup>1</sup>Authors: Pim Bellinga, Andris Kóvári, Tim Markensteijn, Jan Kwakkel

important packages are NumPy and SciPy, which provide very efficient data structures. The following steps will make you do two things: 1) install the programming language Python. 2) Install the packages that the EMA workbench requires.

### 3.1 Windows

- Download **Python(x,y)** from <https://code.google.com/p/pythonxy/> This distribution contains python and a large number of packages, including NumPy and SciPy. Install it.
- Install the **Deap** package: Open a Terminal. (The Terminal can be found by click on the windows start icon, type in Terminal in the search bar, and open the Terminal) Type in the following code:

```
easy_install deap
```

- Check Java type: Still in the Terminal, type:

```
java -version
```

Check whether you have a 64 or 32 bits Java installation. If this command yields an error: make sure you have Java installed. If not: install it.

- Install **jPyype**: For jPyype you will need to download a version for the same number of bits as your java installation. (either 32 or 64b). Download it from <http://www.lfd.uci.edu/~gohlke/pythonlibs/>. Hint: ctrl+F "jPyype". Execute the file and it will be installed. The executable should automatically find the path of your Python installation. If you get an error than you probably do not have a correct installation of python or it is in a different path.
- Install **Orange**: Download the Orange package at <http://orange.biolab.si/>. Execute it. It should find the Python just like jPyype.

If you have made it to this step, you have Python and all the packages installed correctly!

### 3.2 Mac

Currently there is no support yet for Macs. This is caused by problems with the installation of the **jPyype** package. These problems have been solved by others. Users who are willing to try this out: please read <http://blog.y3xz.com/blog/2011/04/29/installing-jpyype-on-mac-os-x/>

## 4 Download EMA Workbench

The development of the EMA workbench is still in progress. Regularly, updates are made: to enhance existing functions, or to enable the connection with new simulation software. Therefore, it is easy if you always have the latest version of the EMA workbench. This is possible by using GitHub. GitHub is a platform where programmers can share their code, let other programmers make improvements and always offer the newest release. For more information on GitHub, what it is and how it works, visit <http://techcrunch.com/2012/07/14/what-exactly-is-github-anyway/>. This

manual offers two ways of installing the EMA workbench: 1) Use GitHub to remain up to date. (More information <http://git-scm.com/book/ch1-3.html>) 2) Alternatively, manually download a .zip file and keep yourself up to date.

If you will be using GitHub (optional):

- Install **Git**: Download Git. For windows: <http://windows.github.com/>, for Mac: <http://mac.github.com/>. Install it.
- Create a GitHub account.
- Go to <https://github.com/quaquel/EMAworkbench>. First login with your new account, then click on the Clone (in Windows/Mac) button. This will create a clone of the workbench folders and files on your computer. Choose a location to your preference.

You now have the EMA workbench installed correctly on your computer.

## 5 Optional: Setup Eclipse

There are many ways to use Python and the functions of the EMA workbench. In this manual one method using Eclipse will be explained. If you are more familiar with Python, the iPython Notebook is something you can also consider (<http://ipython.org/notebook.html>).

Eclipse is an Integrated Development Environment (IDE). This is a program which can be used to write code in several languages (often used for Java) and has all kinds of smart tricks and debuggers to help you write it fast and correctly.

- Install **Eclipse**: download Eclipse at <http://www.eclipse.org/>. Make sure to download and install the same 32/64bit version as your Java and jPyPe versions. Create a workspace at a location of your choice.
- Install **PyDev**: PyDev is a plugin which enables you to write Python in Eclipse. To install it, start Eclipse and go to Help > Install new software. Add this website <http://pydev.org/updates>.
- Configure PyDev: In Eclipse, go to Window > preferences > PyDev > Interpreter - Python > Auto Config. See Figure 1
- Add two .project files to your EMAworkbench folder in the explorer. See Figure 2. These files enable you to link Eclipse to the EMA workbench.
- In Eclipse, create a new project folder. Go to File > New > Project > General > Project. See Figure 3
- Import the workbench to this new folder: In the explorer, right-click on the EMAworkbench project, import > general > from existing project, browse to the EMAworkbench folder on your computer, name the project EMAworkbench. See Figure 4
- Create another folder. Give it an indicative name about your project.
- Reference to the EMA workbench: right-click on your new folder > properties > references, select the EMAworkbench project. See Figure 5.

You now have completed the setup and are you are ready to use the EMA workbench to explore your simulation model!

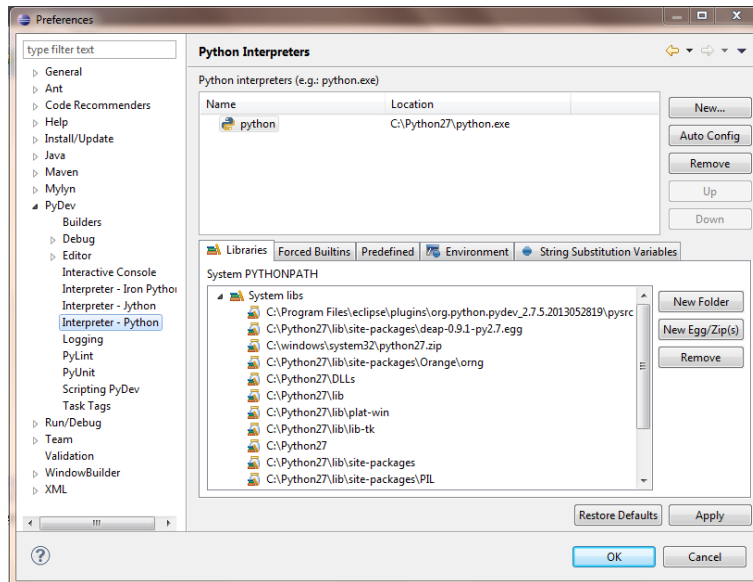


Figure 1: Screenshot of PyDev configuration window

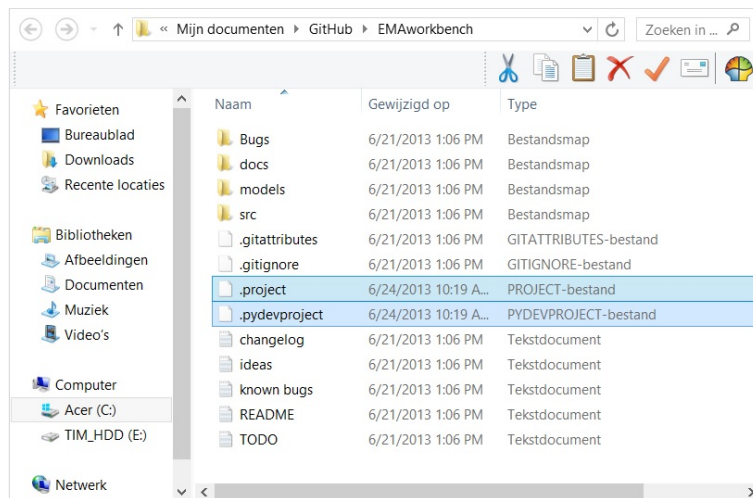


Figure 2: Screenshot: add the two project files

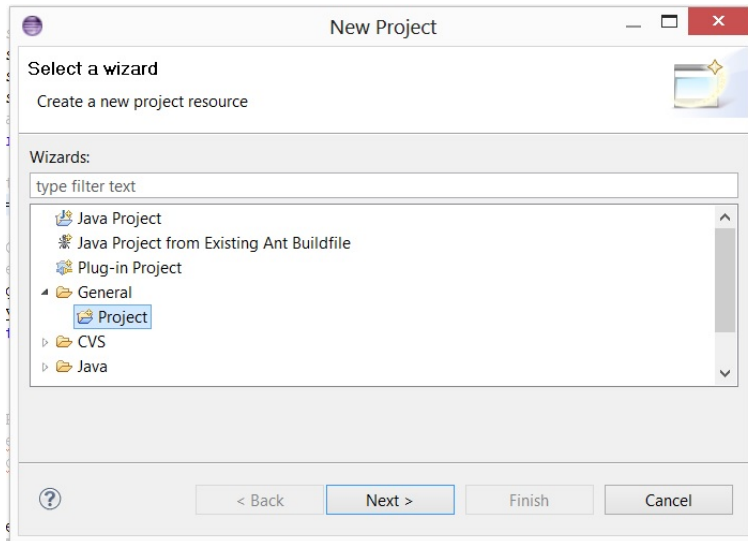


Figure 3: Screenshot: create a new project

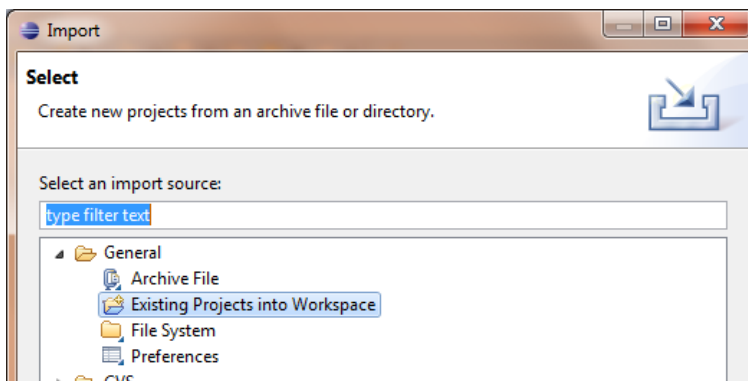


Figure 4: Screenshot of Import window

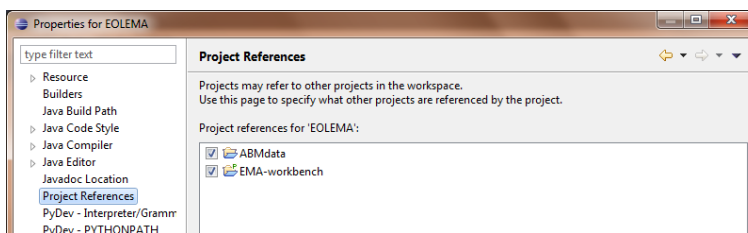


Figure 5: Screenshot of project references window.

## 20 | Appendix: Critical Reflection on Modeling of Socio-Technical Systems

This appendix contains an essay written for the Honours course Critical Reflection on Technology. The essay is appended because it relates directly to the modeling I have executed for this thesis. In addition, it provides a clear line of argumentation on why uncertainty exploration is necessary in models of socio-technical systems.



# Can and should we use agent based modeling to predict the long-term behavior of complex systems such as the climate and the economy?

Pim Bellinga  
student number: 1365487

June 4, 2013

We don't like to be uncertain. Especially not about the future. And so, every day, tens of thousands of people wake up, go to work and spend their days making forecasts, predictions and models to reduce our uncertainty about what future has in store for us. The techniques and methods certainly have got more advanced and elaborate. But even with a million educated economists, nobody predicted the economic downfall that struck the world in 2007, evaporated trillions of dollars and has put the US and Europe in a deep depression. Our climate is also changing, as a consequence of human activity. (IPCC) How exactly will this affect temperature changes, sea water levels and our environment? Thousands of researchers are working hard to find the answer. As systems in the world become more and more connected and therefore complex, these problems will only grow in both number and size. Some are suggesting that modeling, especially agent based modeling, could increase our ability to predict the behavior of these systems.

After six years of education at the Technical University of Delft, I will hopefully graduate in a few weeks; On research involving agent based modeling to predict the effects of government legislation in the mobile phone market on the environment and the economy. For the past months, this has put one critical question on top of my mind: *Can and should we use agent based modeling to predict the long-term behavior of complex systems such as the climate and the economy?*

Let's explore this question. It clearly has two sides to it. The first is technical in nature: *Can we predict the behavior of complex systems and use agent based modeling to do so?* The second question is normative

and moral in nature: *Should we?* In the first part of this article I will show you that we cannot precisely predict the future states of complex systems. But that we can use models to provide us with insights which allow us to better understand the systems we are modeling. In the second part I will argue that, if executed correctly, using models to explore the future is better than not modeling. In both parts, examples and stories will demonstrate the challenges a modeler in this field faces and the accounts of mistakes that have been made in facing them. Finally, I'll conclude with a list of recommendations to mitigate the risks and highlight which traps and fallacies one should look out for.

## 1 Can we? Methodological issues

Can we accurately predict the behavior and outcomes of complex systems under deep uncertainty, using models in general, and agent based models in particular? In this section I will argue that this is not possible. But modeling can provide insights. This section is structured as followed: First I will get our language straight, by providing clear definitions of the terms mentioned in the question. Next we will look at some examples from the past, where modeling has been used and often without the expected results. I will identify five risks a modeler of complex systems under deep uncertainty is facing, including some recommendations to mitigate these risks. Then we will look at agent based modeling, what it is and how it is used. The last section will dig deeper into the issue of validation of agent based models. I will show that the validation of agent based models is im-

possible. Therefore, agent based models will always remain theories. But first, let's be clear on what it is we are talking about.

## 1.1 Clear language

### 1.1.1 Complex systems

What exactly are complex systems? When you listen to policy researchers, politicians or CEOs, it seems that nowadays every problem is complex. In this paper, *complex* systems are strictly different from other *complicated* systems. There is no precise definition of which systems are complex and which are not. A list of characteristics of complex systems, or using their original term Complex Adaptive Systems, might give an indication: (Johnson, 2005)

- The number of parts (and types of parts) in the system and the number of relations between the parts is non-trivial however, there is no general rule to separate "trivial" from "non-trivial";
- The system has memory or includes feedback;
- The system can adapt itself according to its history or feedback;
- The relations between the system and its environment are non-trivial or non-linear;
- The system can be influenced by, or can adapt itself to, its environment; and
- The system is highly sensitive to initial conditions

The climate and the economy are both complex systems. They exhibit a lot of non-linear feedback loops, they are constantly adapting and changing and the trivial and non-trivial parts are hard to separate. When researching these systems, it is very important though to start analyzing the system from the question one wants to answer. A brief example will illustrate the point: A river with water can be a turbulent stream. Turbulence is a highly chaotic phenomenon, which we cannot precisely predict. Suppose we now let some rubber duckies float in the river. If our question is: when will they have floated two hundred meters downstream? Then we can neglect the chaotic complexity of the turbulence and solve the problem with an analytic formula. If our question is: will the rubber duckies collide? Then this time we do need to take the turbulent effects into account and model the behavior of the individuals. This illustrates that

one needs think critically about involving complexity when analysing a certain system.

### 1.1.2 Deep Uncertainty

Climate and economy are also highly uncertain. There are different types of uncertainty:

*"There are known knowns; there are things we know that we know. There are known unknowns; that is to say, there are things that we now know we don't know. But there are also unknown unknowns there are things we do not know we don't know."*

— Donald Rumsfeld, *United States Secretary of Defense (2002)*

Situations with a lot of unquantifiable uncertainty and unknown unknowns is referred to as *deep uncertainty*. This term distinguishes stochastic uncertainty from 'deeper' uncertainty.

### 1.1.3 Difference between prediction and forecasting

Although most people use these terms as if they are similar, there is a subtle difference between forecasting and prediction. The term *forecasting* is reserved for stating specific values in the future. Prediction is a more general term. If someone has made a model, he/she can make predictions about certain phenomena or how choices should be made, resulting from the rules and requirements in the model. These predictions can then be checked by making observations in the real world.

### 1.1.4 Difference between predictive and explanatory use of models

The same model can be used in two very distinct ways: the first is *predictive*. This means the model is used to predict how the system is going to change in the future from its current state to a future state. *Explanatory* use (also called descriptive use) of models means that no predictions about the future are made. The modeler is now only trying to understand how a certain phenomenon in the real world can be explained. By creating a model and replicating the effect, the phenomenon can be explained and described formally.

## 1.2 Lessons from the past

*Those who fail to learn from history are doomed to repeat it.*

— Sir Winston Churchill

Mankind has for a long time tried to forecast the future. Often we do not succeed. In order not to repeat the mistakes we have made in the past, we will look at five areas where mistakes have been made: (1) Role of Technology (2) One model or value is not good enough (3) Don't show certainty you don't have (4) Self-averting prophecies. (5) Black Swans. These issues are not bound to agent based modeling only, but to all forms of modeling. With every issue an example will be provided so demonstrate how it has lead to wrong forecasts.

### 1.2.1 Don't underestimate technology (but don't overestimate as well)

It is the year 1898. New York is a buzzing city. The number of residents per square mile has trippled from 30.000 in 1800 to 90.000 at the end of the century. This leads to New York hosting world's first urban planning and infrastructure conference. The policy makers are concerned. New York will not be able to grow anymore. The reason: the Times of London has estimated that in fifty years, in order to accomodate the expected population growth, the manure of horses would reach the windows on the third floor. New York would be filled, meters high, with horse shit.

Nowadays, this forecast seems unbelievable. At that time though, horses were used for all forms of transport. New York and Brooklyn had a combined horse population of more than 200.000 horses. So why did this manure nightmare not take place? Historians recalculated the forecasts made by the Times of London. The calculations were correct. What happened? Now we know that there was one piece of technology that would change everything: the car. In thirty years time, almost all horses were replaced by cars, and the problem of horse manure disappeared. This story (Morris, 2007) demonstrates the difficulties involved with forecasting the future, when technological changes can happen so fast.

### 1.2.2 Don't rely on one model or one set of parameters

In the 1970's, using computer simulations, a group of researchers, commissioned by the Club of Rome,

wrote the book *Limits to Growth*. (Meadows et al., 1972) They had constructed a system dynamics model, relating a range of effects to each other and computing the effect of their dependencies. The book generated a lot of criticism. "The authors load their case by letting some things grow exponentially and others not. Population, capital and pollution grow exponentially in all models, but technologies for expanding resources and controlling pollution are permitted to grow, if at all, only in discrete increments." This example shows that, even if your model and predictions might turn out to be correct, others will criticize the assumptions you make and dismiss the entire work. Instead of confining your model to one set of assumptions, it would be better to also investigate the implications of the assumptions other researcher might make. This increases the potential use of the model and mitigates the risk that others will reject the entire model because they don't believe some of the assumptions that are made.

### 1.2.3 Don't show certainty you don't have

In the Netherlands, the Centraal Plan Bureau (CPB) makes annual forecasts for the Dutch economy. Politicians rely on their forecasts. However, the forecasts of the CPB are not very reliable. Actually, throwing a coin would give you better odds at forecasting the state of the economy for next year than reading a CPB report. The past 37 years, the CPB only correctly predicted whether the economy would grow or shrink 3 times (ref: NRC Next, 2009). 3 out of 37. These were not accurate forecasts that turned out to be one digit off. The qualitative forecasts on the trajectory of the economy were off. Although the CPB is aware of this inability to forecast, they still report their numbers to two digits, with no uncertainty ranges. This suggests more certainty than they know they can have. This is misleading and therefore a bad practice.

### 1.2.4 Self-averting prophecies

What makes the life of a modeler of complex systems more difficult, is that the implementation of a policy could succesfully avert an undesirable situation, but in doing so, making it impossible to prove that the undesirable situation would have happened otherwise. In addition, by changing the system, one could change the structure of the system which was the target of the model, which is now no longer correct.

### 1.2.5 Black Swans

”Life is great, these humans love me” This is the thought of a rabbit who is cared for by a nice family. ”In the morning one of these humans comes to feed me, clean my cage, for weeks and months on end.” The rabbit starts to see a pattern: this human will keep on feeding me forever. I’ve looked at history and it confirms my prediction very well. One night at Christmas, the rabbit meets its unexpected fate: as dish for the family dinner. This story is used Nassim Taleb in his book *The Black Swan* (Taleb), illustrates how bad it is to rely solely on historic data to confirm our predictions. The title of the book comes from the fact that for centuries it was believed in Europe that Swans are white. There was no reason to doubt it. Nobody had ever seen a swan of a different color. To state that swans might not be white was ridiculous. It was ridiculous until the Europeans went to Australia and discovered black swans. No that the unexpected event had happened, it was no longer unexpected. In his book Nassim Taleb uses these stories to illustrate why we humans are so bad at forecasting on complex systems. A ridiculous forecast is ignored and outcomes are only termed plausible if they align with our expectations. The story of the rabbit shows how wrong these expectations can be. On modeling, Taleb suggest modelers stop modeling systems they cannot possible forecast. But since it is in our nature to still do so, he suggests to use much wider confidence intervals and be prepared to search for the unexpected.

## 1.3 Agent Based Modeling

The question suggests that agent based modeling can perhaps be used to study complex systems. But what is this agent based modeling? The agent based modeling paradigm started just after the war with the work of Von Neumann and Burks (1970) on *cellular automata*. Cellular automata are patches, little squares, which are either 1 or 0, depending on a set of rules and the states of their neighbors. This field then splitted; some went into the physics and mathematics direction, others started studying systems from biology and sociology. Agent based modeling was first really formalized as a concept by Holland (1996). He identified a special set of systems, which he called *Complex Adaptive Systems*. These are systems where the parts interact, according to a specified set of rules. These parts were later called *agents*, entities who make choices

based on specified rules. This is a generalization of the cellular automata systems, which also interact according to a small, strict set of rules. One of Holland’s main contributions was the translation of the biological concept of evolution into mathematics, yielding genetic algorithms. The work of Holland ignited further research into the capabilities of these new concepts.

One of the first to use agent based modeling to explain social phenomena was Axelrod and Hamilton (1981). He generated a set of agents and got them to play against in each other in a tournament of iterated prisoner dilemmas. The agents who got the highest points were then used to breed a new generation of agents, using the genetic algorithms of Holland. This research indicated that the most succesfull agents used a simple tit-for-tat strategy. This showed that small agent based models could be used to explain or investigate social phenomena. The use of small, descriptive models in the social sciences has later been promoted by Gilbert. Around the same time, other researchers were trying to recreate certain elements we observe in our society. Axtell and Epstein started working on *artificial societies*. Their ’Sugarscape’ program showed that with some simple rules, phenomena like the-rich-get-richer could be *grown* in computer simulations. This field of research has since been growing. Researchers are now trying to understand the workings and behavior of large socio-technical systems, systems with a strong connection between their physical and social components, by using agent based modeling. Dam et al. (2012).

## 1.4 Agent based models practically impossible to validate

In order to make reliable claims about the real world, one needs to be sure that the model is actually a relevant description of the real world. Although the model should not be the same as the real world, it should be fit enough for its purpose. (Dam et al., 2012) The process of comparing predictions from the model with observations from the real world is called *validation*. It is an essential step in generalizing statements about the model to the real world. In this section I will show the inherent and practical difficulties in validating agent based models. In practice, it is often impossible to validate agent based models.

This limits agent based models from making reliable forecasts.

#### 1.4.1 Equal input values, different outcomes

Agent based models are stochastic in nature. The choices or interactions of agents often depend in some way on chance. Because of the stochastic nature, two runs with exactly the same input values can generate two completely different results. This can sometimes be amplified by *path dependence*. Once an agent or the system has gone down a particular path, there is no way back and the outcome is very different from the case the system would have gone down another path. At the start, these paths are very close together, chance dictating which path it will be. Then feedback loops start amplifying and the systems gets *locked in* that particular path. Although at the start the input values were the same, the outcome can be totally different.

#### 1.4.2 Not enough observations to compare distributions

Different outcomes under the same input values is not a problem related solely to agent based models. Quantum mechanics is based on the notion that the world is inherently undeterministic. How do physicists then validate their theories? In quantum mechanics it is impossible to state with certainty where a particle will be and what its speed is. What is possible, is make predictions about the distribution of states. Whether a given particle will go up or down cannot be predicted. How *many particles* go up or go down *can* be predicted. By comparing the theoretical predicted amount with the observed amount in the real world, theories can be validated.

In social systems however, this type of validation is often impossible. A lot of times there is only one observation possible. If we are modeling the world market, then there is only one world market to compare our predictions with. Perhaps the model and the world market have exactly the same distribution of outcomes, but with only one observation it is impossible to state whether these are the same. One can at most check if the observation is within the predicted range, but this often leaves too much room for a whole range of theories instead of validating one theory. Secondly, even if there would be more observations possible, this is often expensive or practically impossible. In social systems, companies often play an important role. But companies are often

reluctant to provide data on their actions and behavior. Experiments with consumers are often expensive and might not align with consumer behavior in the real world. Thirdly, validating economic and climate change models is impossible because the forecasts often involve time scales of tens or hundreds of years. This makes it useless to falsify or validate the theory, so many years after the decisions have already been made.

These issues demonstrate the inherent difficulties in validating agent based models, which most of the time makes it impossible to validate these models.

#### 1.4.3 Validation of parts: risk of systemic errors

An agent based model is the result of the agents, their rules, their interactions and their input values. If one could validate these parts, which might be difficult but often possible, one could *infer* the outcome of model is valid as well. Although this line of reasoning is correct, it bears one big risk: this type of validation does not guarantee that all the relevant agents, interactions, rules and input values have been taken into account. There is no way to check that an *unknown unknown* will not have relevant effects as well, which could change the behavior of the system, thus leading to wrong predictions and forecasts.

### 1.5 Sub Conclusion: We cannot use agent based modeling to make reliable forecasts

In this section we have seen the difficulties in using models to forecast outcomes of complex systems. The undeterministic nature of agent based models (and of real life) and the long time scales only aggravate the situation. I have shown you that validation of agent based models is problematic, blocking the generalization of claims about the model to the real world. The conclusion must be: agent based models, just like other types of models, cannot be used to forecast the behavior of complex systems. Especially not over long time scales and if there is only one real world system to compare the model to.

## 2 Should we? Ethical issues

The conclusion from the previous section makes the situation of modelers of complex systems seem dire.

And it is. Although we have discovered that complex systems cannot be forecasted, still numerous of people try every day. But as we have seen in section 1.1.3 there is a difference between forecasting and prediction. As well as there is an important difference between a predictive use of models versus an explanatory use. In this section I will argue that agent based models can, and should, be used to predict or understand plausible behaviors (please note the plural here) of complex systems. This section will first describe why we should even care about the wrong usage of models. Next I will argue that we have no other options besides modeling. Finally I will explain what benefits we can still get from modeling complex systems.

## 2.1 Why would we care?

### 2.1.1 Authority bias

People stop thinking in the presence of authority. In a now well-known experiment, the researcher Milgram asked people to give a small shock to an unknown person at the other side of the wall when they gave the wrong answer to a question. The shocks become stronger and stronger. At some point the person at the other side of the wall was screaming to stop. Most of the people did so. But if Milgram placed an authoritative person in a white lab coat in the room who would reply: "It's okay. Just do it.", most of the people continued to give shocks, to the point where the other person would have normally died (in the experiment the shocks were fake and the person at the other side of the wall was an actor). The Milgram experiment shows the danger in being viewed as an expert. People stop thinking for themselves. I argue that this *authority bias* also exists when we use computer models for policy making. The computer models are often quite difficult to understand, with a lot of lines of code, endless assumptions, mathematics and difficult terms. For a layman, the act of modeling increases the authority of the modeler. Even if we know the assumptions are completely wrong, I argue we are more likely to trust the modeler because of the work he/she has put into it and the way it is presented. This could block our own independent thinking. In the case where we know the modeler is right most of the time, this is quite harmless. It is just a way of effective work distribution. In the case the models have a large impact on our lives and are often wrong, this effect can be harmful. The modeler is now making decisions about the way other people

from the population are leading their lives, on which they might heavily disagree if they would have had a discussion on equal terms.

### 2.1.2 Cargo Cult Science is harmful to the rest of science

In a famous speech, theoretical physicist Richard Feynman explains why he thinks scientist should not work on problems which they cannot possibly predict. The title of his lecture is called Cargo Cult Science. The title is adopted from a phenomena which was observed just after the second world war. On small islands in the Pacific, people had been living for thousands of years without ever coming into contact with other people or technology. Suddenly the Americans landed on these islands with planes. They constructed military bases to fight the Japanese. With them they brought food, tents and all kinds of useful things. After the war was over, the American soldiers left. The inhabitants of the island did not understand it. When are the planes with all the food coming again? Weeks passed, but no planes returned. They started imitating the soldiers as they marched, making guns from bamboo and mimicing the sound of the sirens. They constructed wooden watch towers, made fires as signals and watched the sky as they waited for the planes to return.

This story illustrates what happens if you do not really *understand* why you are doing these activities, but merely *imitating* what you've seen, hoping for a similar success. Feynman argues that social scientists often do the same. Science, as he puts it, is the method to distinguish false theories from true theories. It is a valuable method which, if performed correctly, will distinguish truth from tale. The harm is done if 'scientist' act *as if* they are doing science, but omitting the crucial steps such as validating their theory. Then they make wrong predictions, causing people to stop believing in the power of science, thus doing harm to the entire practice.

As we have seen in section 1.4.3, agent based models cannot be validated. However, it does make predictions (by stating its assumptions) and can thus be *falsified*. In this sense, if done correctly, agent based modeling is a good scientific method. Unfortunately, agent based models are often not used in such a way and if long-time scales are involved, also these predictions cannot be checked. In those cases, I believe it is the responsibility *of the modeler* to guard against the misuse of his/her model. Otherwise the model will not be useful but actually damage the rest of

modern science.

## 2.2 Alternatives and other functions of modeling

When we ask ourselves, should we model or not, we should also think of what would happen if we would not model. What are the alternatives in case of not modeling? Not modeling means going with gut instincts. Instincts here are defined as acting without knowing being able to state the reason why the action is taken. Instincts are not transparent, since a well-defined instinct (if I'm hunting in on plains of Africa and my fellow hunters start running, I predict there is something wrong and I'll run as well) is still a model, although a very basic one. According to Epstein (2008), models have more functions than being used for prediction. (Epstein uses the word prediction, which in this article is defined more strict by forecasting). He lists sixteen uses of modeling, besides forecasting:

1. Explain (very distinct from predict)
2. Guide data collection
3. Illuminate core dynamics
4. Suggest dynamical analogies
5. Discover new questions
6. Promote a scientific habit of mind
7. Illuminate core uncertainties
8. Offer crisis options in near-real time
9. Demonstrate tradeoffs / suggest efficiencies
10. Challenge the robustness of prevailing theory through perturbations
11. Expose prevailing wisdom as incompatible with available data
12. Train practitioners
13. Discipline the policy dialogue
14. Educate the general public
15. Reveal the apparently simple (complex) to be complex (simple)

This article doesn't provide the space to discuss all of these points. There are three points I would like to elaborate on, which are relevant in our discussion on using modeling for long-term policy making of complex systems: (1) Guide data collection, (2) promote scientific habit of mind (3) discipline the policy dialogue.

### 2.2.1 Guide data collection

If one has constructed a model and uses sensitivity analyses to find out which points are most crucial for the outcome of the system, this new knowledge can be used to guide observations. If making observations is expensive and only a limited set can be acquired, using models provides a structured method for finding the most uncertain assumptions. Thus modeling can lead a heuristic for collecting emperic evidence.

### 2.2.2 Promote scientific habit of mind

I paraphrase this point to demonstrate a key benefit of models versus hunches/gut feeling: models are transparent. A key requirement of scientific work is that it should be transparent so others can replicate the experiments or point out weaknesses. Especially when talking about models of large complex systems, this is a big benefit over just writing and arguing about these systems.

### 2.2.3 Discipline the policy dialogue

Modeling structures the policy dialogue by providing guidance to understand the system. In addition, it forces one to construct a *consistent* theory. Third, it forces one to consider unbelievable, but plausible, scenarios. Humans are susceptible to the narrative fallacy, preferring scenarios with a story we can understand or relate to. (Taleb) The computer does not feel this and will treat all scenarios equal. This disciplines the policy dialogue from over weighing more believable scenarios, neglecting other scenarios which might be equally plausible.

## 2.3 Protection of model responsibility of the modeler

A model is a formalized and transparent set of assumptions. But there not a lot of people who take the time to understand the assumptions that make up the model. All modelers are aware of the sometimes very strong assumptions they have to make without more

information. But decision-makers often do not appreciate these inherent uncertainties. If offered a range, they will pick the most favorable scenario and state that the model predicts it. Sometimes that might not even be wrong: the model does predict it. But it also predicts exactly the opposite scenario! However, the job of a decision-maker often does not allow him or her to spend endless days to understand the limits of a model. It is therefore the responsibility of the modeler to ensure that the model is used in the right way and not stretched beyond its use. One could even think of a legal document that accompanies a model which states how it can be used. As a society we do this with elevators and all other technical products. We should do the same with our intellectual products.

## 2.4 Conclusion: We Should. But never to forecast and always be cautious

In this section I have shown you the dangers of using agent based modeling for tricks the tool is not meant to be used for. If people, despite these limitations, keep making forecasts, or officially not making forecasts, but still generalizing the behavior of the model to the real world, these are harmful practices. It is harmful because as modelers we are abusing our expert authority and harming the credibility of the rest of science as well.

I have also shown you the alternative is worse. Modeling at least makes our incompetence explicit and transparent. It provides a way to discover new insights about the system, guide the collection of data, protect us against the availability bias and structure the policy discussion. If agent based modeling is used in this explanatory way, it is an improvement over not modeling. Not modeling means no transparency and no formalized theory which can be falsified. Models do have these favorable features. But with modeling comes a responsibility. I believe it is the responsibility of the modeler to ensure his/her model is used in the correct way, and not in other wrong ways. This places a heavy load on the shoulders of the modeler, but one we have to bear.

## 3 Conclusion: Transparent, Consistent Theories

In this article I have shown you why models, including agent based models, cannot be used to precisely

predict future states of complex systems. I have also argued that models can be used successfully to gain insights and learn more about the workings of the system, which can be used to make better informed decisions. This though, is not without any errors or mistakes. This can have negative effects on the trust of people in these models and in science in general. But not modeling has a bigger disadvantage: by not being *transparent*, there is no possibility of improving the reliability of future models. Secondly, modeling forces the theories to be *coherent*. You only know that you have a working theory until you have grown the whole thing. (Epstein, 1999) Lastly, I would like to make three recommendations to myself and other modelers of complex systems:

1. Reason from the question: Do you really need to include the complexity to answer your question? If not, then don't.
2. Don't just make one model: Instead, make multiple models from sets of plausible assumptions and test for the differences between them.
3. Protect your model: Make sure people draw the right conclusions and feel responsible if you notice people do not.

Agent based modeling of complex systems still has a long way to go before it reaches the maturity of other established modeling practices, but I hope this article has presented you a critical overview of the possibilities and limits of agent based modeling of complex systems.

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