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Agent Based Modeling the e-waste recycling sector in Bangalore

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Summary

While the production of electrical and electronic products continue to increase globally, the flow of electric and electronic waste grows as well. Considering that 50 to 80% of the ewaste from industrialized countries ends up in developing countries like China, India, Pakistan, the Philippines and countries in Africa, and recognizing that the economical growth and the demand for electronical products rises fast in countries like China and India, a solution has to be found for the safe dismantling and recycling of ewaste in these countries. The vast amount of personal computers, flat screens, laptops, PDA's, mobile phones, mp3-players, and many other electric and electronic products are now largely ending up in an informal sector that has specialized itself in the recycling and recovery of precious materials in these products. This has become known as backyard recycling. However, the methods of doing so are in most cases crude and, due to the hazardous material content of electric and electronic products, poses a threat to the health of workers in this sector and the environment.

One approach to cause a change in these informal recycling sectors and to avoid the negative health impacts is the introduction of a professional and formal recycling company or a professional end refiner into the system, that can recycle and dispose of ewaste safely. This professional end refiner can buy the e-waste from the local recyclers, but only if they are formal. For informal recyclers this means becoming formal themselves and, possibly - from their perspective - making an uncertain decision regarding their current work and security of income.

This research focusses on the informal sector in Bangalore, India, and models the system with Agent Based Modelling (ABM), to understand the factors that may influence the system into a situation where cooperation between former informal recyclers and a professional recycling company is established. This is done by using a newly developed framework called MAIA, that incorporates Institutional Analysis in the conceptualization of the model. Through ABM, we can attempt to simulate the system from bottom-up, allowing agents to interact with a set of predefined rules.

The model was made and an experiment was performed with the model. The experiment, due to time constraints, reflected mainly on economical factors. The results showed that cooperation with the professional end refiner occured when (1) the starting capital of agents was high, (2) taxes were low, (3) the investment costs were low and (4) the e-scrap price offered by the professional end refiner was high.

There are many possibilities for follow-up work. The social characteristics of the model can be tested in a new experiment. The institutional analysis of the system that was started in the conceptualization of the modelling process can be improved. There is potential for the model to help gain an insight into local recycling of backyard recyclers on a larger scale as well and how institutions influence the decision making behaviour of agents.

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List of Abbreviations

ABM	Agent Based Model(ing)
BPO	Business Process Outsourcing
CAS	Complex Adaptive System
CRT	Cathode Ray Tube (computer-monitor component)
E-scrap	Scrap of electronic products
E-waste	Electric and electronic waste
EC	European Commission
HPC	High Performance Computer, located at the TPM faculty at the TU Delft
IAD	Institutional Analysis and Development
IE	Industrial Ecology
INR	Indian Rupees (Rs)
LHS	Latin Hypercube Sampling
MAIA	Modeling Agent systems based on Institutional Analysis
NGO	Non Governmental Organization
PCB	Printed Circuit Board, same as PWB
PER	Professional End Refiner, an agent in the case study model
PWB	Printed Wiring Board, same as PCB
SQL	Structured Query Language
t-SNE	T-distributed Stochastic Neighbor Embedding
UPMR	Umicore Precious Metals Refining
WEEE	Waste Electric and Electronic Equipment

Chapter 1

Introduction

In this first chapter an introduction is given to the subject of this thesis. It discusses the growing response in science to answer local and global environmental problems. One relatively new method of gaining insights into environmental, technical or social systems is Agent Based Modelling. These insights may help us determine how to address a problem appropriately.

We look in this report specifically to an Agent Based Model that was built to help understand factors that may attribute to the improvement of the informal e-waste recycling sector in Bangalore, India. By incorporating the institutional characteristics of the system, an attempt is made to address environmental problems not only from a technical or purely financial point of view, but also incorporating more complicated social functions into the model.

Section 1.1 introduces Industrial Ecology as an overarching concept for the approach of this research. In section 1.2 complexity and Agent Based Modelling is discussed. After that, section 1.3 sketches briefly the background of the problem that will be adressed. The method for conceptualizing the system by the MAIA framework is the topic of section 1.5, after which the research questions are given in section 1.6. The following sections 1.7 and 1.8 reflect on the methodology and data collection respectively. Finally, a reading guide in section 1.9 is meant to help the reader understand the structure and content of the remainder of this report.

1.1 Industrial Ecology: a 'natural' perspective on an industrial system

Ecology and ecological problems have in recent times evolved to a much discussed subject in scientific research. As our society and it's production and consumption system grows, the problems become more complex. While end-of-pipe measures may have sufficed to alleviate the direct problems of toxicity, waste and pollution forty years ago, the issues now require a more integral and systemic approach. The effects of environmental problems cannot be allocated to the final outcomes only. The use of resources, the design of products and systems, the production process, the product use by consumers and the disposal of products all need to be addressed. It is imperative to combine efforts between a multitude of disciplines to gain an understanding of the emergence, establishment, and effects of the problems. We need to look at economical, political, technical, social and ecological factors.

We see an uplift in the scientific fields to face the environmental problems appropriately, looking not only at the technological or ecological system, but also including social, political and economic aspects. Emerging fields and concepts like Industrial Ecology, Ecological Engineering, Cradle to Cradle, and others, quickly gain in popularity.

It was in 1989 that Frosch and Gallopoulos first used the term 'industrial ecosystems', referring to the analogy they saw in industry with the behaviour of the natural world with respect to the use of materials and energy (Frosch and Gallopoulos, 1989). This was partly, Frosch says, due to a paper of Robert U. Ayres on 'industrial metabolism' (Frosch, 1992). Industrial ecology goes further than what is called 'industrial metabolism'. Industrial metabolism refers to the circulation of material and energy flows linked to human activity, and the understanding of this metabolism. Industrial ecology adds to that the aim of understanding how the industrial system works, what the interactions are with the biosphere, how the system can be regulated, and then, with the knowledge that we have about ecosystems, determine what can be done to restructure the industrial system to "make it compatible with the way natural ecosytems function" (Erkman, 1997).

Being a new emerging concept in the evolution of environmental management paradigms, "Industrial ecology is a framework for thinking about and organizing human social production/consumption systems in ways that resemble natural, dynamically stable ecosystems. Further, at some appropriate scale, this idea considers human societies to be part of and operating within the natural ecosystem" (Ehrenfeld, 1995; Ehrenfeld and Gertler, 1997).

Braden Allenby (Allenby, 2000) describes Industrial Ecology as follows:

> "Industrial ecology is the objective, multidisciplinary study of industrial and economic systems and their linkages with fundamental natural systems. Two fundamental premises of this new field are: reflecting the reality of the world within which human and environmental systems operate, industrial ecology always takes a systems view, and second, it is about technology and the evolution of human culture and economic systems." (Allenby, 2000)

While Ehrenfeld (2004) reflects on the debate on whether Industrial Ecology is an actual field or simply a metaphor - a debate that will not be part of this report - we can see Industrial Ecology as an emerging framework that combines key concepts like systems analysis, material and energy flows and multidisciplinarity (Garner and Keoleian, 1995). In the next section we reflect on 'systems', and discuss the complexity of systems and introduce a method for modelling complex systems.

1.2 Complexity and modelling socio-technical complex adaptive systems

In our society as well as in nature we can identify complex, layered and dynamic systems (Dijkema and Basson, 2009). Complex systems, or complex adaptive systems (CAS) is a term used in different disciplines and is described in different ways (Nikolic et al., 2009, p.29). For this research the definition of John H. Holland will be used. In this definition, a Complex Adaptive System is:

> "... a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behaviour in the system, it has to arise from competition and cooperation among the agents themselves. The overall behaviour

of the system is the result of a huge number of decisions made every moment by many individual agents."

John H. Holland, cited in Nikolic et al. (2009, p.32)

One way to gain insight in such a system is to model it. There are various different modelling techniques. Agent Based Modelling (ABM) is one way of modeling a CAS. ABM is a tool that takes agents and their interactions as central modelling focus points (Nikolic et al., 2009, p.51). The agents are programmed into a computer model and thus described by computer algorithms. By programming the agents to behave in a way that reflects their real-world counterparts we can simulate what happens in the system over time. This information can help to understand the system, how initial conditions can influence the results and how the behaviour of the agents is affected by their surroundings.

Modelling a complex socio-technical system requires a system boundary, identification of appropriate system elements and a definition of the span and nature of the interactions (Dijkema and Basson, 2009). A brief overview of the problem and the system that is to be modelled in this research is given in the next section.

1.3 Electronic waste

"Electronic waste or e-waste is one of the fastest growing areas of the international waste stream and is increasing at a much higher rate than all other waste streams" (Herat, 2007). A cause of concern is the flow of e-waste to the developing world, while upcoming countries like China, India and African countries are picking up on the consumption of electronics themselves. Due to the valuable content of these electronics - many of them contain precious metals like gold, silver and platinum, amongst other materials - the recycling of e-waste has become a lucrative business for what are called 'backyard recyclers'. These unskilled workers recycle e-waste with unsafe and crude methods. These businesses have settled themselves as a largely informal sector in many developing countries. It is a labour intensive task, wherein the extended family is involved (Sinha, 2004).

Bangalore is one of the eight biggest generators of e-waste in India, and a city with a rapid growing economy due to the booming IT-sector (Keller, 2006). Umicore Precious Metals Refining, located in Belgium, has recently started a pilot project together with local partners in Bangalore called Crystal with the aim of sustainable recycling in India. Instead of backyard recyclers processing and refining the e-waste in Bangalore, Umicore gives local recyclers the opportunity to cooperate with them, and let Umicore, a professional end refiner, perform the recycling of the e-waste under safe and controlled conditions in their recycling plant in Antwerp, Belgium. It requires trust from the local recyclers to do so, as they receive their money only after their container with e-waste has reached Antwerp and the lot is analysed by Umicore.

In light of this project, and the current e-waste situation in India, it becomes interesting to look at factors that would influence the now largely informal backyard recyclers to cooperate with a formal foreign company. Because a formal international company like Umicore cannot make contracts with the informal sector, a transition from the informal to the formal sector is required by the local backyard recyclers.

1.4 Why model this sector?

The case of informal e-waste recycling in Bangalore is an interesting subject because

- it has a technical component considering the recycling of mainly computer waste and its precious metal content, its efficiency and the consequent loss of these valuable products,
- it has a complex social structure where mainly direct family is involved in the recycling of electronic waste and where some recycling units also make use of patronage and child labour to work,
- it is economically relevant for marginalized groups in the local area who earn their livelihood in this sector and from the perspective of the precious metals that are lost in the process,
- the processes of leeching and the use of toxic chemicals causes harm to the workers and their direct environment, making it ecologically relevant,
- the sector has been largely informal and local laws are practically non existent, and
- there are many formal and informal institutions within the system.

Modelling a complex system of this size requires an adequate understanding of the behaviour and beliefs in the real world system before designing the model. It cannot straightforwardly be deduced, however, at or from what point the understanding is adequate, or 'sufficient'. Therefore, it is strived to understand and implement as much as possible given the time constraint of this research. The study will have to focus on the important social elements, besides the financial and political aspects. To identify the most important characteristics will be essential for the realism of the model. More on the methodology can be found in section 1.7, the background of the case study is extensively discussed in chapter 2. In the following section we introduce the MAIA framework, by which the model will be conceptualized.

1.5 IAD and MAIA

Currently, the process of agent based modelling is usually executed in three steps: (1) the identification of a question and the observation on the required parameters and conditions, (2) translation of the focal system into computer program considering a set of assumptions, and (3) the validation and verification of the implemented model (Ghorbani et al., 2011). However, a step that focusses on the conceptualization and the design of the model before implementation is missing. Ghorbani et al. (2010) propose the use of institutional frameworks in the process of conceptualizing complex socio-technical systems as agent-based models. Figure 1.1 shows the flow of this process.

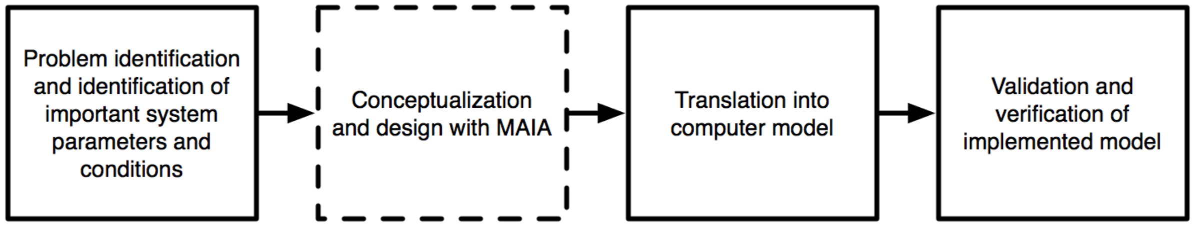


Figure 1.1: Modelling process: the usual steps taken in ABM, complemented with the conceptualization and design phase proposed by Ghorbani et al. (2011).

Based on the institutional analysis and development framework (IAD) by Ostrom, Ghorbani et al. (2011) developed a a methodology called MAIA (Modeling Agent-based systems based on Institutional Analysis). "MAIA allows the balance of global institutional requirements with the autonomy of individual agents, thus enabling system evolution and reflecting more of reality in artificial societies" (Ghorbani et al., 2011). Institutions are defined as "the set of rules actually used by a set of individuals to organize repetitive activities that produce outcomes affecting those individuals and potentially affecting others" (E. Ostrom et al, cited in Ghorbani et al. (2010)). The MAIA framework and its components are further detailed in chapter 3.

1.6 Research question

The object of this research is to gain new insights in possible transitions from the current largely informal e-waste sector in Bangalore toward a cleaner and healthier situation where a professional end refiner disposes of the e-waste safely. By modelling the e-waste sector with ABM we can see how the modelled system behaves under different initial settings, allowing us to analyse factors that promote or hinder such a transition. Given ABM as the method of choice for modelling in this research, and MAIA as a tool for conceptualizing the system and a method for incorporating institutions in ABM, the research question that is of interest is:

Research question: "How can we understand the factors influencing the transition of the informal recycling sector in Bangalore into a system cooperating with a professional end refiner, by using ABM and MAIA?"

Being a new method, the incorporation of an institutional context for agents in a formalized structure and assessing the outcomes from that perspective is a goal in itself. We can split the research question into sub-questions, dealing with parts of the problem:

Sub-question 1: What are possible influencing factors for a transition in the informal recycling sector in Bangalore?

Sub-question 2: When, according to the model, does cooperation between informal local recyclers with a professional end refiner occur, and which of the modelled factors contribute to that?

The methodology in the next section explains what steps are taken to answer the research questions.

1.7 Methodology

First, regarding sub-question 1, what is needed is data and information on how the informal e-waste sector functions. This collection of data will be done through literature study and expert interviews. More on this can be found in section 1.8. By gathering and analysing this knowledge, actors, institutions and the recycling network become clearer. This information will serve as the input for designing the agents, their behaviour, their connections, their way of decision-making and the institutions that the agents follow.

After that, the information will be structured for implementation into an ABM with the MAIA framework. The structured output of this MAIA framework will consist of tables and diagrams listing the resources, roles, agents, institutions and events (action situations) in the system.

This structured output will then be used to build the model in Java. The model will be tested and debugged. Once having obtained a model that reflects the system, experiments will be done testing the outcome of the model with different parameter settings. Every run will be repeated multiple times, to also gain an understanding in the variability of the outcome. This data will be analysed in R, a program for statistical computation. Finally, the results will be discussed.

1.8 Data collection

There is very little research done into the social institutions and networks that cause backyard recyclers to informally recycle e-waste as is happening now. Also, as far as known to us, no agent-based model has previously been made on this topic. Nevertheless, from the literature available, data relevant to the model has been extracted. Saahas (2005) describes the situation of the informal sector, drawing from an extensive research done by Saahas in close contact with informal recyclers. Studies that focus on the e-waste recycling in India (Rochat et al., 2007, 2008; Streicher-Porte et al., 2005; Sinha-Khetriwal et al., 2005; Keller, 2006) were conducted by or in cooperation with EMPA, an interdisciplinary research and services institution for material sciences and technology development in Switzerland[1]. This gives an insight into the informal recycling sector in India.

Also information provided by Christina Meskers and Steven Art from Umicore Precious Metals Refining and personal communication with e-waste management expert David Rochat and sociologist Marijk Huysman give insights into the social, political and technological aspects of the system.

1.9 Reading guide

The next chapter (2) describes the e-waste situation in Bangalore from the context of the bigger, global e-waste problem. Through this, we gain an insight in not only the complexity and embeddedness of the problem, but also how the case study and the model relate to the broader e-waste problem. Chapter 3 discusses the MAIA methodology and framework. In chapter 4 MAIA is applied to the informal recycling sector. The system that will be modelled, its boundaries, properties, design and functioning are all detailed in the same chapter. Many of the tables that accompany the MAIA framework can be found in Appendix A. The design of the

[1] http://www.empa.ch/

experiments and results are the subject of chapter 5. We find here an analysis of the output data of the model runs. A discussion on the results of modelling proces and the experiments, and what this means for current projects and future work, is given in Chapter 6. Also the relevance for scientific research in a more general perspective will be discussed here. The discussion is followed by the conclusion in the same chapter.

Chapter 2

E-waste: system and problem analysis

In the previous chapter an introduction was given into the subject and method of the research. This chapter continues with an overview of the system and the problem and discusses the present recycling system in Bangalore that will be modelled.

An introduction is given in section 2.1 on e-waste issues globally and more specifically related to those in the developing world, and a more detailed outline on the recycling of e-waste in India and Bangalore is given in section 2.2. Section 2.3 deals with legislations on e-waste and also discusses the Crystal project, a pilot project by Umicore. Sections 2.4 and 2.5 reflect on the actors in the system and the social characteristics that we find in the system. After this, we move toward framing the model. Section 2.6 outlines the system boundaries. The relevance for addressing this case and a description of the model is given in section 2.7. Finally, a conclusion on this chapter is given in section 2.8.

2.1 Introduction

Electronic waste, or e-waste, is a growing global problem. E-waste comprises of the end-of-life electronic products, like personal computers, flat screens, laptops, PDA's, mobile phones, mp3-players, game consoles, televisions and many other electric and electronic products. "The production of electrical and electronic equipment (EEE) is one of the fastest growing global manufacturing activities." (Babu et al., 2007) As the production of electric and electronic products increases worldwide, so does the waste electric and electronic equipment (WEEE) (Cui and Forssberg, 2003). Due to the hazardous material content, the disposal or recycling of e-waste without any control leads to "predictable negative impacts on the environment and human health." (Widmer et al., 2005)

Although electric and electronic products are produced all over the world, the e-waste mainly ends up in developing countries. About 50-80% of the e-waste from industrialized countries ends up in developing countries like China, India, Pakistan, Vietnam, the Philippines and even increasingly in Africa too (Ha et al., 2009). In developing countries the recycling is done mainly by backyard recyclers, in an often unskilled and harmful way. This is of great concern due to the direct and/or indirect exposure of people and the environment to chemicals and their toxic effects (Ha et al., 2009). Disregarding or unaware of the harmful effects, backyard recyclers continue because of the economical motivation: e-waste contains valuable metals like gold, silver, copper and palladium (Rochat et al., 2007).

2.2 Production and handling of e-waste in India

The per capita waste production in countries like China and India is relatively small, and estimated to be less than 1 kg per capita per year. This contrasts with for instance the 9 kg per capita per year in a country like Switzerland (Sinha-Khetriwal et al., 2005). With fast growing markets, the number of PC users in China increased by 1052% and in India 604% from 1993 till 2000 (Streicher-Porte et al., 2005).

Exact information on the amount of e-waste in India is unavailable (Sinha, 2004), and this is true for many developing countries. National consumption of electronics and import of waste in 2008 estimated to be respectively 330.000 tonnes and 50.000 tonnes (Rochat et al., 2008). The most significant flow of e-waste due to the enormous amount and production rate is computer waste. Additionally, the recycling of computer waste is a complicated process, and involves hazardous materials (Toxics Link, 2004). Regarding computers, it is estimated that annually 1.38 million computers become obsolete in India. However, what precisely happens to these obsolete computers is unknown (Sinha, 2004). Most of the e-waste is likely to end up in the informal recycling sector (Rochat, 2011).

In 2005, the state of Karnataka counted 36 computer hardware manufacturers and 1.322 software companies registered as Export Oriented Units (EOUs). Together, these companies employ 100.000 people. Additionally, some 60.000 people are working in the Business Processes Outsourcing (BPO) segment. These three sectors generate the largest contribution to the total e-waste in the region: an estimated 6.790 tonnes per year, equivalent to around 150-200 computers per company per year. (Saahas, 2005)

Bangalore is often called the silicon valley of India with respect to the large IT sector. This sector contributes a significant amount to the e-waste prduction. Considering IT scrap[1] in Bangalore: this accounts for 45-50% of the total e-waste, and 75% of it is generated from within the city. Compare this with Delhi, where IT scrap accounts for 25% of the total e-waste and 60% is generated from domestic sources (Saahas, 2005).

While it was estimated by Saahas that in 2005 about 6500 tonnes of e-waste was produced in the city (Saahas, 2005), it is estimated that in 2009 this has increased to 8000 tonnes per year. (Saahas, cited in Hasan et al. (2010))

2.3 Improving e-waste recycling?

A challenge at hand is to find safer ways to recycle e-waste in developing countries, without compromising the livelihood of backyard recyclers. This section mentions some of the regulations that exist to control the e-waste problem from a global perspective. However, we will find that in India no dedicated regulations or legislation on e-waste management exists. A second point that this section touches upon is the cooperation of a (foreign) professional end refiner with the local recycling sector. This concept has been employed by Umicore Precious Metals Refining in a pilot project called Crystal.

[1] "IT scrap would include all hardware and accessories including networking equipment, monitors, Central Processing Units, (CPU), Printed Circuit Boards (PCB), wires, printers, keyboards and mouse." (Saahas, 2005)

2.3.1 Legislation

Basel Ban

In 1989 the Basel Convention was created to control the transboundary movement of hazardous waste and their disposal. This lead to the Basel Ban in 1994, which became legally binding in 1995. This ban included a coalition of developing countries, some Eastern and Western countries, and Greenpeace. Since then 68 countries have ratified this convention. In 1998 the export of hazardous waste was effectively banned from the "29 wealthiest most industrialized countries of the Organization of Economic Cooperation and Development (OECD) to all non-OECD countries." (Basel Action Network, 2008) However, though successfully ratified by many countries, The Basel Ban still stumbles upon resistance from some major western countries like the United States, Canada and Australia. (Basel Action Network, 2008)

Legislation in the European Union

The European Commission (EC) has issued various directive that deal with e-waste. In the WEE Directive (2002/96/EC) the EC acknowledges the need to address the e-waste issues, and defines e-waste into categories. It furthermore, amoung other points, touches upon product design, seperate collection, treatment of WEEE and recovery of WEEE by member states of the EU (European Parliament, 2003). The EC also issued a directive that deals with the contents of e-waste: "Member states shall ensure that, from 1 July 2006, new electrical and electronic equipment put on the market does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE)" (from EC, cited in Streicher-Porte et al. (2005)).

Legislation in India

At this moment there are no proper laws and regulations in place for the recycling industry and the e-waste handling in India. It seems that (1) the government doesn't acknowledge the problem, (2) the State Pollution Board doesn't want to do inspections and (3) they would rather have foreign companies and businesses to build factories in India to deal with the problem (Rochat, 2011).

From the perspective of the informal recycling industry it is not easy working with the government. It is administratively complicated to become formal. The recycling 'factory' needs to be outside of the populated area, which requires an investment or a starting capital from the unit boss (Rochat, 2011). On the other hand, there is the fear of having to deal with corrupt government officials.

2.3.2 Crystal project

Umicore Precious Metals Refining (UPMR) is a one of the largest recyclers of precious metals from electronic scrap in the world. This department of Umicore, located in Belgium, together with partners in India - E-waste Agency (EWA), E-Parisaraa Pvt Ltd, Bangalore, and Karnataka State Pollution Control Board (KSPCB) - has launched a project named Crystal, aiming at sustainable e-waste recycling in India. "The aim", as mentioned on their site, "is to demonstrate to the informal sector - which is dominating e-waste recycling - that proper collection and dismantling in cooperation with the right partners for efficient recycling (Umicore) is beneficial for all parties. Moving away from unhealthy and inefficient "backyard" refining can maximize the return for the Indian recycler as well as set up a truly sustainable e-waste recycling business" (Umicore, 2010).

In the Crystal project, local recycling units, through the local partners mentioned before, have the option to cooperate with Umicore. The option they are given is to send their e-scrap by container to Antwerp, Belgium, where the lot will be analysed for its quality. We define e-scrap here as the e-waste consisting of the concentrated valuable parts of electronics only, for instance plated connectors and circuit board. The local recycling unit has to pay for the container and the transport himself. Because the container takes time to travel from Bangalore to Antwerp, and because the lot is analysed first, the payment for the e-scrap takes place only after 4 to 5 months. The value is based on the analysis of the container contents on arrival. The value of the metal content is calculated and the handling fee for refining the e-scrap is calculated as well. From these, the nett value of the lot is determined.

For local recyclers, this means taking a leap of faith: during the 5 months the recycling unit still needs to run and pay its employees. At the same time, they can be sure of a price that reflects the material value. Because UPMR has capabilities to extract more gold (and other metals) out of the boards, it can return a higher value to the agent supplying the boards. This is a win-win situation.

It is not possible to precisely predict what the outcomes of a project like Crystal will be. One very important difficulty for the local recyclers that they cannot stay informal if they want to join the Crystal project. Umicore and the local partners require formal backyard recyclers to deal with. Since the largest part of the sector is informal, the challenge for the system becomes finding the right motivators for becoming formal.

2.4 Actors in the system

To understand how the system functions, we first need an overview of the actors in the system. In figure 2.1 a schematic of actors that are somehow involved in the flow of computers and e-waste in Bangalore is given. Mentioned here are the actors that physically deal with computers or components of computers. The government and NGOs are also relevant actors, not mentioned in the diagram.

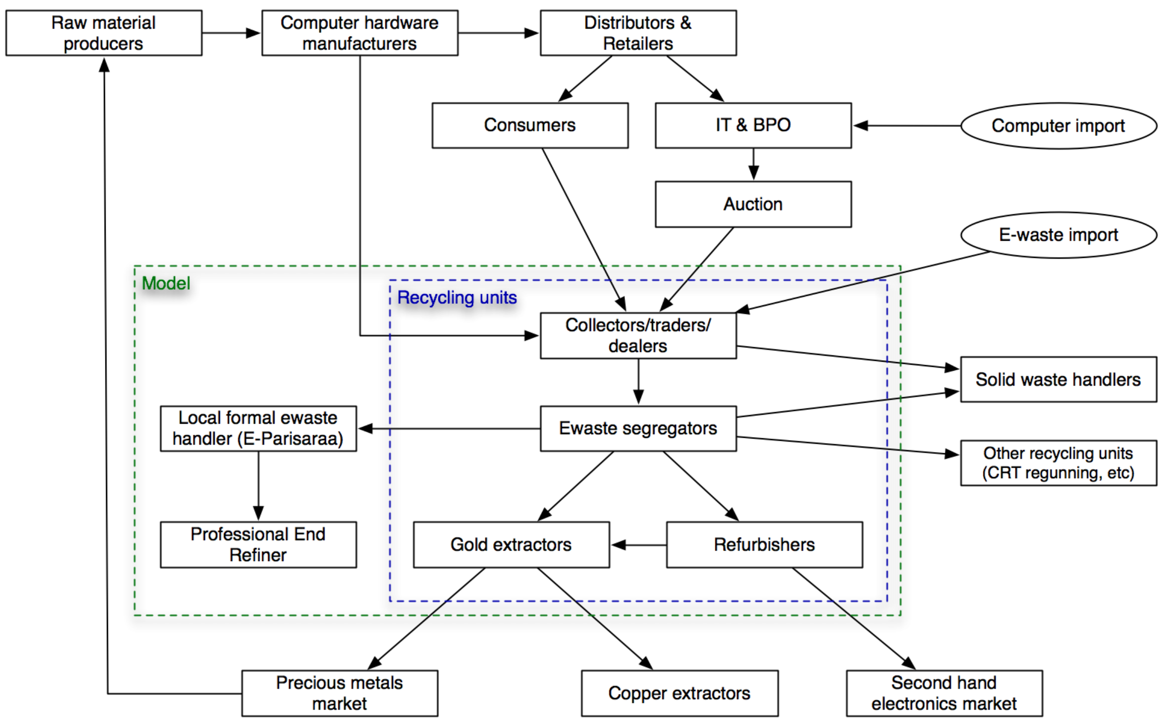


Figure 2.1: The actors physically involved in the Bangalorean computer e-waste sector. The arrows indicate a flow of electronic products or waste. A number of dealers, segregators, refurbishers and extractors, in any kind of combination, can form a recycling unit, shown by the blue box. In the green box the actors that will be modelled in this research can be seen.

In the case study, we'll focus on a subset of these actors. This is done for various reasons.

- It is theoretically possible, but technically impractical to model around 20 actors, with properties, choices and actions. A computer model of this size would be difficult to make and slow to run.
- The whole system is big and not all data on all actors is available to us. Analysing and investigating the behaviour of every aspect in the model will take more time and effort.
- In this case study, we choose not look at the full chain of electronics production and use. Therefore we simplify the model and choose e-waste to be readily available as input, thereby not incorporating computer manufacturers, distributors, IT/BPO companies, retailers and consumers.
- We take segregators, refurbishers, and extractors as core entities in the model, assuming that these cover the most basic recycling functions in the chain. The segregator seperates the e-waste, the refurbisher fixes useful parts and is economically relevant, and the extractor performs the actual extraction of precious metals.
- What happens after segregating, refurbishing and extracting with other types of waste is

not part of the case study. Also other use of the products in the model (CRT-regunning[2], aluminium/copper/plastic recycling, etc.) is not considered. Hence, we leave out the downstream actors that are involved in these activities.

- We combine in some cases several actors as one, to simplify the relations in the model. For instance, we define a unit boss as the head of a recycling unit, having employees working for him. Besides that, he also functions as a dealer/trader in the model.

- All the local markets have been combined into one market that sells computers and buys all products. This in the model is called the world market, being the only market in the 'world' of the model.

For these reasons, we focus in the case study on: segregators, refurbishers, extractors, the government, the professional end refiner, and the so called world market. We also define a unit boss, the boss of a recycling unit. In the next section we attempt to capture some of the social characteristics of the system.

2.5 Social characteristics

We identified a couple of social characteristics. In this section we explain the recycling units and their composition, the boss of a recycling unit and his role and patronage and corruption.

2.5.1 Recycling Units and family

The workers in the local recycling business are generally marginal groups within the bigger community. For Bangalore, this translates into mainly muslim families and people working in the recycling and extraction business (Huysman, 2010; Rochat, 2011). Generally, 10 to 25 people work in a recycling unit. The units consist of mainly family members (about 95% of the workforce) with some additional workforce (2-3 people) from outside the family (Saahas, 2005).

2.5.2 The boss and workers of a recycling unit

Recycling units are part of a somewhat bigger community of people in the local recycling business. Within a community, there are units that do segregation and dismantling and units that do extraction. Refurbishing is often not a part of the same community: this is a very different specialization and a completely different market. There is communication and contact within a community. There can be different communities (with their own units) in the area, competing with each other.

The boss of a recycling unit is generally a skilled and entrepreneurial person. He is the person with the expertise to extract precious metals from circuit boards, and it is generally him who does that work himself. He employs dismantlers to do the dismantling work for him, or buys processed parts from within the community. The employees working for him are not very skilled or educated, and are doing the labor intensive work, earning very little in comparison. The boss explains to them how to do the segregation, but keeps the skill of extraction to himself. The boss earns most of the money being at the head of the recycling unit. (Rochat, 2011)

[2] CRT-regunning is a method to refurbish old tube monitors

2.5.3 Patronage and corruption

Patronage and corruption are likely to play a big role in the system (Huysman, 2010). Within the recycling units there often exists a patronage system: the employees of a boss may be indebted to him in one way or another. The result is a complex situation where employees don't have the freedom to leave a unit, and a boss has power over his workers, keeping them poor.

One reason for recyclers to stay informal is the corruption present in the system. When becoming formal, there is the danger for inspections by the government and possibly corrupt officials. There is a high level of corruption in the law enforcement (Schluep et al., 2009).

2.6 System boundaries for modelling

Before starting any modelling exercise, the system and its boundaries need to be defined. The reason for modelling the informal e-waste recycling sector in this research is to test and show how the MAIA framework can be applied to model a complex socio-technical system. Regarding the case itself, the modelling exercise of this e-waste sector has two objectives:

1. We want to see whether we can simulate the growth of a recycling network similar to the real world, and

2. We want to see what parameters and situations may have the ability to steer this simulated recycling network toward a more environmentally friendly system where agents cooperate with a professional end refiner, without their livelihood being compromised.

Thus, the case study allows us to test the modelling process as well as the possibilities for ABM to answer questions through the results.

For this model, we consider the following:

- We only take into account the situation of Bangalore in the state of Karnataka.

- Instead of looking at the full e-waste flow, we only look at the recycling of computer-waste, as this is one of the biggest e-waste flows in Bangalore and the bigger Karnataka-area, due to the large amount of IT and BPO companies. We also look at computer waste in terms of the precious metal content it has.

- We simplify the model resources in terms of product composition. Our goal is to emulate the network dynamics, the resources are considered instrumental to this in the model.

- The wholesale, retail and manufacturing industry will not be taken into account. Though these are important factors and contain relevant actors for the e-waste industry, we assume that the network grows in a similar way with simplified input streams.

- Individual dealers are not considered. We simplify the flows of resources in the model, having the bosses of recycling units deal themselves.

- The copper extractors, CRT regunning industry, the copper, plastics and solid waste markets are not considered specifically. We define a market that buys all end-products in the model, as if it was the sum of all these markets and industries.

- Import of e-waste is neglected, as it is not especially dominant in Bangalore. The same goes for the export of e-waste.
- Family relations are considered. We take into account that recycling units largely consist of members of the same family, and that recyclers generally deal products with their own family (in different units).
- We consider segregators, refurbishers, extractors, recycling unit bosses, the government, the professional end refiner and the market as actors in the system.
- For institutions we choose to look at corruption, safe extraction, child employment and registration (becoming formal or staying informal).

2.7 Description of model

This section gives a description of the model. It first analyses the system, to understand the scope of the model in 2.7.1. We can furthermore find a narrative of the model in 2.7.2, and additional choices and assumptions are mentioned in 2.7.3.

2.7.1 Analysis: problem description

What is the problem?

E-waste, specifically gold containing connectors from PWBs of old computers, is being recycled under unhealthy and harmful conditions by unskilled workers in the Bangalore area. From an economic and materials perspective, one can also note that another problem is the poor efficiency with which this happens (up to only 25% of gold is extracted) and therefore many precious materials - but also other metals like lead, copper and tin - are lost.

What is the emergent pattern?

An informal recycling sector emerged, constituting of e-waste collectors, dealers, and e-waste handlers with different tasks like the segregation, refurbishing and recycling or extraction of precious metals. The sector shows specialization of work, many small recycling units or clusters of 10-25 workers, working decentralised under poor working conditions. In the sector there is also patronage and child labour. The sector evolved from an already existing solid waste handling sector, in the context of an IT-intensive city and state (Bangalore, in the state Karnataka, houses near 1400 IT companies and Business Process Outsourcing companies). The sector is driven by the +6000 tonnes of computer waste that flows into the system every year. The informal character of the system allows illegal trade and import of e-waste. The informality of the sector causes difficulty in analysing the system by researchers. Workers believe they are immune to the chemicals they use since they don't see the health effects directly.

Why is this a problem?

The health condition of workers deteriorates through the use of toxic chemicals, the working conditions are bad and the processes have poor efficiencies: many precious metals are lost. About the ownership of the problem: The problem is a problem to the informal recyclers mostly, and other workers due to the poor working conditions. It is also a problem to the larger community. However, many of recyclers do not consider it a problem themselves. Responsibility and initiative is taken by NGOs and companies in the formal sector, like Umicore Precious Metals Refining, to alleviate the workers and find better non-harmful solutions for recycling.

Model use

We as modellers will try to capture the system in a model, focussing on social and economical aspects. If we are successful in creating a model that reflects the real system, we could continue to research how different kinds of policies and solutions influence the model and cause it to become more 'healthy'. We will interpret the results, and present 'answerspaces' if possible, suggesting what possibly happens given the circumstances and initial assumptions and settings in the model. The results will be for the purpose of gaining insights in the modelling of social systems in general, but also to understand the factors that surround a project like the Crystal project.

2.7.2 Basic model flow: Narrative

A simple narrative of how the model will be set up is given here. **Actors** are made bold, *physical components* are made italic. *Properties* are italic as well, and institutions are underlined (institutions will be explained in section 3.3.1). This should help to give an overview of how the model functions.

- **Workers** walk around in the system. Each of them is a **UnitBoss**. They are all initially self-employed. They can hire other **workers** in the model, as long as it is someone of the same *family*. This agent then becomes an **employee** for the **UnitBoss**. **UnitBosses** can buy and sell products, hire and fire workers or register and unregister at the **Government**, making them formal or informal. All employees that belong to one UnitBoss are together one Recycling Unit.

- There are *old computers* available. These are part of the **WorldMarket**. **UnitBosses** can buy these *old computers*, but only do so if they have **Segregators** as employees. **Segregators** have the *specialization* to process *old computers* into segregated products that the **UnitBoss** can re-sell. They change *old computers* into *refurbishable parts*, *connectorsPWBs* and *waste*. The boss of the RecyclingUnit can sell these products.

- **Refurbishers** and **Extractors** have the *specialization* to respectively process *refurbishable parts* into *refurbished products* and extract *gold* from *connectorsPWBs*. A *UnitBoss* will buy *refurbishable parts* and/or *connectorsPWBs* if they have **refurbishers** and/or **extractors** as employees.

- **Refurbishers** process the *refurbishable parts* into *refurbished products*, and **Extractors** extract *gold* with an efficiency of around 25% from the *connectorsPWBs*. Extraction can be done through SafeExtraction, but this costs more money. The **Boss** can sell these products to the **WorldMarket**.

- The **Government** has a *RegistrationOffice*, where companies can register. When a **UnitBoss** comes to the **Government**, he can register and become formal. Being formal allows him to make a connection with the formal and foreign **ProfessionalEndRefiner**. However, the **UnitBoss** needs to pay an investment cost at the moment he becomes formal and starts paying tax every tick.

- The **Government** checks if formal companies adhere to laws and regulations. If not, they are fined. The government has a *ListOfFines* that states how high the fine is for a penalty. The size of the company and the type of felony matters. The **Government** has a number of inspectors (not an agent, only a number to indicate the capacity of the Government to inspect). They can be *corrupt* and ask more money than they should.

- The **ProfessionalEndRefiner** can offers to buy *e-scrap* for a very reasonable price. The **ProfessionalEndRefiner** can only make an agreement with other formal companies. If a registered local RecyclingUnit exists, and the **UnitBoss** is willing to deal with the **ProfessionalEndRefiner**, and he believes the deal is profitable, he will sell *e-scrap* to the **ProfessionalEndRefiner**. However, the **UnitBoss** must wait for his payment for a couple of months, which may influence his decision, and the cost of the container may need to be paid by the **Boss** himself.

2.7.3 Modelling choices and assumptions

For every model choices and assumptions need to be made. There are practical limitations to the size of the model. The limitations can be of any kind: real data availability, number of agents, model complexity, output-data size, time constraints, and other related factors. The biggest challenge, however, is to adequately translate the real world functions of the system into relevant and programmable objects, rules, parameters and indicators. Below a list of choices and assumptions is given to define and outline the model.

- The model will focus on the way computers flow through the system. Computers are taken as flow, since this seems to be by far the biggest e-waste flow in Bangalore. According to Saahas (2005), there are 1322 software companies in Bangalore and Karnataka and 36 manufacturing units, together producing around 6790 tonnes of obsolete equipment per year.

- Considered is only the recycling system in Bangalore. The model focusses on social and economical mechanisms that are specific to Bangalore.

- It seems that in Bangalore, the recycling of computers focusses on the gold-plated connectors on printed wiring boards (PWBs). Plastic recovery, copper recovery is also done, though not in the same recycling units. The re-gunning of CRTs takes place in the city in the city as well, however only to a limited extent. In other cities, this is more prevalent (for instance, in Delhi there are many specialized units for re-gunning CRTs). (Saahas, 2005) Therefore, the segregation, refurbishing (generally) and the recycling of gold-plated connectors are taken as focal point. The plastic and copper recycling are considered, but not part of the main activities in the model.

- Locational properties are left out of the model. We assume that agents can contact each other without having to overcome distance. Distance for single workers is mainly important for female workers that have a strong connection and responsibility to their home. (Huysman, 1994) About 5% of the workers are female. (Saahas, 2005) Furthermore, we assume that in most cases, the distance-aspect is marginal to the price of products.

- The physical and chemical composition of products will be simplified. Attention is given to the social network between agents, the business connections that agents make and the institutional characteristics of the system.

- Health and environmental effects are not part of the model. It is not known what the exact harmful effects are. As is already mentioned, in the model attention is given to social and economical characteristics rather than environmental issues.

- Though time will be taken into account wherever possible, the results cannot be said to be accurate where time is concerned.

- The model focuses on the agents that are working in recycling units. Basically, we strive to know if recycling units can become formal or cooperative companies with safe and healthy recycling. Therefore, agents considered are: all workers in recycling units, the government, and the ProfessionalEndRefiner.

- One major choice we made is that we will look at the emergence of a recycling network consisting of segregators, refurbishers and extractors, and the consequent possibilities for the Crystal Project in such a network. The network build-up is based on family-relations, the availability of products and financial choices (costs of products, fines, taxes, salaries, etc). The feed for the model is old computers. The physical composition of old computers is simplified to refurbishable parts, connectors and printed wiring boards containing the gold, and the rest to be 'waste' for the system, with a market value: it still contains metals like copper, steel, iron, silver, and plastic. The possibility of the Crystal Project to succeed is confined by the pay out time, the price of e-scrap and the existence of trustful and formal unit bosses.

- A unit boss cannot hire the employee of someone else, nor can he hire a unit boss that has employees. He can only hire a "unitBoss" that has no employees. Not being able to hire the employee of someone else makes sense from a patronage point of view: usually workers in this business don't have the freedom to leave their current boss, either because of poverty or because of debts with the boss. Also: the products that a self-employed unit boss has, become transferred to the new unit when he gets hired.

- The order during hiring is: first check availability of connectors in family, if yes: look for 'hireable' extractors from within family, is the salary affordable? if yes: hire. If no, AND I am willing to do child labor, search for children, if salary affordable: hire. The same process is repeated for refurbishers, and segregators. The reason we chose to do this, is because gold has the highest price/kg, and we assume that UnitBosses will want to go for the most profitable options first. This order, we believe, may result in the appropriate network pattern.

- Informal companies are outside the reach of the government, and are thus not fined. We thus assume in the model, that the government does not have/impose legislation for informal companies.[3]

2.8 Conclusion

In this chapter we have seen that e-waste is a global problem. Only in the Bangalore area thousands of tonnes of e-waste are produced every year. The issues in developing countries

[3] In reality, the government does impose regulations on formal companies that discourages doing business with informal companies, thus indirectly deals with the informal sector (Meskers, 2011).

are pressing due to the informal and unsafe methods of recycling. In Bangalore we can see that computer waste is one of the biggest flows. There is no dedicated e-waste legislation and regulation in India. The Crystal project, a pilot project by Umicore Precious Metals Refining, proposes a cooperation of local formal recyclers with Umicore. Umicore buys the e-scrap of local formal recyclers after it arrived per container and the lot has been analysed. This project and method can create a win-win situation. At the same time, a UnitBoss has to make the decision to become formal. Being formal costs him money (investment, taxes) as well.

We defined 7 main actors to model: the UnitBoss, Segregator, Refurbisher, Extractor, Government, Professional End Refiner and WorldMarket. There are social characteristics in the system that will be considered in the modelling process. These are: the formation of recycling units, the close family ties, the unit boss hiring workers from the family, patronage and corruption.

For the modelling process many choices and assumptions have been made. This is necessary, since it is not possible in the given time to model everything.

Chapter 3

MAIA

Where the previous chapter dealt with the subject of this research and framed the model with the system boundaries and choices, this chapter discusses the details of the MAIA framework and the method for conceptualizing the model. Before we actually conceptualize the model, this chapter gives an overview of the different aspects in MAIA that are needed for modelling.

Section 3.1 Gives an introduction into MAIA. The meta-model concept of MAIA can be found in section 3.2, while in sections 3.3 and 3.4 the conceptual level and detailed design of the MAIA framework are discussed. Section 3.5 gives the conclusion of this chapter.

3.1 Introduction

Computer modelling any system requires a translation of real-life indicators and parameters into digital code. Depending on the size of the system, the modelling of social systems can become very complicated. We therefore need a systematic and systemic approach for modelling.

The MAIA framework being developed by Amineh Ghorbani is based on the IAD framework of Nobel Laureate Elinor Ostrom. MAIA serves as a bridge between identifying the important parameters of the system and translating this to into a computer model by adding a conceptualization and design step (see figure 1.1 in section 1.5). The framework is a way of structuring the socio-technical system that we wish to model. In my view, it stretches the possibilities for agent based modelling, by:

1. Providing an institutional view on the system by defining roles, groups and institutions, apart from only defining agents,
2. Allowing complicated role-institution functioning, reflecting the complex motivations of real life agents,
3. Allowing events and actions to occur optionally, successively or simultaneous, and have agents respond in unique ways according to their properties, roles and institutions, and
4. Through a deliberate object oriented analysis of the system, enable a fluent implementation into parameters and logical operators for programming.

MAIA has a conceptual level and a detailed design. The conceptual level defines basic parts and properties of the model. The detailed design reflects upon more complicated functions within the model and design details regarding implementation. The next section 3.1.1 is meant to provide an overview of the MAIA framework and how it works, the sections 3.2, 3.3 and 3.4 discuss the meta-model, conceptual level and the detailed design of MAIA respectively.[1]

3.1.1 How should the MAIA approach be understood?

Though the full MAIA framework is much bigger and will be discussed extensively from section 3.2 onwards, we give here a simple representation of how agents are built up in the model to guide the reader in what follows.

At the basis of the model there are agents. They can be seen as 'core' subjects. They are not allowed to do anything, but to take up a role in the model. For instance, an agent can take up the role of a refurbisher at one moment, and the next moment become a Boss because he decided to expand his business and hire workers. His role in society changes. Both are different roles, and give different added properties to the agent. As an agent, he only has some defining properties, but cannot do anything in the model without taking up a role. As a role, he can do things, talk to people etc. It is like putting on a coat before going out: you need a role in society before stepping into the big world. Institutions are rules programmed within the model. They can be formal (laws) or informal (culture, norms). Only roles or groups can have institutions. 'Having' an institution does not mean following it, it rather means that the role or group in question has the choice of following it or not - or in a more abstract vision: it can have an 'awareness' regarding it. See figure 3.1 for a representation of agents, their role and institutions.

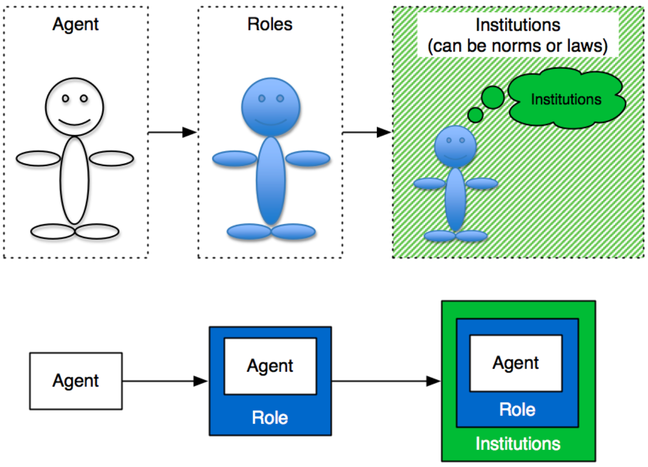


Figure 3.1: Pictorial schematic of agents, roles and institutions

In this way, through MAIA, we can define actors to be more complicated and realistic in their decision making behavior.

[1]The information on MAIA in these sections is taken from Ghorbani et al. (2011) and from personal communication with Amineh Ghorbani.

3.2 MAIA meta-model concepts

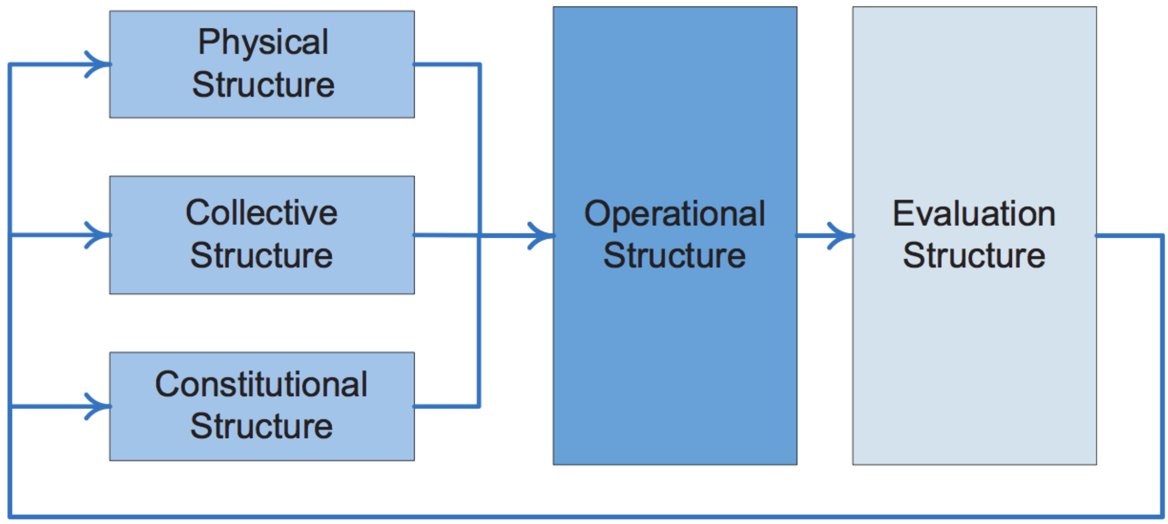


Figure 3.2: The MAIA framework, following IAD, has a contextual (physical, collective & constitutional), operational and evaluation structure.

In this section we explain the ontological concepts that are needed to decompose a socio-technical system. The MAIA framework consists of a contextual structure (physical, collective, constitutional), an operational structure and an evaluation structure. A diagram of these structures can be seen in figure 3.2. This serves as the meta-model of the MAIA framework.

The constitutional structure holds the information on roles, institutions, groups and dependencies between roles and groups.

The physical structure defines the material flows in the model. Any resource with their properties are mentioned here. This is done in the component table. There is also a physical connection table, and a composition diagram belonging to the physical structure.

The collective structure discusses the agents and their properties and the social network.

The operational structure defines the action situations and the role enactment agreement.

The evaluation structure contains output-matrices and criteria to which the model should function and the results should comply. If these are not met, the iterative process requires a reconsideration and/or redesign of the above structures.

In the next section, each of these structures is discussed in detail.

3.3 MAIA framework: Conceptual Level

3.3.1 Constitutional structure

Roles

A role is a representation of activities that is available to an agent. These activities can enable an agent to reach a social objective he may have, and take place according to rules. Different roles can be defined to enable agents to choose between them. It is therefore possible that an agent can take up multiple roles throughout the model. MAIA defines the following properties for a role:

- Objective: the general goal of a role. A boss of a company will have the general objective of making profit.
- Sub-objectives: intermediate states and actions that support securing the objective. For a boss this means: hire workers and buy raw materials.
- Institutions: the set of ADICO rules that is this role follows. These are defined in the institutions part in the next section.
- Entry condition: defines the rules by which an agent can take up this role. For instance, only an adult can become the boss of a company.
- Institutional capabilities: what an agent is allowed to do when he takes up this role. It defines its possibilities.
- Physical components ownership: the physical components that an agent can access if he has this role.
- Information ownership: the kind of information the agent knows when assuming this role.

Institutions

Institutions and norms are rules that agents that take a role have to adhere to. They can be formal or informal, thereby incorporating Wiliamson's model. These institutions and norms are defined according to the ADICO concept defined by Ostrom (Ghorbani et al., 2011). ADICO stands for 'Attributes', 'Deontic type', 'aIm' (action), 'Condition', and 'Or else'.

- Attributes: these are the roles that follow a particular institution.
- Deontic type: an institution can be a prohibition, an obligation or a permission.
- aIm (action): the aim or goal of the institution, and the actions the role performs when following this institution.
- Condition: the conditions for following this institution.
- Or else: agents with a role can choose whether or not to follow institutions. In case they don't follow the institution, the effect for not following the institution is given here.
- Institutional type: can be formal or informal, referring to laws/regulations (formal) and unwritten rules, cultural or socially constructed (informal).

Groups

Groups are sets of agents with certain similar preferences, properties or attributes. These groups can have their own unique institutions. In this way, the behaviour of the group can be different than that of individuals, and a certain form of group dynamics can be modelled. Also, a group may have access to a different set of physical components than an individual agent.

- Members: the roles that belong to the group.
- Institutions: the institutions that the group follow.
- Physical component access: the physical components to which a group has access.

Dependencies

Dependencies are relations that show how roles can be dependent on each other for reaching their objectives. A dependency diagram is used to visualize this, where the depender is the role that is dependent on the dependee.

3.3.2 Physical structure

Physical components

The physical component table lists components that will be modelled. Roles and groups, but also agents, can have physical components, which can be anything like a raw material or a product.

- Properties: attributes of a physical component. For instance a product may have a value or a price, weight or dimensions.
- Type: the type can be open or fenced. A fenced component is only available to agents that have a right to obtain it. An open component can be a common pool resource for any agent.
- Behaviours: components can be modelled to have a 'behaviour'. This could be for instance a variable price (modelled through an algorithm).

Physical connection

When two different components belong together, or are linked together, this link can be defined as a physical connection.

Physical composition

A physical composition diagram shows the constituents of a specific physical component. These constituents are physical components in the model themselves. A computer, for example, contains the components of printed wiring boards or circuit boards, connectors, cables, metal enclosure, plastic, etc.

3.3.3 Collective structure

The collective structure defines the agents in the model, their objectives, properties and relations in the model.

Agents

An agent is an entity in the model, that can take up a role and thereby follow institutions. For example, a person can take the role of an employee or a boss, and will follow institutions belonging to those roles: a worker follows the institution of working, and a boss follows institutions that allow him to hire workers to work for him.

- Properties: various properties can be attributed to an agent, for example age, money or skills. Also characteristics and other traits that need to be modelled can be part of the properties.
- Personal values: the intentions of an agent can be defined here: to gain profit or status, to be safe and healthy, etc.
- Information: the information that is available to the agent.
- Physical components: the different physical components that are available to the agent (refers to the physical components in the physical structure).
- Type: there are two types of agents in the model: institutional agents and external agents. Institutional agents are allowed to take roles and participate actively in the model. External agents don't take any roles, and are intrinsic to the model rather than institutional. The environment can be seen as an external agent.
- Roles: the roles the agent is allowed to take (refers to the roles in the constitutional structure). If the agent is an external agent, there won't be any roles mentioned here.
- Intrinsic capabilities: capabilities that belong to the agent, irrespective of his role. He can pertain these capabilities even when taking a role.
- Decision making behaviour: the way an agent makes his decisions, what criteria he will follow if given a set of options.

Social network diagram

A social network diagram shows how agents are interacting. It can show how physical components flow through the system, and are passed on by agents.

3.3.4 Operational structure

The operational structure tells *how* things happen in the model.

Action situations

Action situations describe how the system functions through time. During an action situation related events occur, such as the selling of products, or the hiring of workers. During an action situation each agent can only take up one particular role.

- Roles: the roles that are involved in a particular action situation.
- Action: the (set of) events that happen during an action situation, and the actions that can be performed by the roles.
- Cost and benefits: during an action situation there can be costs and benefits for the roles involved. These costs and benefits are described here.
- Physical components: these are the components that are used in the action sitution.
- Institutions: the roles that take part in the action situation may be required to follow institutions while doing so.

Role enactment

In the role enactment table, an overview is given of which agents with specific roles do an action in a specific action situation. The Role enactment thus shows the relation between the agent, the role it takes, and the action situation in which it performs an action.

3.3.5 Evaluative structure

An important part of the modelling process is the evaluation of the model. However, this is often neglected and only discussed after the model has been built. The evaluation and indicators should be addressed at the start of building the model. Through the evaluative structure parameters that will be needed for the evaluation are indicated. By addressing the evaluation from the start, we can develop and test the model more comprehensively.

Scope matrix

The scope matrix is an overview of important parameters and the action situations in the model. It links the action situations to expected outcomes and is meant for the verification of the parameters. In the matrix direct and indirect relations between action situations and parameters are pointed out, showing which values are affected directly or indirectly in which of the action situations. This matrix can help to analyze and understand the model once it is developed and shows where in the model the parameters are influenced.

Reality closeness matrix

The reality closeness matrix works like the scope matrix, but is intended for debugging the program of the model and to check whether the outcomes reflect the real world values.

3.4 MAIA framework: Detailed Design

One level deeper, beyond the conceptual level is the detailed design of the model. While the conceptual level mentions the actors, their preferences and their options, detailed design further adds the decision making behavior and the action sequences.

The conceptualization phase results in 8 tables[2], 4 diagrams and 2 matrices: roles table, institutions table, groups table, physical components table, physical connection table, agents table, action situations table, role enactment table, dependency diagram, physical composition diagram, social network diagram, action situations diagram, scope matrix and reality closeness matrix. These are all filled in for the model in chapter 4.

Decision making behaviour

The decision making behaviour specifies how agents decide on their options in the model. MAIA allows complicated decision making behaviour. When an actor takes a role, he gains options according to this role. This (institutional) capability of making a decision is thus stored in the role. However, the agent is making the decision. A detailed description of this decision is given in the decision making behaviour, and the execution of the decision is modelled in the action situations. The decision making behaviour is a set of algorithms.

Action sequence

The action sequence diagrams show how agents talk to each other, what they say, and what the possible reactions are. It is the way agents in their roles act during the action situations. There is an action sequence diagram for each action situation.

3.5 Conclusion

In this chapter we went through the MAIA framework theoretically. The MAIA framework is a comprehensive method for analysing the system and conceptualizing the model. There are five structures, each dealing with a different aspect of the model: the constitutional structure, physical structure, collective structure, operational structure and the evaluation structure. The outcome of the system analysis is a set of tables, diagrams and matrices. These contain information that help implement the model.

The next chapter will apply the MAIA framework to the e-waste sector in Bangalore and conceptualize the model for programming. We will fill up every table, diagram and matrix with information on the e-waste sector, following the structures and content that we described in this chapter.

[2] Ghorbani et al. (2011) describe one more table in their article, the environmental setup table. This is not used in this research.

Chapter 4

Using MAIA to build an ABM of the recycling sector

In the previous chapter we described the MAIA framework theoretically and explained the different parts of the framework. In this chapter, we will apply this framework to the e-waste model and discuss the resulting conceptualization of the model as well as the implementation. This has been the main part of the research, where the literature findings were translated into - amongst other aspects - roles, institutions, physical components, agents and action situations. This chapter follows the same structure as chapter 3 where the MAIA framework is concerned. In section 4.1 an introduction is given on how we are going to fill up the tables. The tables are filled up in sections 4.2 and 4.3. These sections reflect the same content as sections 3.3 and 3.4, and discuss the conceptual level and the detailed design of the e-waste model respectively. After having designed the model with the MAIA framework, section 4.4 deals with the implementation of the model. The design of the data input and the data output of the model are described in sections 4.5 and 4.6. Section 4.7 gives the conclusion for this chapter.

4.1 Introduction

In chapter 2 we have discussed some of the details of the e-waste sector in Bangalore. We identified 7 actors in the system that we want to model. Also, we defined the formation of recycling units, the family ties, patronage and corruption as social characteristics, and the Crystal project as an option for local recycling units to cooperate with a Professional End Refiner.

In chapter 3 we described the MAIA framework in detail with all its structures. In this chapter we will use the information from chapter 2 to conceptualize the model with the structures, tables, diagrams and matrices that results from chapter 3.

4.2 E-waste recycling system in MAIA: Conceptual level

4.2.1 Constitutional Structure

Roles

From the 7 actors that we defined, we will extract and define five of them as roles for the model. These are the Unit Boss, Segregator, Reburbisher, Extractor and the Government. The

Professional End Refiner and World Market Agent are considered external agents because they won't follow any institutions in the model. Therefore they are not defined as roles. These five roles follow institutions and do activities during action situation.

- Unit Boss: The Unit Boss is the head of his recycling unit (see section 4.2.1 on Groups). Every adult worker in the model starts as a self-employed worker in the field and is therefore his own unit boss. He can buy and sell products to earn a profit. He can also hire other workers to work for him, and fire them if he doesn't need them. If he is hired himself, he loses the role of Unit Boss, and becomes a segregator, refurbisher or extractor. A Unit Boss can furthermore choose to become formal. This has to be done at the Government (see section 4.2.4 on Action Situations).

- Segregator: A segregator can segregate old computers. From computers it gets refurbishable parts, gold containing connectors/PWBs and waste (for information on the definitions of products, see section 4.2.2 on Physical Components).

- Refurbisher: A refurbisher changes refurbishable parts into refurbished parts.

- Extractor: An extractors extracts gold from the gold containing connectors/PWBs.

- Government: The government has a 'registration office' where Unit Bosses can come to register their recycling unit. Registered companies are formal; if they are not registered, they are informal. Formal companies can more easily contact other formal companies. In the model this means that they are allowed to cooperate with the Professional End Refiner Agent. Informal companies can not contact the Professional End Refiner. The Government can inspect formal recycling units, to see if they follow regulations. If a recycling unit does not follow regulations, the Unit Boss of that unit is fined.

These roles have objectives, sub-objectives, institutions, entry conditions, institutional capabilities, physical components ownerships and information ownerships, as mentioned in 3.3.1. These are all detailed in the role table. The role table can be found in Appendix A.1, table A.1.

Institutions

For institutions, we chose to define Government Registration, Corruption, Safe Extraction and Child Employment. Patronage is embedded in the model, because workers do not have the freedom to quit their job. Also FamilyRelations is embedded, agents will be defined to only deal with family members.

- GovernmentRegistration: All workers in the model start in the informal sector. Unit Bosses can choose register at the Government to become formal. When registering, a Unit Boss has to pay an investment cost. While being formal, he also has to pay a tax every tick. A Unit Boss may choose to unregister so that he becomes informal again.

- Corruption: The concept of corruption in the model is simplified. For this model it is chosen that the government can have corrupt officials. Corrupt officials ask more money than they should when they fine a Recycling Unit.

- SafeExtraction: A Unit Boss can choose whether he wants to do safe extraction. This would mean that he provides safe worker conditions for his extractors (not using toxics without protection, etc). However, this procedure costs more money. Both formal and informal Unit Bosses can do SafeExtraction. When a Unit Boss becomes formal, the government can fine him if he doesn't do safe extraction. The government cannot fine him is he is informal. We assume that the government doesn't look at the informal sector at all.

- ChildEmployment: A Unit Boss can choose whether he wants to employ children. Children's salary is in the model defined as half the salary of an adult. Both formal and informal Unit Bosses can choose to do ChildEmployment. The government can fine him if he does ChildEmployment. The government can't fine him if he is informal, just like with SafeExtraction.

The institutions have also more detailed information following the ADICO concept: Attributes, Deontic type, aIm, Condition and Or/else. The institutions and norms tables can be found in Appendix A.1, tables A.2 and A.3.

Groups

In the model there is one type of group defined: Recycling Units.

- Recycling Unit: A recycling unit consists of a Unit Boss and all workers that are his employees. Together they are one unit. In They don't follow specific institutions, but were defined to make the modelling easier: recycling unit members are workers of the same boss and bosses can hire and fire people from his own family. He can also buy and sell products only to his own family members. The products he buys are placed in the recycling unit, so that his workers can have easy access to it (also from a programming perspective).

Groups have members, and can further follow institutions and have physical component access. The group table details these. This table can be found in Appendix A.1, table A.4.

Dependencies

Figure 4.1 shows the dependency diagram for the model. In this diagram we can see the dependencies that are defined between agents in the system. These dependencies are as follows:

- The Unit Boss is dependent on the World Market Agent for the supply of old computers. He is also dependent on the World Market Agent for profit when he sells his products.
- The Unit Boss is dependent on his employees for profit. He can have Segregators, Refurbishers and Extractors as employees. His employees are in turn dependent on the Unit Boss for their job security.
- The Unit Boss is dependent on the Professional End Refiner Agent for profit, if he chooses to do Crystal and send e-scrap to the PER. The PER is for its profit and e-scrap dependent on the Unit Boss.
- The Refurbisher is dependent on the Segregator for refurbishable parts, and the Extractor is dependent on the Segregator for Connectors/PWBs.

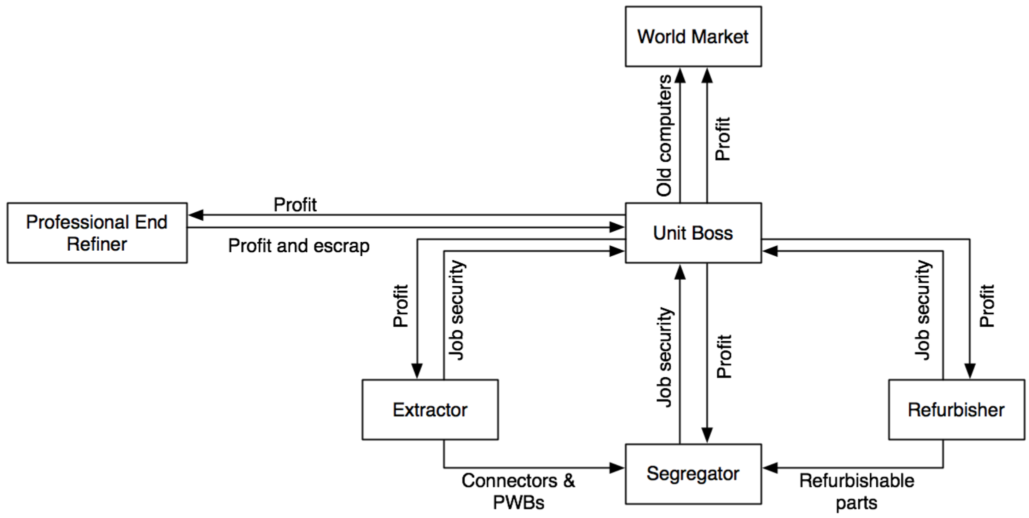


Figure 4.1: The dependency diagram shows the relation between roles and external agents. A depender has its arrow pointing to the dependee.

The Government is strictly not dependent on the system, and the agents in the system are not defined to be dependent on the Government. They could function without it. Therefore, the Government is not mentioned in this diagram.

4.2.2 Physical structure

Physical components

For the model, the products and their material composition is simplified since the aim of the case study is not to model the flow of electronics and their exact composition, but to model the growth and the decision making within a system. There are 7 types of physical components defined in the model. These are: old computers, refurbishable parts, refurbished parts, connectors/PWBs, gold, e-scrap and waste.

- Old computers: Old computers are the basic resource in the model. Old computers can be bought by Unit Bosses for a low price at the World Market Agent. A segregator can segregate old computers into refurbishable parts, connectors/PWBs and waste.

- Refurbishable parts: A refurbishable part can be refurbished by a reburbisher into a refurbished part and waste. Both refurbishable parts and refurbished parts can be bought and sold by a Unit Boss.

- Refurbished parts: A refurbished part has a relatively high value on the market. Unit Bosses can sell this to the World Market Agent.

- Connectors/PWBs: Connectors/PWBs stand for the gold containing parts of a computer. The gold can be extracted from the connectors/PWBs by an extractor, the rest is treated as waste. The gold and the waste can be sold to the World Market Agent by the Unit Boss.

- Gold: Gold is the precious metal in the connectors/PWBs from old computers that is of interest for the Unit Bosses in this model.

- E-scrap: E-scrap is for this model technically the same as connectors/PWBs: gold containing remnants of an old computer. It has the name e-scrap to differentiate with the goal: e-scrap will be sold the Professional End Refiner, and connectors/PWBs will be processed into gold and waste.

- Waste: In this model waste is an umbrella concept: everything apart from the physical components mentioned above is considered waste. For example, when an old computer is segregated, the aluminium enclosure, metal frame, plastic and copper wires and screws are all considered to be waste; it is not necessary for this model. The value of waste at the World Market Agent is calculated with respect to the fractions of these products in this waste stream, to reflect the valuable materials (aluminium, copper, plastic, steel, etc) still that are still present in the waste stream.

The physical components can have a property, type and behaviour, which is detailed in the physical pomponents table in Appendix A.2, table A.5.

Physical connection

The physical connection table is not used in the model. It could be left out because no links or connections were defined for the physical components.

Physical composition

The composition diagram in figure 4.2 shows that in the model old computers can be segregated into refurbishable parts, connectors & PWBs and waste, refurbishable parts can be processed into refurbished parts and waste, and connectors & PWBs can be refined for their gold and having waste as by product. E-scrap is mentioned with a dashed line, since it is an option for the extractor to make e-scrap instead of connectors & PWBs.

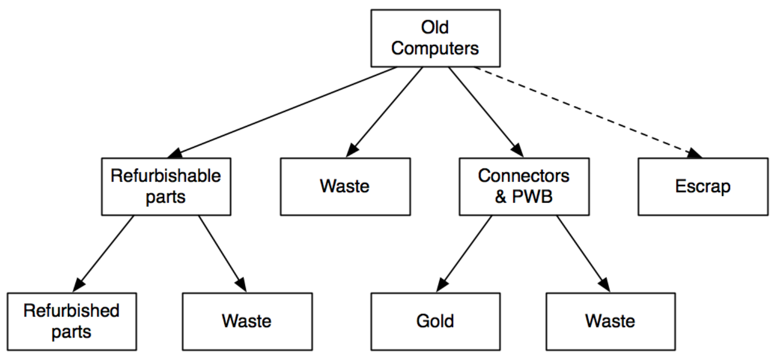


Figure 4.2: The composition diagram shows the composition of resources in the model.

4.2.3 Collective Structure

Agents

In the model four different types of agents are defined: Worker, GovernmentAgent, ProfessionalEndRefinerAgent and the WorldMarketAgent. Below we can find a general description. These agents have more details: properties, personal values, information, physical components, type, roles, intrinsic capabilities and decision making behaviour. These are listed in the agent table in Appendix A.3, table A.6.

Workers and the Government are institutional agents. The workers can take up different roles in the model. As employees they can be a Segregator, a Refurbisher or an Extractor by speciality. If they have employees or are self-employed workers, they have the role of a Unit Boss.

- Worker: In the model the workers are predominant in number, and can take up different roles depending on their type and employment status. A worker in the model can take up the role of a segregator, refurbisher or extractor.The workers belong to different families. They strive to earn an income, start dealing in e-waste products, and because they can hire other workers from their own family, a network of recycling units can appear. A recycling unit is any a combination of segregators, refurbishers and recyclers. A boss is at the head of the unit. All workers can be a UnitBoss, if he has workers work for him. The UnitBoss takes care of deals, and the workers do their job and get paid.

- GovernmentAgent: A unit boss can register at the government if it wants to become formal. It has to pay a one time investment cost and an amount for tax regularly. The government keeps track of the recycling units that became formal. It will randomly inspect a couple of recycling units. If there is child employment, or unsafe extraction being done, the government fines the recycling unit.

- ProfessionalEndRefiner: The Professional End Refiner is a big foreign company that has technical knowledge and capabilities extract more gold and other valuable metals from e-scrap. If an recycling unit is formal, it can cooperate with the PER to send their e-scrap by container to them instead of recycling it themselves. The Unit Boss will get a price for the e-scrap.

- WorldMarket: The world market is the provider of old computers as a resource in the model, and is the buyer of the end products gold, refurbished parts and waste. It is in fact a collection of various local markets. This is done to simplify the system and help keep an overview of the flows in the model. The term 'world' market, as mentioned before, refers to the world within the model and should not be confused with the world market in reality.

Social network diagram

Although the social network diagram in MAIA is normally a diagram, for this model a table is made that serves the same purpose. In table 4.1 we can see how physical components are passed on from one agent or role to another agent or role.

Table 4.1: Social Network

Sender	Content	Receiver
WorldMarket	OldComputers	UnitBoss with Segregators
UnitBoss	Refurbishable parts	UnitBoss with Refurbishers
UnitBoss	Connectors & PWBs	UnitBoss with Extractors
UnitBoss	E-scrap	ProfessionalEndRefiner
UnitBoss	Refurbished parts	WorldMarket
UnitBoss	Gold	WorldMarket
UnitBoss	Waste	WorldMarket

4.2.4 Operational Structure

Action situations

There are 10 action situations in the model defined. Action situations are moments in the model when things happen. These are given below.

- Fluctuating prices: In this action situation prices and values of products in the World Market can change by preset algorithms. Due to time constraints, this action situation is left out in the remainder of the modelling process. It is still mentioned here to give an overview of the possibilities in this model for future work.

- Hire workers: Unit Bosses decide whether they need employees. They can hire a segregator, refurbisher or extractor only from their own family.

- Register: During this action situation, a Unit Boss weighs the options to stay informal or become formal. By staying informal he can avoid making necessary large investments and paying tax. Becoming formal, however, could be financially relevant, but only if the profits from selling e-scrap to the Professional End Refiner outweigh the costs of investments, tax, possible fines and salary for his employees.

- Buy products: The time when a Unit Boss can buy products from the World Market and from other Unit Bosses. He can buy old computers, refurbishable parts and/or connectors/PWBs.

- Crystal project: The Unit Boss has to choose whether he will cooperate with the Professional End Refiner. This means that he will make e-scrap instead of connectors/PWBs during the action situation called 'Treat old computers', and will sell the e-scrap to the Professional End Refiner.

- Treat old computers: Segregators in a recycling unit take old computers and segregate these.

- Treat refurbishable parts: Refurbishable parts are processed by Refurbishers.

- Treat connectors/PWBs: Extractors extract gold out of connectors/PWBs.

- Sell products: A Unit Boss can sell refurbished parts, gold and waste to the World Market.

- SafetyInspection: The Government performs an Inspection on the formal recycling units. Any unit that performs unsafe extraction or employs children is fined.

The order in which the situations happen is shown in figure 4.3. The table with full details on the action situations (roles, actions, costs and benefits, physical components and institutions) can be found in Appendix A.4, table A.7.

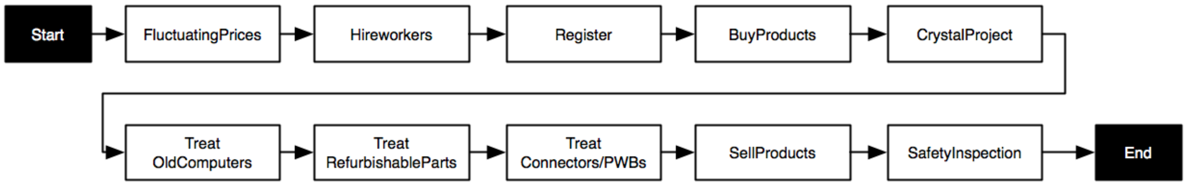


Figure 4.3: A MAIA action situation diagram. The action situations occur in the model in this sequence. At the end the sequence is repeated. This continues till the preset time of the model has been reached.

Role enactment

Table 4.2 gives the role enactment of the model. It shows in which action situation an agent can take up a specific role. For example, during HireWorkers, the worker agents that have employees take the role of a Unit Boss, so that they can hire or fire workers, and so on. This table serves as an overview and reference during programming the events in an action situation.

Table 4.2: Role enactment table

Agent	**Action situation**	**Role**
Worker	HireWorkers	Unit boss
Worker	Register	Unit boss
Worker	BuyProducts	Unit boss
Worker	CrystalProject	Unit boss
Worker	SellProducts	Unit boss
Worker	SafetyInspection	Unit boss
Worker	TreatProducts	Segregator
Worker	ProfitCalculation	Segregator
Worker	HireWorkers	Segregator
Worker	ProfitCalculation	Refurbisher
Worker	HireWorkers	Refurbisher
Worker	BuyProducts	Refurbisher
Worker	TreatProducts	Refurbisher
GovernmentAgent	Register	Government
GovernmentAgent	SafetyInspection	Government
Worker	TreatProducts	Extractor
Worker	ProfitCalculation	Extractor
Worker	CrystalProject	Extractor

4.2.5 Evaluative structure

Scope matrix

The scope matrix is a matrix that shows important parameters and the action situations in which they are influenced. The scope matrix can be found in table 4.3. This matrix can help to analyse the outcomes of the model.

Table 4.3: Scope Matrix

	Fluctuating Prices	HireWorkers	Register	BuyProducts from Market	BuyProducts from units	CrystalProject	Treat old computers	Treat refurbishable parts	Treat connectors and PWBs	SellProducts	SafetyInspection
no. Refurbishers in unit		d		i	i						
no. Segregators in unit		d		i							
no. extractors in unit		d		i	i						
money (unitBoss)	i		d	d	d		d	d	d	d	d
money (worker)							d	d	d		
no. recycling units		d									
no. registered			d								
gold/waste/refurbished in World market										d	
e-scrap for refiner						i				d	
e-scrap per unit						i	d				
no. crystal contract						d					
fines											d

In the table, for example, the number of refurbishers in a unit is directly (indicated with a 'd' in the matrix) influenced by the HireWorkers situation, and indirectly (indicated with an 'i' in the matrix) influenced by the BuyProducts situation. During BuyProducts, a UnitBoss may buy refurbishable parts, and in the next round during HireWorkers discover that he needs more refurbishers in his recycling unit and hires a refurbisher. In this way all parameters listed in the matrix have at least one direct relation and possible more direct or indirect relations.

Reality closeness matrix

The reality closeness matrix can be found in table 4.4. This is used during the debugging of the program.

Table 4.4: Reality Closeness Matrix

	Fluctuating Prices	HireWorkers	Register	BuyProducts from Market	BuyProducts from units	CrystalProject	Treat old computers	Treat refurbishable parts	Treat connectors and PWBs	SellProducts	SafetyInspection
Money	i		d	d	d		d	d	d	d	d
no. product per unit					d		d	d	d	d	
no. resources per unit				d	d		d	d	d	d	
World market values	d									d	
Average negotiated prices					d					d	
Composition of units		d									
no. crystal contract						d					
Unit members		d									
Weight of products per unit				d	d		d	d	d	d	

For example, if the values of the average negotiated prices in the model turn out to become negative, there must be something wrong in either the BuyProducts situation or the SellProducts situation. The money of agents is influenced in almost every action situation, and the unit members only in the HireWorkers situation. In this way, if some of the values show irregular or illogical behaviour, this matrix helps to track down in which action situation the error could be found.

4.3 E-waste recycling system in MAIA: Detailed design

Decision making behavior

The decision making behavior can be found in Appendix A.5, table A.8. This is a more detailed flow of the model and discusses what happens in what order.

Action sequence

Action sequence diagrams are in Appendix A.5, figures A.1 to A.9. The way agents interact is worked out in these sequence diagrams. We can see in the diagrams a sender and a receiver. Generally the sender wants something and sends a message to the receiver. The receiver replies. The action sequence diagrams show what they 'say' to each other, and reflect in a simple way how they think.

4.4 Implementation: Model building

In the previous sections we conceptualized the system according to the MAIA framework. We went through all the structures and constructed all tables, diagrams and matrices. They contain the agents, their roles, the institutions, the action situations and all kinds of other properties of the system. These tables, diagrams and matrices together form the blueprint by which the model is made. From this blueprint we built the model in Java, an object oriented programming language, using the software Eclipse. The java-code and .jar file of the resulting model can be found on SVN.[1]

Apart from the information stored in the MAIA tables, diagrams and matrices, some additional information is used in the process of programming. The next section reflects on the data that is.

4.4.1 Data

Apart from designing the model with the help of the MAIA framework, the model needs settings. Some of these can be found in the literature, but not every value is known. Data that could be found in literature is mentioned in table 4.5 and data that is estimated or simply chosen to our best knowledge and insight is listed in table 4.6.

Table 4.5: Data used for model, based on literature findings

Parameter	Values	Source / info
Total number of worker agents in system	2000	Art (2011)
Approximate number of segregators in system	1200	Art (2011)
Approximate number of refurbishers	500	Art (2011)
Approximate number of extractors	250	Art (2011)
Inflow of e-waste into system	6790 tonnes/year	Saahas (2005)
Shipment cost, container 10 tonnes (Chennai-Antwerp)	180.000 INR	Rochat et al. (2008)
	189.000 - 252.000 INR	Meskers (2011)
Average computerweight	25kg	Citation needed
PWB content in computers	812g/pc	Keller (2006)
Gold containing parts in 1 desktop pc	approx. 1kg	Meskers (2011)
Gold content in PWBs	0.25g/kg	Estimated from Keller (2006)
PayOutTime (= time of shipping, sampling and processing)	5 months	Rochat et al. (2008)
Approximate size of refurbishables stream from e-waste	60-65%	Meskers (2011)
Approximate value of a refurbished computer	10000 INR/pc	Streicher-Porte et al. (2005)
Value of refurbished computer (if pc = 25kg)	400 INR/kg	Estimated
Gold price	2000000 INR/kg	Rounded value from Goldprice.org
Waste value	30 INR /kg	Estimated from Saahas (2005)

Table 4.6: Estimated or unknown data

Parameter	Values	Source / info
Productivity of segregator	470 kg/month	Estimated
Productivity of refurbisher	680 kg/month	Estimated
Productivity of extractor	30 kg/month	Estimated
Connector and PWB production from computers	0.016 kg/kg	Calculated
Refurbishable parts production from computers	0.6 kg /kg	Calculated
Waste production from computers	0.384 kg/kg	Calculated
Refurbished parts production from refurbishables	0.6 kg/kg	Unknown / guess
Waste production from refurbishables	0.4 kg/kg	Unknown / guess
Gold production from connectors and PWBs	0.00025 kg/kg	Calculated
waste production from connectors and PWBs	0.99975 kg/kg	Calculated
E-scrap production from computers	0.016 kg/kg	Calculated

4.4.2 Verification

Before experiments can be done, the model needs to be verified. The main question is whether the model functions in the way this was intended. The reality closeness matrix from the MAIA framework was used during the debugging process of the model. The most significant problems and solutions:

[1] https://svn.eeni.tbm.tudelft.nl/AminehGhorbani/MAIAcaseStudies/Ewaste/EwasteIII/EwasteIII_fat.jar

Negotiations stop in certain cases This was a reason for us to believe that perhaps the negotiations were not modelled in an optimal way.

Registration doesn't always work This was solved by editing the function of the the government.

Increasing amount of old computers in World Market instead of depletion, the resource for old computers was growing. This was due to negative money of some workers, who thus bought 'negative products'.

Negative values various parameters (money, physical components) became negative while this should not happen. Going through the model and making sure that all payments and buying of products result in values of 0 and higher solved the problem.

Hire workers Initially, bosses could hire up to 3 workers at a time. This was not intended, but happened because he could hire a segregator, a refurbisher or an extractor, and in some cases hired all of them consecutively. This was solved by creating a system for hiring that ensured stopping the procedureafter he has hired.

Fire workers The firing of workers gave confusing results. It appeared that the workers didn't update the employee-number when firing.

Model stops After a while, in some cases, no one would sell products any more. Because it was found that this didn't happen with different parameter settings, this was interpreted as possibly runs with unrealistic or 'fatal' input variables. Adjusting the parameters made it less of a problem. We left it in, assuming this is part of the model.

A test experiment was performed. This was a relatively small experiment, with 100 runs and 5 repetitions each. Due to time constraints no other tests were performed. This test is analysed in the next chapter, where it is also used to extract results on the research.

4.5 Data input design

After having designed the model, built it, and added data to append the MAIA framework, we need to design the inputs and outputs of the model. We need to define over which parameters we will test, these will be the inputs. We also need to define which variables will be measured for the data analysis, these will be the outputs. There are many possible parameters in the model. In an ideal situation, we would test many of them to calibrate the model and gain an understanding of the whole model. However, due to the limitations of this research we chose to test 9 parameters, which is still a lot. The parameters are:

1. Number of Worker Agents (always a ratio of 12 Segregators : 5 Refurbishers : 3 Extractors)
2. Number of Families
3. Initial money that Workers have at the start of a run
4. Tax that formal Recycling Units have to pay
5. Investment cost needed at the time of becoming formal

6. Corruption on or off
7. E-scrap price
8. Container cost for shipping e-scrap
9. Time it takes before e-scrap producing units are paid by the Professional End Refiner

The reason that these parameters are chosen is because they reflect different areas in reality as well. First of all, the number of worker agents, the number of families and the initial money that workers have could influence the ability of a network to grow. The tax, investment cost and corruption may reflect the influence that the government has. The e-scrap price, the container cost and the pay-out time are part of the economic motivations and play a role in scenarios in the crystal project. Because it is unknown to us what could drive the system to change, we test over this many parameters. This is not an ideal situation. Testing many parameters results in long computing time and a big data output. Therefore, when using these parameters we have to be selective in range and number of data points.

It would have been desirable to test the model more extensively on the institutions and the choices for fixed variables. This will be a point for future work.

4.6 Data output design

Since we do not exactly know how the model functions, SQL tables are designed to store the output data. The output data gives detailed information regarding the agents, recycling units, the world market and the professional end refiner. The government, in this model mainly having a registrative function, is considered through the registration status of units. The following sections discuss the data that is printed out by the model.

4.6.1 Agent table

The agent table gives information on all the agents individually. Every measurement in the model happens at the end of a tick and is printed out in a single row in the data file. Below, the details are given on the agent table.

Table 4.7: Data output: agent table

runnumber	The current runnumber, to identify the data.
repetitionnumber	The current repetitionnumber, to identify the data.
tick	The current tick, to identify the data.
agentid	Every agent has a unique id by which he can be identified. This is printed here.
role	The role that the agent has. Only segregator, refurbisher or extractor is printed here.
boss	Whether the agent is a boss or not (true/false).
whoisboss	If the agent is not a boss, the id of his boss is printed here. If he is self-employed, his own id is shown here. If he is a child and unemployed, this number is -1, to denote that he has no boss.
production	The amount in kg of product that the agent has treated.
age	Whether the agent is an adult or a child (adult=1, child=0).
family	To what family the agent belongs (1-5).
money	How much money the agent has.

4.6.2 Data table

The data table lists data on the stocks of products in the World Market, the amount of e-scrap that is sold to the Professional End Refiner, and details on the negotiations in the model.

Table 4.8: Data output: data table

runnumber	The current runnumber, to identify the data.
repetitionnumber	The current repetitionnumber, to identify the data.
tick	The current tick, to identify the data.
worldmarketcomputers	The amount of old computers that are left in this tick in the World Market.
worldmarketrefurbished	The cumulative amount of refurbished parts at the World Market during the run.
worldmarketgold	The cumulative amount of gold at the World Market during the run.
worldmarketwaste	The cumulative amount of waste at the World Market during the run.
perescrap	The cumulative amount of e-scrap at the Professional End Refiner during the run.
totalnegotiationsrefurbished	This number counts the negotiations that are done to sell or buy refurbishable parts.
avgnegotiatedpricerefurbished	The average negotiated price for refurbishable parts in the model.
totalnegotiationsconnectorspwbs	This number counts the negotiations that are done to sell or buy connectors/PWBs.
avgnegotiatedpriceconnectorspwbs	The average negotiated price for connectors/PWBs in the model.
totalnegotiationsescrap	This number counts the negotiations that are done to sell or buy e-scrap among Unit Bosses in the model.
avgnegotiatedpriceescrap	The average negotiated price for e-scrap in the model.

4.6.3 Unit table

The unit table contains data on the recycling units in the model. Below are the parameters measured in the unit table.

Table 4.9: Data output: unit table

runnumber	The current runnumber, to identify the data.
repetitionnumber	The current repetitionnumber, to identify the data.
tick	The current tick, to identify the data.
boss	The id of the boss of the recycling unit.
size	How many workers there are in the recycling unit.
registered	Whether the recycling unit is formal or not (true/false).
crystal	Whether the recycling unit wants to cooperate with the Professional End Refiner or not (true/false).
safeextraction	Whether the recycling unit does safe extraction or not (true/false).
finedforchildemployment	Whether the recycling unit is fined for child employment this tick (true/false).
finedforunsafeextraction	Whether the recycling unit is fined for unsafe extraction this tick (true/false).

4.7 Conclusion

In this chapter we used the literature findings of chapter 2 and combined this with the theoretical explanation of the MAIA framework in chapter 3. Combining the information from these two chapters, we made a blueprint for the e-waste model. The tables, diagrams and matrices of the MAIA framework contain the necessary roles, institutions, agents, physical components action situations, and other aspects of the model. We made a computer model from this new information.

The model was appended with some additional literature data, and an input and output data design. The verification was partly done. Not all institutions are tested. The experiment that we conducted for verification was a small experiment and due to time constraints will also be the focus of the next chapter, in which we will analyse these results.

Chapter 5

Experiment and results

In the previous chapter we discussed the concept of the application of the MAIA framework on the e-waste sector. The model was built, and additional data was given on the in- and outputs of the model. In this chapter we discuss the experiment that is done with the model, and reflects on the outcomes of the model.

In section 5.1 we look back at what we have done so far and what we are experimenting. After that, section 5.2 gives the background of the experiment and the method for data analysis. The model outcomes for e-scrap sold to the professional end refiner is given in 5.3. In section 5.4 we look in more detail at the results of a large scale analysis of all the runs, using a distribution method t-SNE. Further comparisons of outcomes are given in section 5.5, The final section 5.6, gives the conclusion for this chapter.

5.1 Introduction

The research is focussed on the question: how can we understand the factors influencing the transition of the informal recycling sector in Bangalore into a system cooperating with a professional end refiner? We want to see how a relationship is formed between local recycling units and the Professional End Refiner. We now have an agent-based model which used the MAIA framework for conceptualization and institutional analysis. This was conceptualized with the literature information of chapter 2 combined with the MAIA framework of chapter 3. This was put in tables and diagrams in chapter 4, and afterwards implemented into computer code.

One reason why we used MAIA is because it is based on institutions, and we hope that this is a good way of implementing institutions. The incorporation of institutions allow more complicated functions to exist in the model. We know from chapter 4 that during implementation not all institutions were tested. Only a relatively small test was conducted for verification, and due to limitations this test is also used for the results in this chapter.

What we primarily want to see from the results is when cooperation with the Professional End Refiner occurs and what factors contribute to that. As an indicator for cooperation we take the amount of e-scrap that is sold to the Professional End Refiner.

We only used the input variables that are mentioned in 4.5. Since we only did one test experiment, we were not able to iterate the experiment with different values. In the test experiment we varied economical parameters mostly and some institutional parameters. We also get institutional data out of the model. This is analysed as well. Thus, although the economical parameters are tested more intensively, we hope we can say something about the institutional side of the model as well. The next section discusses the experiment setup and the methods for data handling.

5.2 Experiment setup and data handling

The model size requires us to make choices. The need for this quickly becomes clear by looking at the parameters options. Having 9 variable parameters and doing a full parameter sweep over these would result in an experiment with billions of runs: if we would for instance take 10 data points on each parameter, this would lead to 10^9 runs. If every run would take 15 seconds per processor, the model would run for 476 years on a computer with a single processor. This would take one full year on the high performance computer (HPC) at the TU Delft, which has 480 cores.

But that is not the only difficulty. Since we do no exactly know if and how the model functions, the data output is designed to give detailed data on agents and their money, bosses and their workers, the world market products and the products of the professional end refiner (also see section 4.6). This has the added drawback of creating a large amount of data. Even with ten thousand runs, which is a more realistic number for modelling, the data size coming from this model would be over 1TB of plain text data.[1]

Because we want to have an idea of the model, we will confine the test to 100 runs, each repeated 5 times. To choose a set of 100 data points over 9 parameters, we make use of what is called Latin Hypercube Sampling (LHS).

5.2.1 Latin Hypercube Sampling

Latin Hypercube Sampling is a statistical method that uses stratified sampling. In a multi-dimensional area, each component of the sample space is partitioned into N strata of equal marginal probability 1/N. These are all sampled once. The components are matched randomly. This way, we get a more even distributed input parameter set to test (McKay et al., 1979). Figure 5.1 gives a representation of an LHS for a simple set of 2 parameters to illustrate how it works.

[1] To consider how much 1TB of data is: if printed on A4-size paper, assuming 1kB takes up half a page and we print double sided, this would approximately be 250.000.000 pages. If a page is 80 micrometers thick, a stack of 250 million pages is 20km high.

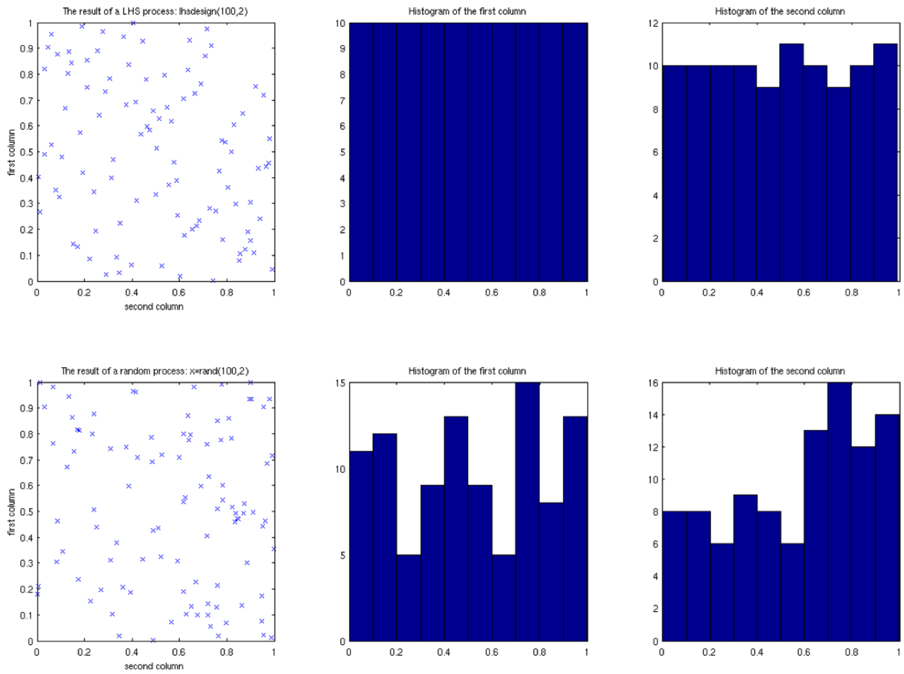


Figure 5.1: An example of how a Latin Hypercube Sample provides a more even distribution of values over different parameters. The above row shows a LHS. The below row shows a random distribution. We can see through the histograms that in the LHS the distribution is much more even than in the random distribution. Pictures are from Nikolic et al. (2009).

The LHS of the input variables is made in R. See the file located on the SVN repository[2]. This output file, a .txt file with the variables of 9 parameters over 100 runs, is used as input for the java model. This file can also be found on the SVN repository[3].

5.2.2 Data analysis

The model ran on the high performance computer (HPC) of the E&I section of the TPM faculty at the TU Delft. The 500 runs completed in approximately half an hour on the 480 core HPC, creating around 18.8 GB of data. The data is analysed with R. Indexing of the data was done to reduce the query time when accessing the data.

R makes use of packages to extend the basic functionalities of the software. One such added functionality is the use of Structured Query Language or SQL, through the packages *sqldf* and (for use of SQL with the online HPC server) the combination of packages *RJDBC* and *RpgSQL*. The use of SQL to extract data from dataframes in R and databases on an online server effectively simplifies data handling that would normally be more complicated when using R-syntax only.

Another package that is used, for processing the multi-dimensional dataset, is the *tsne* package. This is discussed in section 5.4. The use of these packages and more can be found within the R files on the SVN repository[4].

The next section discusses the outcomes of the test experiment.

[2]https://svn.eeni.tbm.tudelft.nl/SathyamSheoratan/MSc/R/MakingLhsFile.R
[3]https://svn.eeni.tbm.tudelft.nl/SathyamSheoratan/MSc/R/lhsParameters.txt
[4]https://svn.eeni.tbm.tudelft.nl/SathyamSheoratan/MSc/R/

5.3 Model outcomes of experiment

The model was tested with 9 variables: (1) Number of Worker Agents, (2) Number of Families, (3) Initial money that Workers have at the start of a run, (4) Tax that formal Recycling Units have to pay, (5) Investment cost needed at the time of becoming formal, (6) Corruption on or off, (7) E-scrap price, (8) Container cost for shipping e-scrap, and (9) Time it takes before e-scrap producing units are paid by the Professional End Refiner.

The 500 runs that were done with these variables were put on a timeline to check how the model behaves over long times and the amount of e-scrap sold to the Professional End Refiner is measured.

5.3.1 Timeline

In the model it is chosen to perform 1000 ticks of every run. This is, considering the settings of the model very long: a tick is meant to reflect one month on real life, so 1000 ticks would reflect roughly 80 years. However, it must be noted that time in the model does not have to reflect reality. There are a couple of reasons why time in the model does not have to correspond real time: (1) timesteps in ABM are discrete instead of continuous, (2) events in a model happen almost always instantaneous, (3) in this e-waste model products like old computers are chosen to be highly and readily available for buying, (4) location, distance and transport time are not considered in this model, and (5) though care has been taken in setting internal parameters, a small deviation of values may cause a model to run very different than in the real world timewise.

If we take the buying of old computers as an indicator for the activity in the model, we can say that all runs become stagnant or stop before the 1000 ticks are over. Figure 5.2 shows a graph where the last tick in which computers are bought is plotted for every run. The runs are ordered by their highest outcome per run. The red line shows the standard deviation between different repetitions for that run.

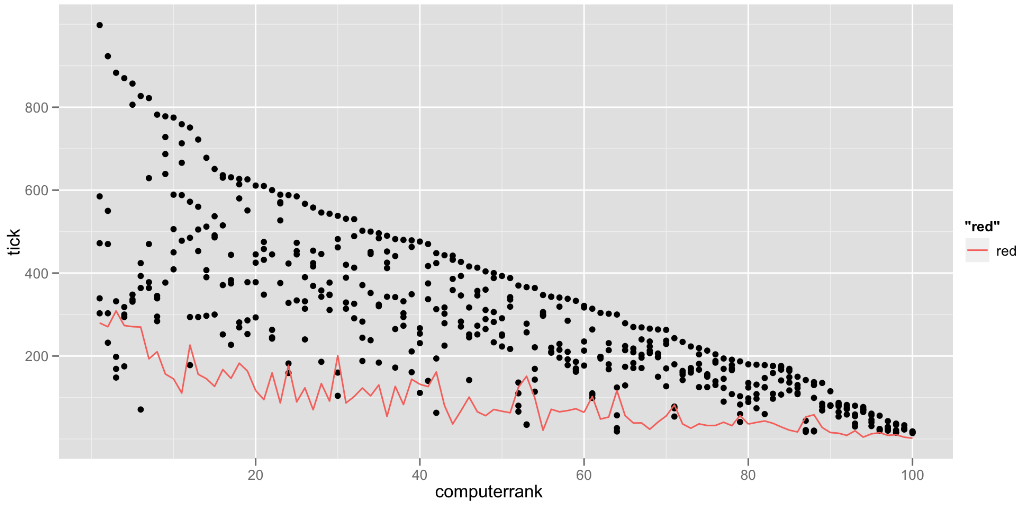


Figure 5.2: This graph shows only the final ticks of the model, taking the buying of old computers as indicator. The dots show how long the model ran become stopping. The red line is the standard deviation. The runs are ordered in this graph by highest tick per run. Notice that the axis are here different than the previous picture, to show the standard deviation.

To understand what each dot in this graph means, the computers bought in the longest run and the shortest run are shown in 5.3 and 5.4, to see how the profile looks like.

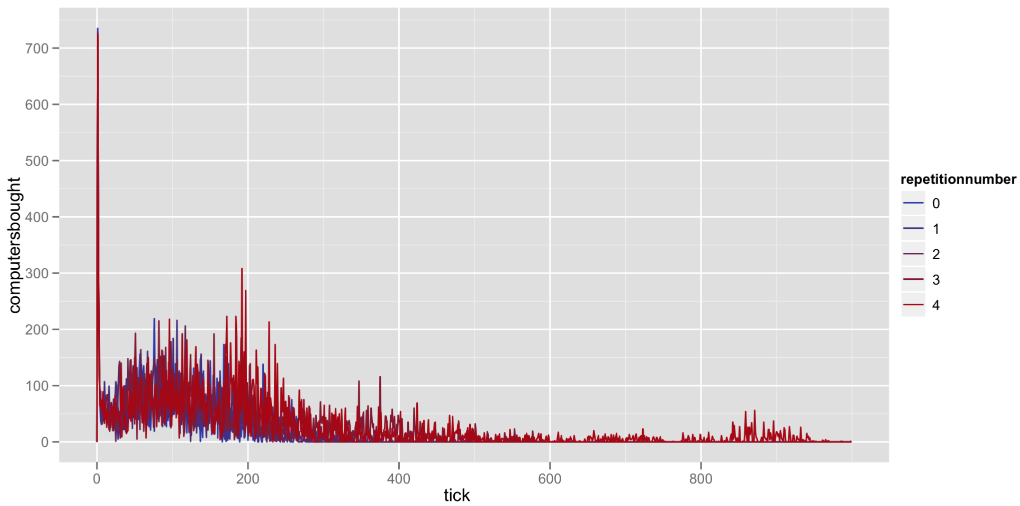


Figure 5.3: Computers being bought in run 51, one of the longest running runs. Here the y axis shows the sum of all the computers being bought per tick. Notice that only one repetition is long, the others end before 600 ticks.

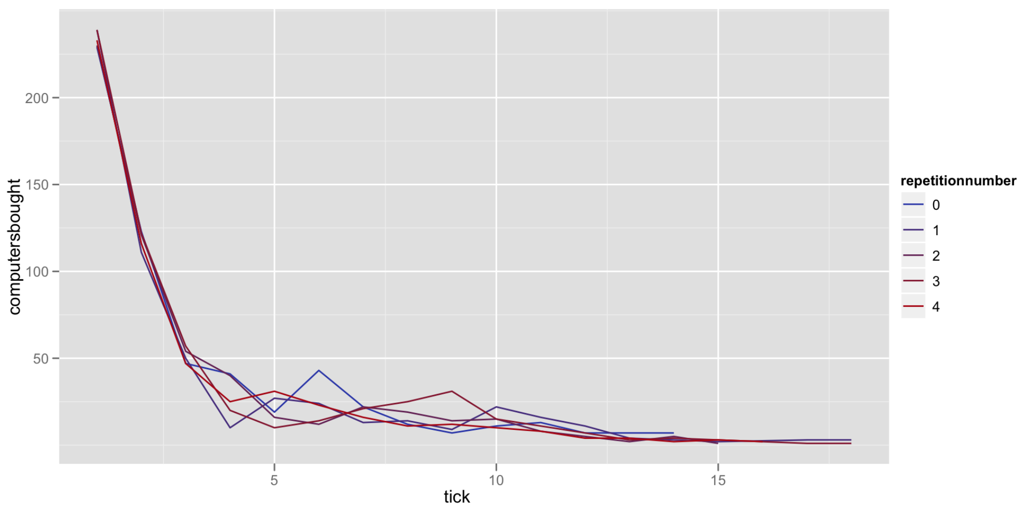


Figure 5.4: Computers being bought in run 22, one of the shortest runs. Notice that already after 18 ticks no more computers are bought.

We can see a big difference in the profiles of these runs. In the longest run (figure 5.3) there is a sharp peak at the start, and after that a big drop, which slowly declines further, with some peaks in the graph. This could indicate that Unit Bosses buy many computers in the first round, but lose too much money to pay their workers. The reason for the model to continue for so long can be found in the input parameters: there was a low e-scrap price, high tax and high investment cost. As a result practically no Unit Boss chose to do crystal. In 4 of the 5 repetitions, no one became formal. Staying in the informal sector meant having less costs, and the agents in the model survived for a long time.

In the shorter run (figure 5.4) we see a simpler profile, that collapses rather quickly. This run is characterized by very favourable conditions regarding e-scrap selling: the inputs were a high e-scrap price, a quick pay out time and a medium containercost. Also the investment cost was set to low. However, the taxes were set to be extremely high. As a result many workers chose to do crystal, but couldn't 'survive' the burden of high taxes.

5.3.2 Crystal in model

Figure 5.5 shows a graph where the fraction of units that choose to do crystal in the model is plotted per run. The runs are ordered by the crystal result in this graph, and therefore do not correspond to the runs in figure 5.2.

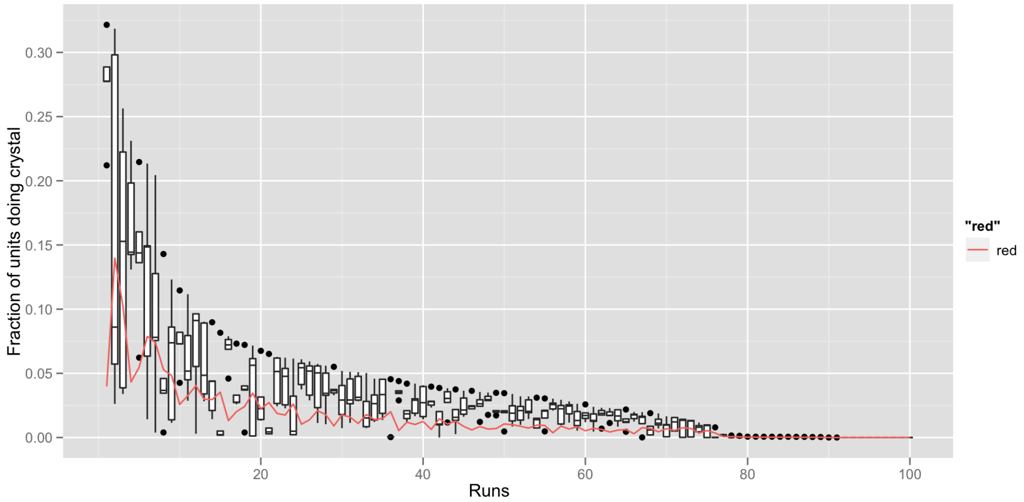


Figure 5.5: This graph shows the standard deviation over the different runs.

Figure 5.5 shows that in nearly 80% of the runs a number of Unit Bosses in the model made the decision to do crystal, and that in 20% of the runs no Boss chose to do crystal. However, this is not necessarily the actual effect of the model.

This can be explained thus: the conditions for doing crystal may be very favourable (high e-scrap price, low investment cost, low taxes, etc), and a Unit Boss may choose to become formal and do crystal. However, the Boss may not have enough money to pay enough workers to make e-scrap. With no e-scrap made, the result is that no e-scrap is sold to the professional end refiner.

Another point worth noting, is that the runs with units doing crystal have a higher standard deviation, indicating higher variation in different repetitions of the same run. In fact, we should also consider this result in light of the previously discussed point of the model stopping after a certain amount of ticks. Agents stop buying or selling products, and thus don't sell e-scrap, even if they would want to. Therefore, these results of units choosing to do crystal should be viewed in a broader perspective. The run with the highest percentage of crystal is runnumber 22, which we had seen earlier is also one of the runs to collapse the quickest. Hence, the results on crystal are not corresponding to the actual result. We find that the 'actual behaviour' in the model is different from the decision, or the intent to do crystal.

To get a more practical view on the findings, we will look at the actual amount of e-scrap that is sent to the Professional End Refiner in the next section 5.4, and compare this with various input parameters to understand what causes the results. We will also look at other output data, to see whether we can indicate some relations between the output. This is done by T-distributed Stochastic Neighbor Embedding (t-SNE).

5.4 Analysis of model outcomes with t-SNE

The main research question from 1.6 has as goal the understanding of factors attributing to the transition toward a situation where cooperation with a professional end refiner occurs. To understand where this happens, and to get an overview of what happens in each run of the model, we use a method called T-distributed Stochastic Neighbor Embedding (t-SNE). t-SNE is a way to visualize a high-dimensional dataset into a two-dimensional graph, or in short: a technique for dimensionality reduction. This method is supported in R through the *tsne* package, that was used to calculate the distributions of the graphs in this section. We use these graphs to identify locations in the model to compare the results.

5.4.1 t-SNE of the model

We applied this t-SNE method to the products that recycling units make in the model, specifically e-scrap that is sold to the professional end refiner. The values that are used in the distribution calculation are:

- Total number of computers bought by units,
- Total amount of refurbished parts sold to local market,
- Total amount of waste sold to local market,
- Total amount of gold sold to local market, and
- Total amount of e-scrap sold by formal units to the professional end refiner.

Because of the amount of data and the calculation time while preprocessing the data, only data in the first 100 ticks of every run is used. The values used for the t-SNE are the cumulative amounts at the end of 100 ticks. A hundred ticks would amount to approximately 8.3 years in real life, considering that a model-tick is meant to simulate one month. However, time in the model does not have to coincide with actual time in reality, as is discussed earlier in 5.3.1.

The result is a two-dimensional graph, where every point signifies a particular run of the model. Figure 5.6 shows the outcome: a graph where the numbers indicate the position of the run in the t-SNE graph. In a t-SNE graph the distance between data points show how similar these points are. Dots close to each other (clusters) have some similarity in their outcomes, and dots or clusters that are far from each other are different in their values. The graphs that are made with t-SNE are abstract: values of the x and y axis have no direct meaning. Reading the graph is a matter of pattern recognition.

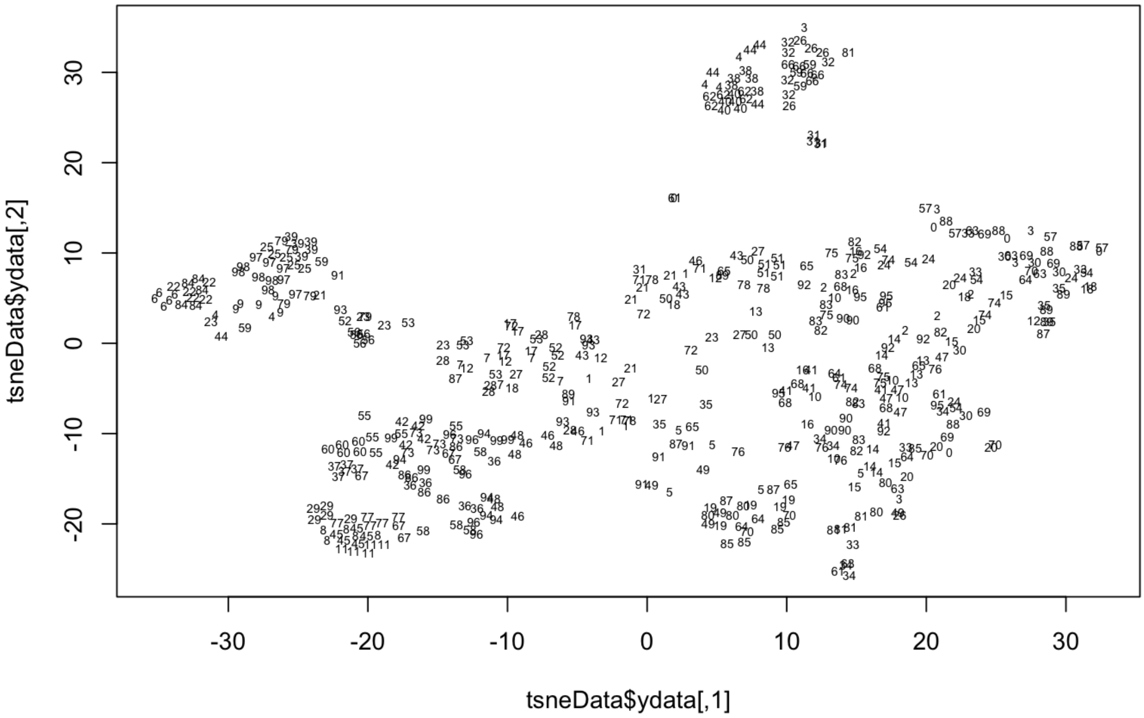


Figure 5.6: T-SNE graph of the runs. The numbers represent the runnumber, and the distance between them shows how similar or dissimilar they are considering the outcomes.

5.4.2 t-SNE of output parameters

By plotting data into the t-SNE by use of a new dimension like size or color - for instance input variables of the model - we can see how these values correlate with the multi-dimensional outcomes. First we will do this with the output variables with which this distribution is calculated. In the next three figures, the amount of computers bought from the world market (figure 5.7), the amount of gold sold to the local market (figure 5.8), and the e-scrap sold to the professional end refiner (figure 5.9) are indicated by the size of the dots in the t-SNE graph. These graphs will serve as the template for the patterns we are looking for: we look for dots that show a high amount of e-scrap sold to the professional end refiner, and preferably little gold sold to the local market (this would indicate that recycling units are extracting the gold themselves). Each dot represents a single run of the model.

The graphs on refurbished parts and waste can be found in Appendix B. These are similar to figure 5.7.[5]

[5]Workers in the model do not make choices regarding the sale of refurbished parts and waste, these are sold directly to the World Market. Because there are fixed ratio's for segregating computers, the amounts of refurbished parts and waste are consistent with the computers bought.

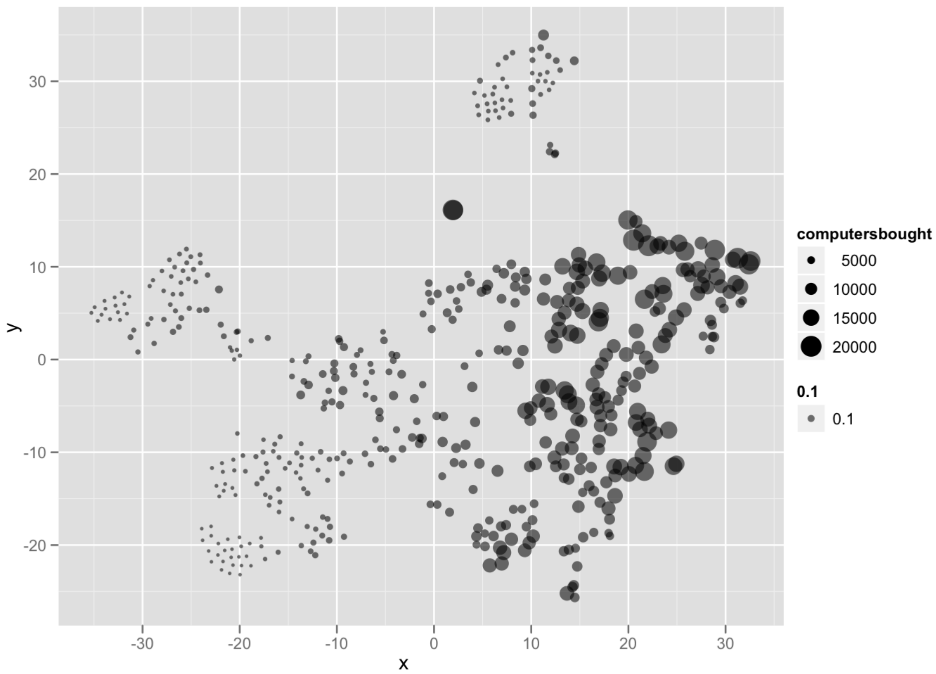


Figure 5.7: Computers bought from the World Market, plotted into t-SNE graph. The size of the dots show the amount of computers bought in kilograms.

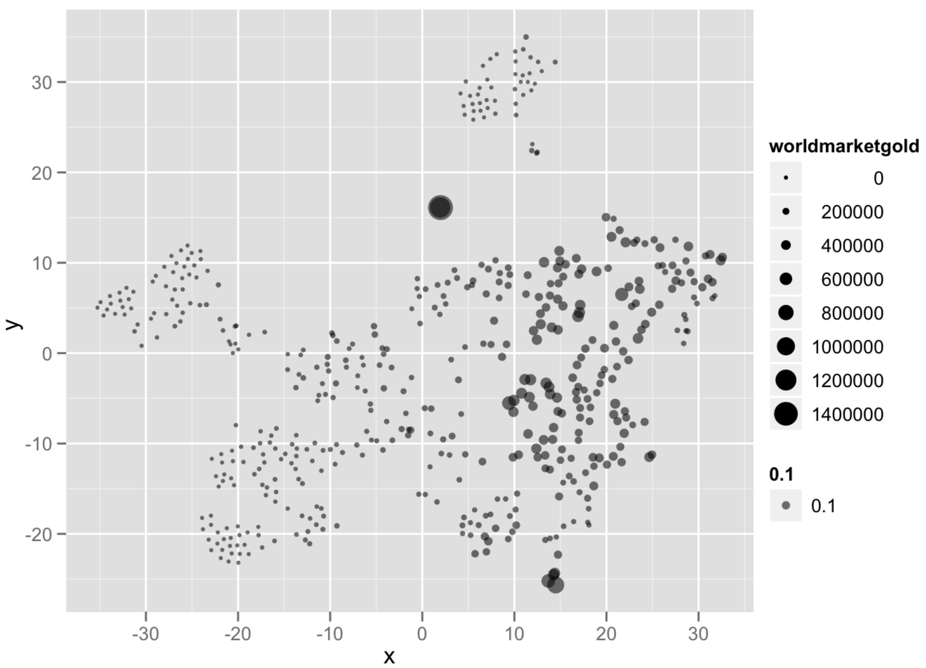


Figure 5.8: Gold sold to the World Market, plotted into t-SNE graph. The size of the dots show the amount of gold sold in grams.

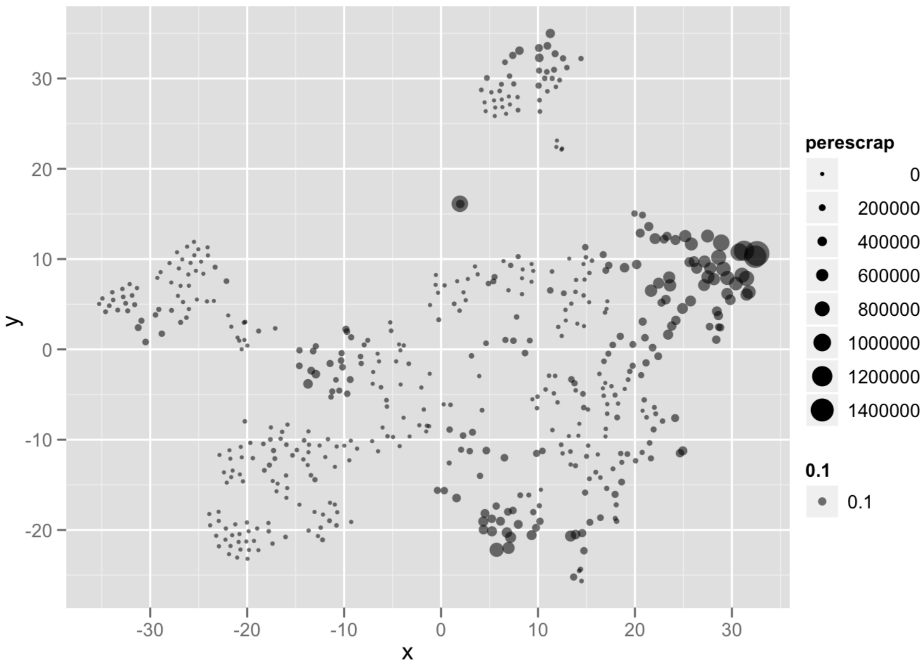


Figure 5.9: E-scrap sold to the Professional End Refiner, plotted into t-SNE graph. The size of the dots show the amount of e-scrap sold in kilograms.

Figure 5.7 shows significant areas on the left of the graph where very little computers are sold. In the runs plotted on the right more computers are sold. This is an important starting point: the runs on the left side will have had little activity in the model. Figure 5.8 shows that there the runs where gold is sold are to the right of the graph. There is an interesting dot of two runs at (x=2, y=16) that sells a lot of gold. Figure 5.9 shows that there are many runs that sell little to no e-scrap to the professional end refiner. There is however a significant cluster at x>25, on the right of the graph.

Taking these graphs into account, and also the graphs that will come hereafter, we identified 5 clusters or areas in the graphs that we will closely look at in the following graphs. These areas are shown in figure 5.10. Table 5.1 will sum up the findings. We chose for these areas for the following reasons.

- Area 1: This is an area with relatively high e-scrap selling to the Professional End Refiner.
- Area 2: This area has e-scrap selling, but not as much as area 1.
- Area 3: This area has much less e-scrap selling, but seems still interesting. Perhaps this is a borderline-case.
- Area 4: This is an area where the productivity has been very high. Though there are only 2 runs located here, it is interesting to find out what the cause might be.
- Area 5: This area has little to no e-scrap. We hope to find out why.

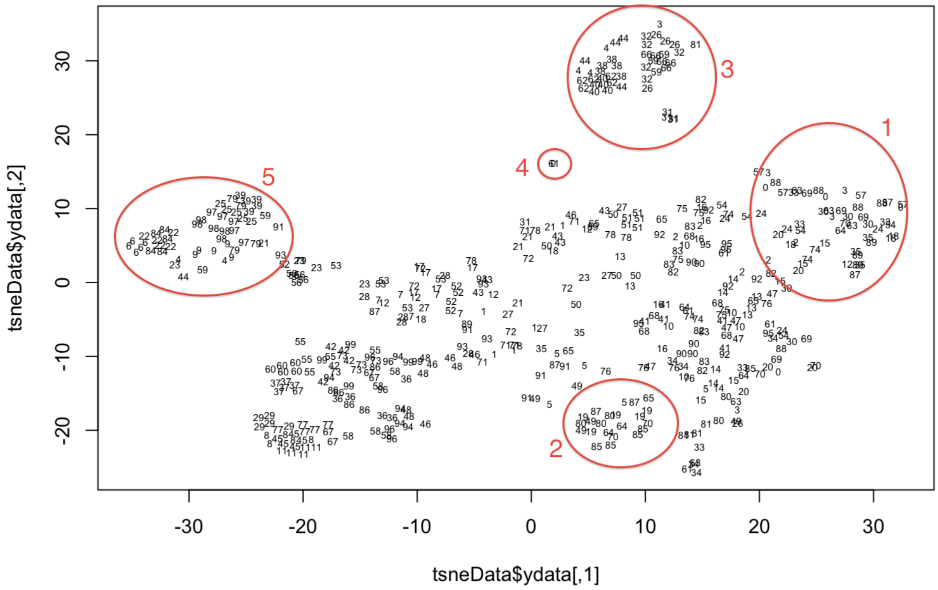


Figure 5.10: The t-SNE graph with the five areas that will be analysed.

5.4.3 t-SNE of input parameters of the model

In the following 9 graphs, from 5.11 to 5.19, the input parameters of the model are plotted into the t-SNE graph. These input parameters do not change within a run. By plotting these into the t-SNE graph, we can gain an understanding into the effects of these parameters with respect to the whole parameter space. In the remainder of this section, only reference is made to area 1, to give an idea of the process of comparing the graphs. In the final table 5.1 all 5 areas will be reflected upon.

Figure 5.11 shows the number of worker agents in the models. We can see that in the desirable area on the right, there are many workers. This indicates that the number of workers may be a factor for the system to move towards e-scrap selling to the professional end refiner. It is however not the only factor. We can see that other runs have a high number of workers. Comparing this to 5.9 leads us to conclude that e-scrap-selling may need a high number of workers in the system, but a high number of workers in the system does not automatically lead to e-scrap-selling.

Figure 5.12 shows that there are high numbers of families in the desired area, but this is not conclusive for all dots in the cluster. This does not seem to be a big contributing factor. It may be influencing the system in some cases, but not all of them.

Figure 5.13 shows that in the desired area agents have a high starting capital. However, just like with the number of workers, this may be a factor, but is not the only one: many runs where the starting capital is high don't show e-scrap-selling.

Figure 5.14 shows that corruption plotted in the t-SNE graph. There are runs with corruption (small dots) and runs without corruption (big dots). Like the number of families, this may not have a big influence.

Figure 5.15 shows that the tax is low in the desired area. This seems to have a significant

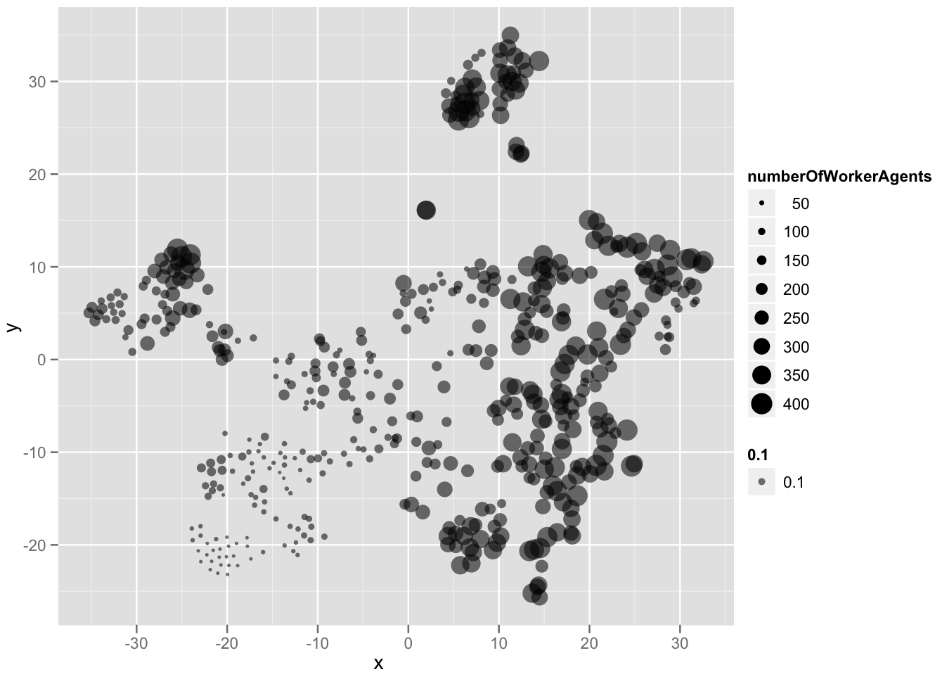


Figure 5.11: Number of Worker Agents, plotted into t-SNE graph.

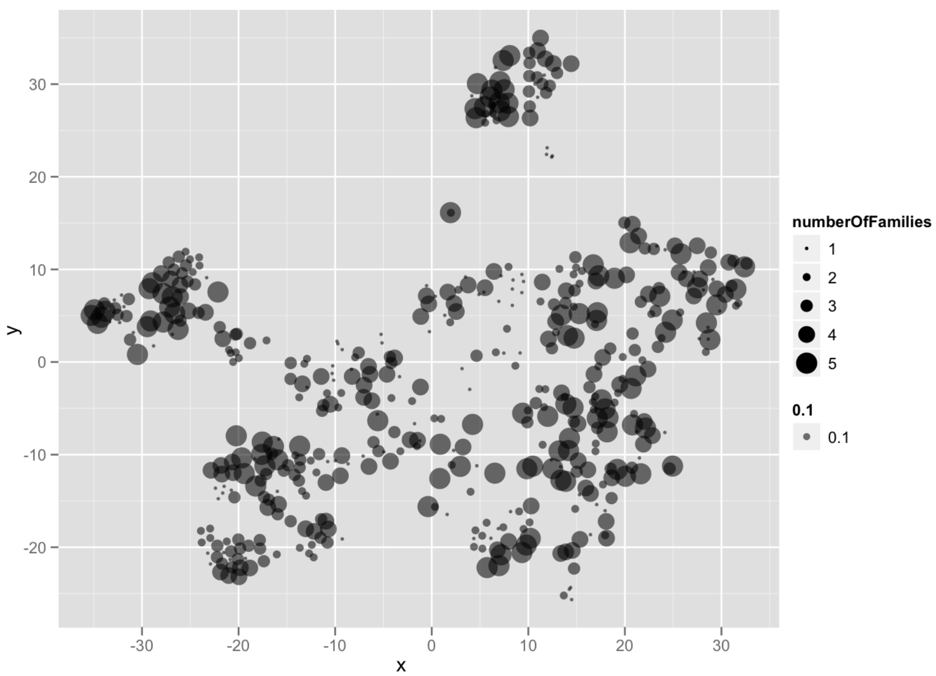


Figure 5.12: Number of Families, plotted into t-SNE graph.

influence. We can see that the clusters with no to little e-scrap-selling have high taxes, which may indicate that the situation does not favor becoming formal. With the exception of a few

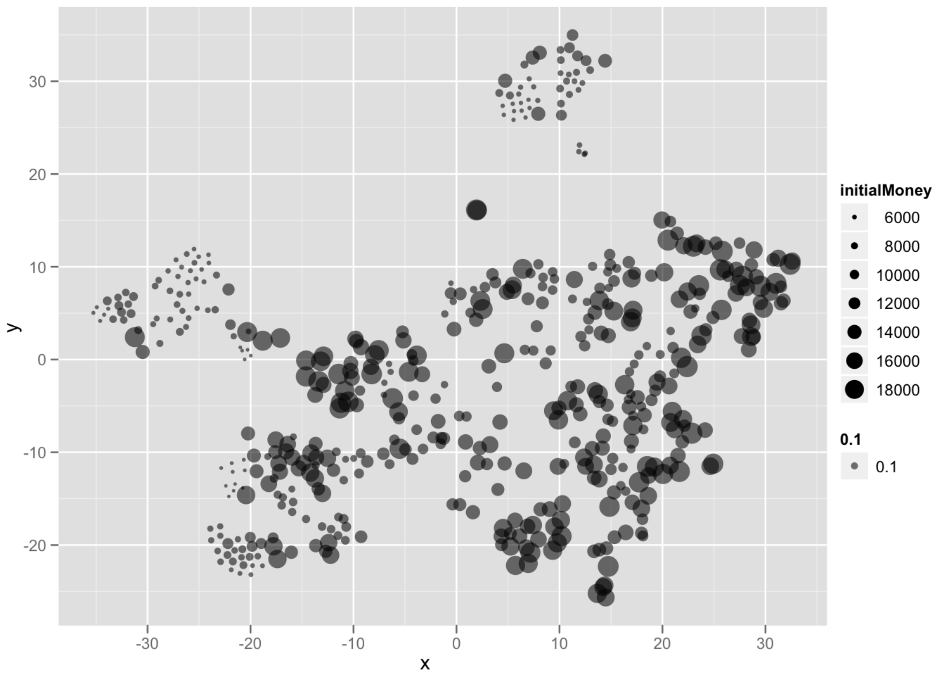


Figure 5.13: Starting capital, or initial money, plotted into t-SNE graph.

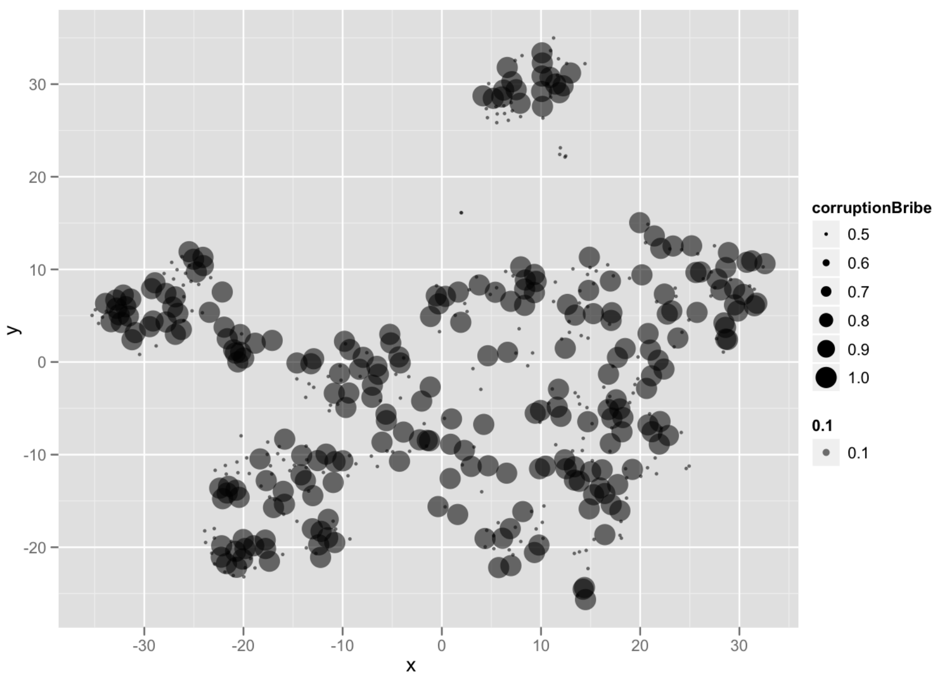


Figure 5.14: Corruption of the government, plotted into t-SNE graph. A small dot denotes that corruption is ON, and a big dot means corruption in the model is OFF.

dots in the desired area all runs have low taxes. (In the cases of the few high-tax runs where e-scrap was sold, this could have been made possible due to other factors, such as low investment costs and high e-scrap price.)

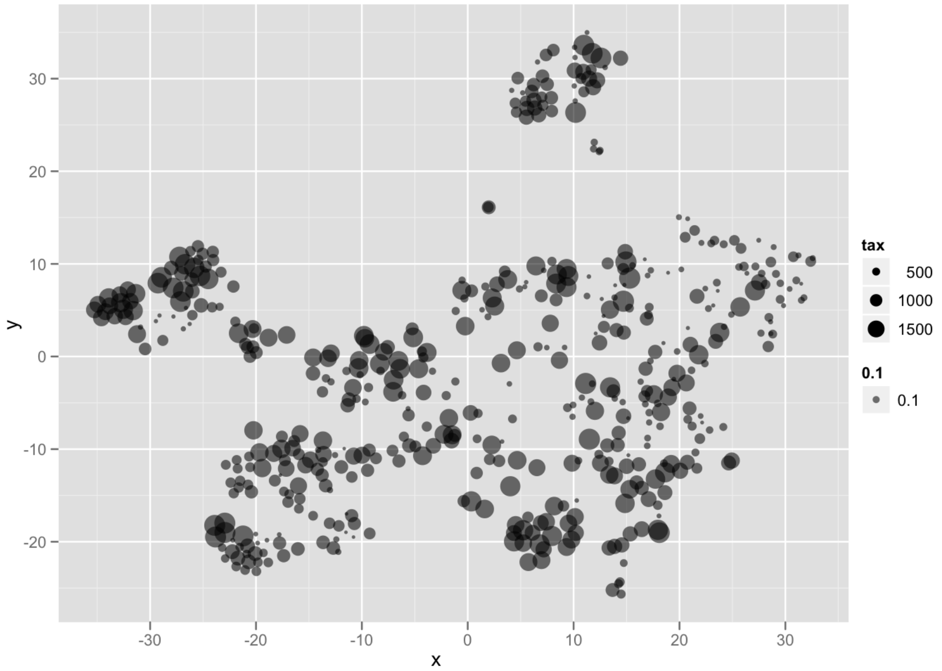


Figure 5.15: Tax to be paid by formal companies to the government, plotted into t-SNE graph.

Figure 5.16 shows that the e-scrap price is an important factor as well. Many of the dots in the desired area have a medium to big size. Just like we have seen in previous graphs, this is not the only factor, considering the high price in other clusters. (That e-scrap was not produced and sold there, may be due to other factors like high taxes or low starting capital.)

Figure 5.17 shows that the investment cost for many of the runs in the desired area is low. However, some runs have high investment cost. It seems that the investment cost is a sginificant factor for many of the runs in the desired area. Like previous graphs however, it is not the only one.

Surprisingly, figure 5.18 shows that high container cost doesn't necessarily discourages units to become formal and sell e-scrap. There are quite some runs with a relatively high container cost. This is not true for all runs in the desired area, but it is an interesting result, considering that we believed the container cost to be a significant factor.

We have to be aware that choices in the design and implementation of the model influences the outcomes strongly. The container cost was chosen to be a fixed cost per kg sent to the end refiner, to avoid the model becoming more complicated. With the bulk shipping of e-scrap in the real world, and the storage room needed for keeping large amounts of e-scrap at the recycling unit implemented into the model, this may give different results. Now, the container cost per kg may be just a fraction of the e-scrap price.

Figure 5.19 shows that the pay-out time does not have a big influence, as we would have expected. There are almost equally small and big dots in the desired area. This is a surprising result as well, and cannot be explained like in the case of the container cost. It should be

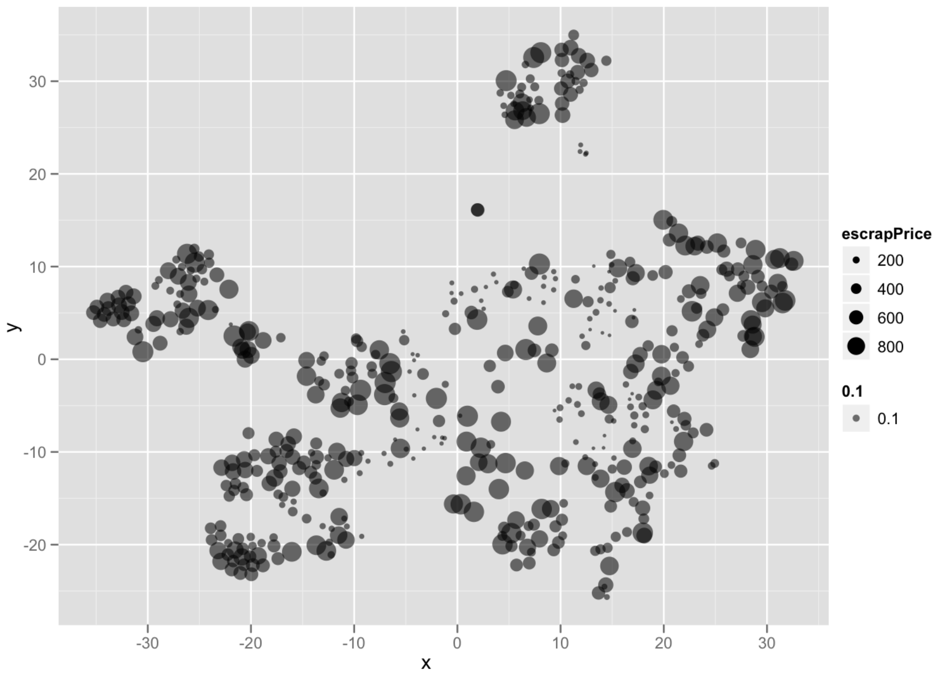


Figure 5.16: E-scrap price that is given for the e-scrap sold to the professional end refiner, plotted into t-SNE graph.

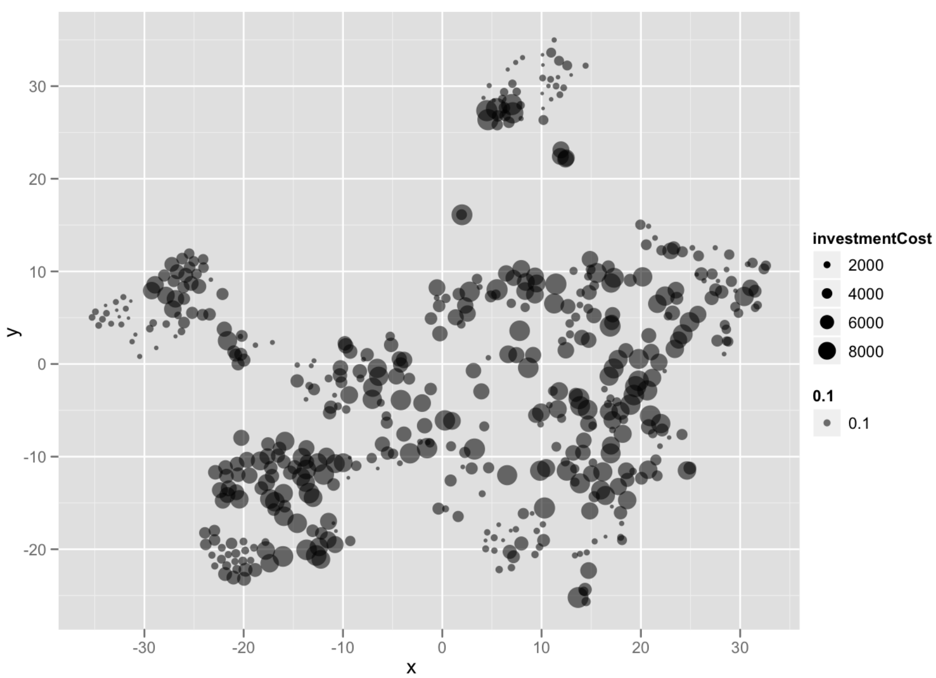


Figure 5.17: Investment cost for a unit to become formal, plotted into t-SNE graph.

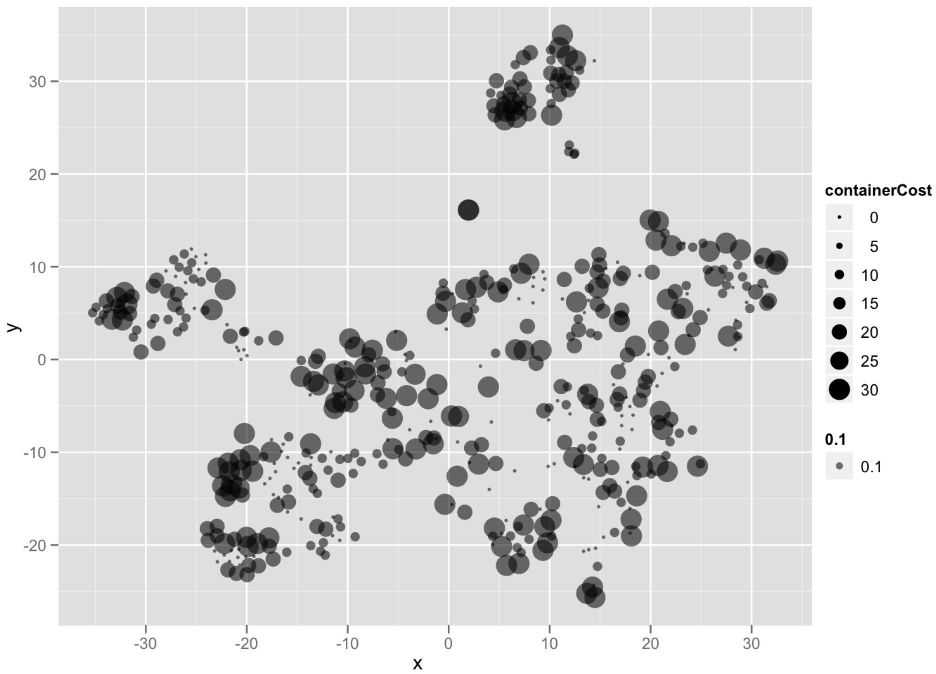


Figure 5.18: Container cost to be paid when shipping e-scrap to professional end refiner, plotted into t-SNE graph.

checked if the function of this parameter was programmed correctly, and then tested again.

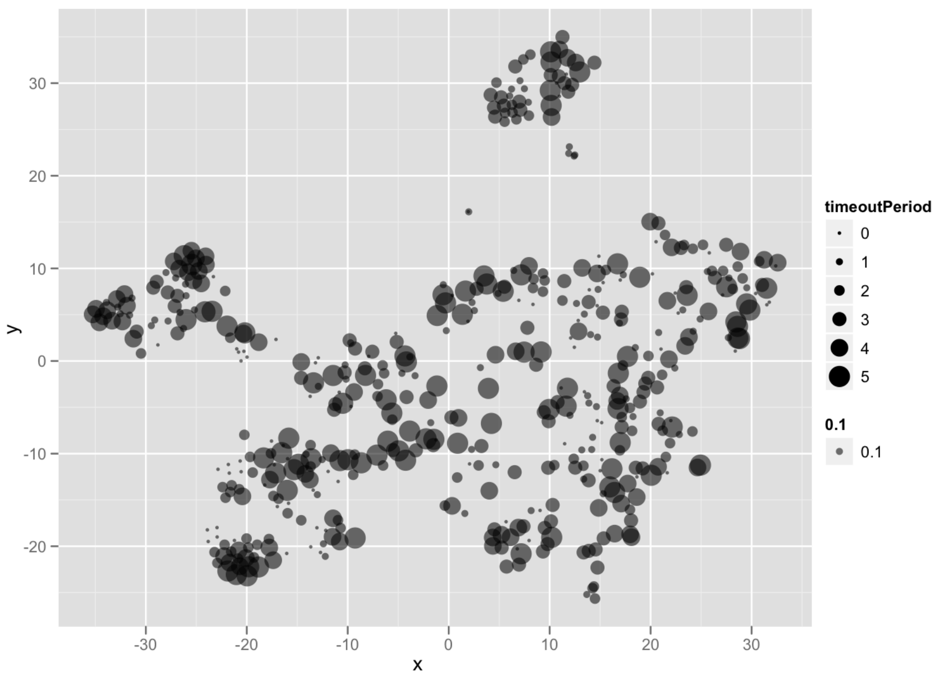


Figure 5.19: Pay-out time of professional end refiner in months, plotted into t-SNE graph.

5.4.4 t-SNE of additional outputs

Figures 5.20 to 5.24 show three additional outputs. Figure 5.20 shows the average unit size in the model. The results for the unit size are quite constant overall. Figure 5.21 shows when the model stops in the timeline. The runs in the desired area have a medium lifetime compared to other runs. Figure 5.22 shows the percentage of units doing safe extraction. We can see from the legend on the graph that all runs have values close to 50%. This means that in the model the safe extraction is done by approximately 50% of the recycling units, with little variation. Figure 5.23 shows that the child employment is also fairly constant. Figure 5.24 shows that there is a high percentage of formal local recycling companies in the desired area. This was to be expected considering the results of the e-scrap selling. If there is much e-scrap selling, there must be a larger amount of formal companies that sell the e-scrap.

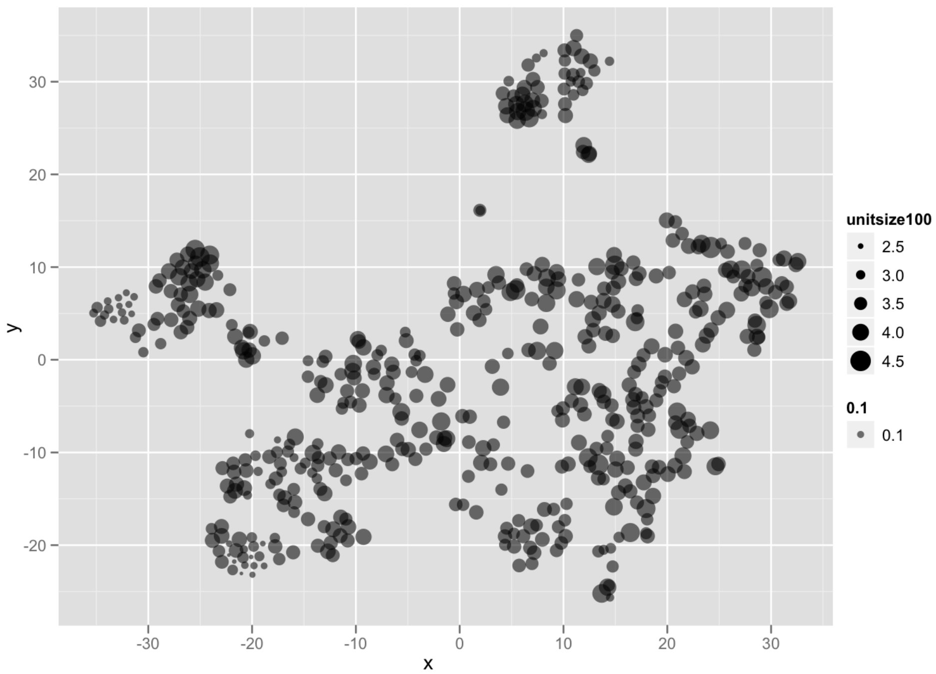


Figure 5.20: Average unit size in the model, plotted into t-SNE graph. For the calculation all units of size one (single, self-employed workers) were left out.

5.4.5 Results of t-SNE analysis

In table 5.1 the five areas are characterized by the results of the t-SNE graphs. Pay out time is left out of the analysis.

Through the table, we can describe the areas, and try to find indicators and characteristics of these areas.

Area 1: High cooperation with PER This area describes an ideal situation where there is a high starting capital, low tax, low investment cost and a high e-scrap price. Even though the container cost is high, the workers feel no hindrance in becoming formal. These very favourable conditions in reality would suggest that the government needs to be very

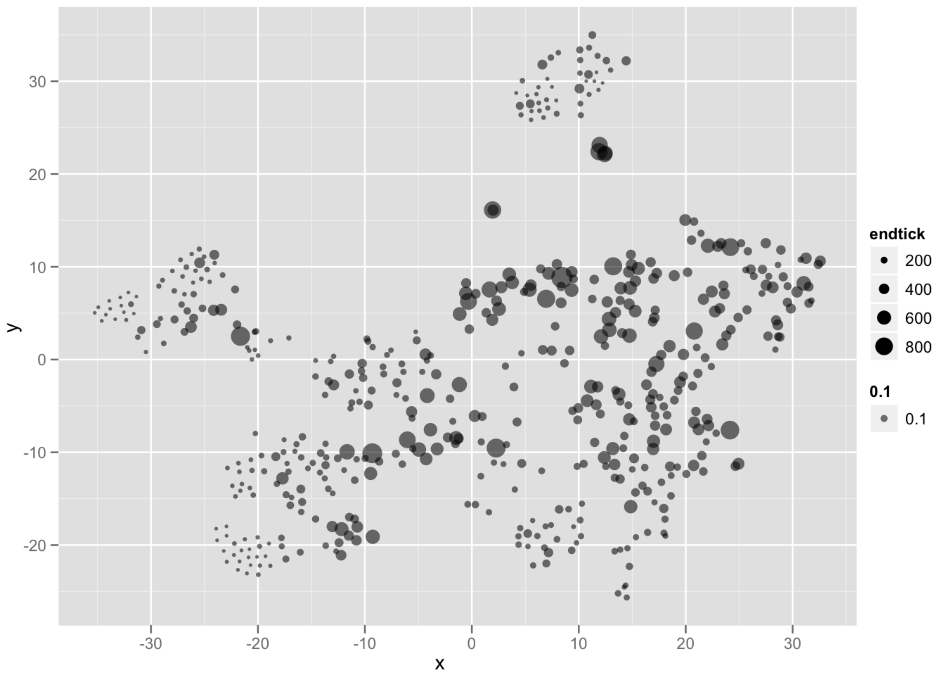


Figure 5.21: Final ticks of the runs, plotted into t-SNE graph. The final tick is determined to be at the last tick that computers are still bought.

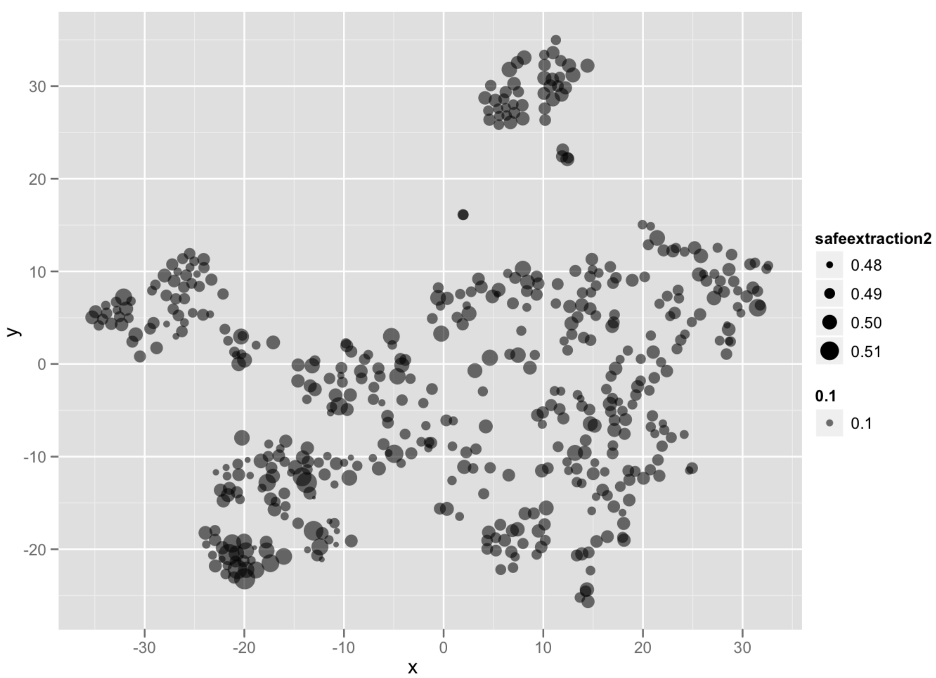


Figure 5.22: Percentage of Recycling Units doing safe extraction, plotted into t-SNE graph.

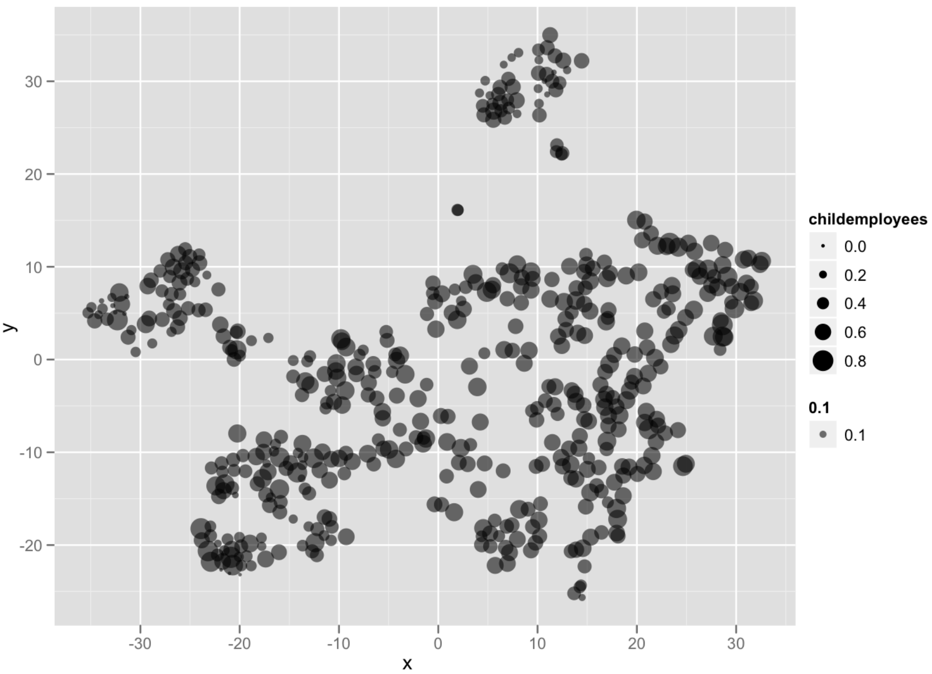


Figure 5.23: Percentage of children in child employment, plotted into t-SNE graph.

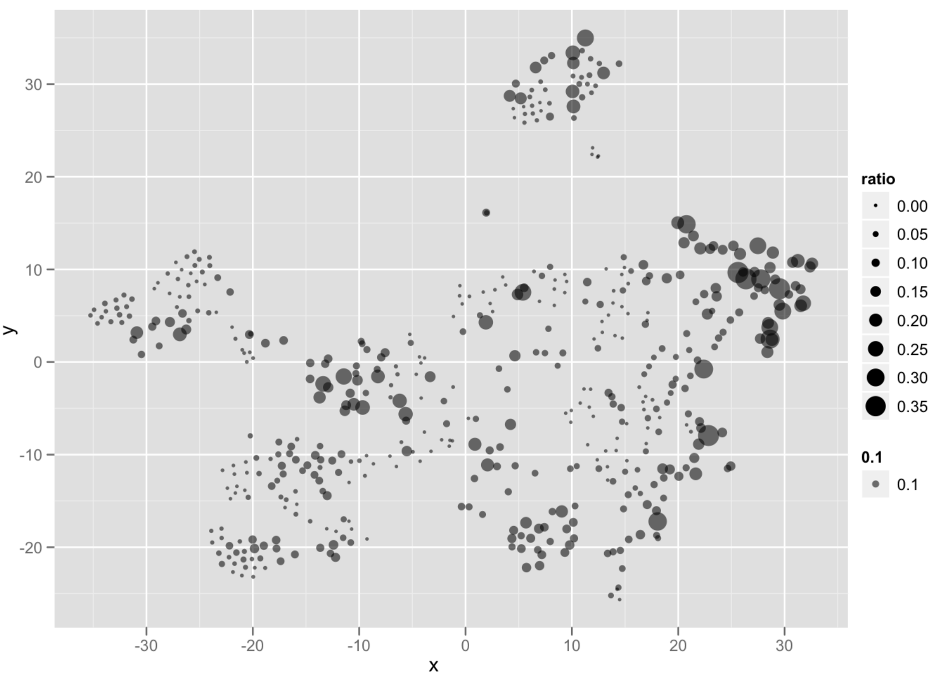


Figure 5.24: Ratio of formal/informal units, plotted into t-SNE graph.

cooperative to this sector (low tax and low investment cost) and the professional end refiner should offer a high price. Also, the workers have a high starting capital, so this is

Table 5.1: Analysis of 5 areas in the t-SNE graphs

Name	Area 1	Area 2	Area 3	Area 4	Area 5
Outputs					
Computers bought	High	Medium	Low	High	Low
Gold sold to Market	Medium	Medium	Low	High	Low
E-scrap sold to PER	High	Medium	Medium/low	Medium	Low
Average unit size	Medium	Medium	Medium	Medium	Medium
Ending of model	Medium	Low	Low	High	Low
SafeExtraction	Medium	Medium	Medium	Medium	Medium
ChildEmployment	Medium	Medium	Medium	Medium	Medium
Formal/informal ratio	High	Medium	Medium	Low	Low
Inputs					
Number of workers	High	High	High	High	Medium
Number of families	High	High	High	High	High
Initial money	High	High	Medium /low	High	Medium/low
Corruption	Average	Average	Average	Average	Average
Tax	Low	High	High	Medium	High
E-scrap price	High	High/medium	High/medium	Medium	High/medium
Investment cost	Low	Low	Medium/low	High/medium	Medium/low
Container cost	High	High	High	High	High/medium
Pay out time	-	-	-	-	-

likely to be a scenario for successful local recycling units that have built up their capital.

Area 2: Medium cooperation with PER This seems to be a second area that has a desirable result. In this area less e-scrap is sold, and less units are formal than in area 1. There is a high tax, but the low investment cost and relatively high e-scrap price cause several units to become formal nonetheless. We could view this system as one where the investment cost is subsidized by the government or an NGO. A downside is that the model ends quickly. This may be because a recycling unit can't keep up with the tax, or because of competition and prices.

Area 3: Very low cooperation with PER In this area conditions are not favourable: high tax and medium investment cost. Still some recycling units become formal. Perhaps this area describes the minimum requirements or the borderline-case: the medium investment costs are low enough for some units to become formal. The model, however, stops quickly.

Area 4: High continuous activity This area is characterized by a high activity. Many computers are bought, and a lot gold an e-scrap are sold. There is a high starting capital that enables this. Also, because becoming formal isn't directly favourable (medium tax, relatively high investment cost, medium e-scrap price), the majority of workers stay informal. Some caution has to be taken when interpreting this area: there are only 2 runs in this area.

Area 5: No activity and high poverty In this area, the workers don't buy products and therefore don't produce much gold or e-scrap. They start with a low capital, which may thus reflect a system with poor workers. The high tax doesn't encourage the workers at all to become formal. The quick ending of the model may be attributed to these factors, and possibly also the fewer number of worker agents in the model.

5.5 Looking closer at economical factors

We have seen in the t-SNE graphs that the economic factors have a high influence on the model outcomes. To gain a better understanding of the relation between the factors and the e-scrap selling, the following graphs show single factors against the e-scrap sold to the professional end refiner.

The first figure in table 5.2 shows the initial money of the workers against the e-scrap sold to the professional end refiner. We see that a higher starting capital leads in some runs to higher e-scrap selling. Figure (2) in table 5.2 shows the tax plotted against the e-scrap sold. It is more difficult to point out the relation. At lower taxes there are some runs that do very well and much e-scrap is sold to the end refiner. Figure (3) in table 5.2 shows the e-scrap price plotted against the e-scrap sold. This shows that a higher e-scrap price increases the chance for cooperation. Figure (4) in table 5.2 shows the investment cost plotted against the e-scrap sold. The relation is not apparent from the plot. Figure (5) in table 5.2 shows the number of worker agents in the system, plotted against the e-scrap sold. A higher number of workers in the system means a higher amount of e-scrap sold to the end refiner. Figure (6) in table 5.2 shows the unit size plotted against the e-scrap sold. Here we can see a relation in the output, since unit size is an output as well. We see that there seems to be an optimum around 3.5-4.0. So in the model, a high amount of e-scrap sold is accompanied by a unit size that is on average around 3.5 to 4 workers.

To understand the impact of the number of families on the unit size, we can look at how these relate. Figure 5.25 shows the number of families plotted against the unit size in a boxplot. We see that less families in the model lead to bigger units.

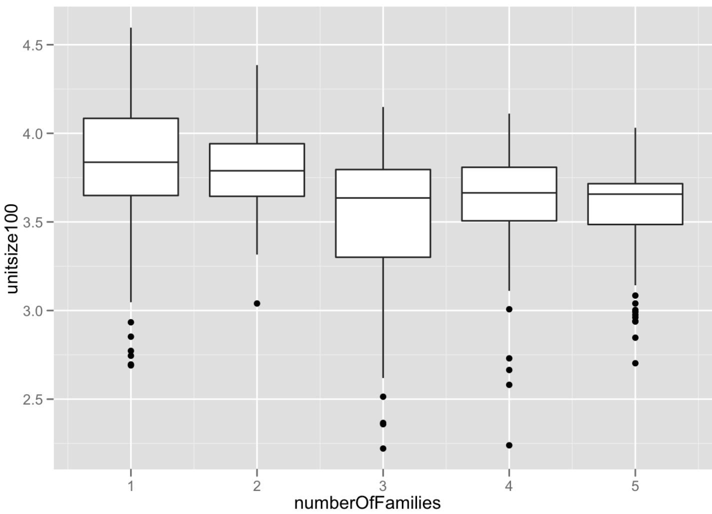
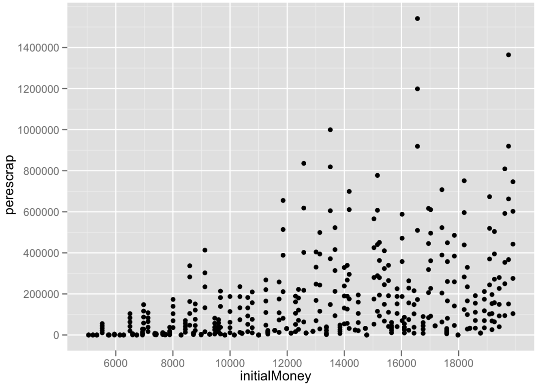


Figure 5.25: Number of families versus the unit size.

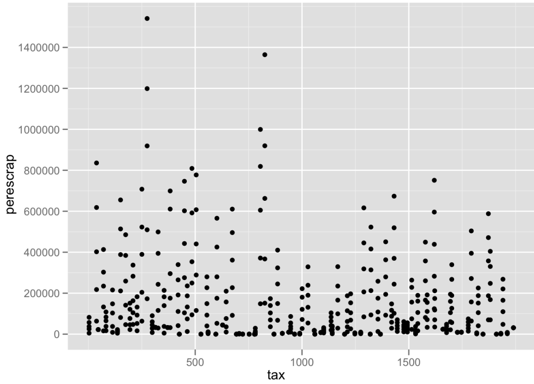
5.6 Conclusion

In this chapter we tested and compared various factors to understand how they influence the decision of a local informal recycling unit to become formal and start cooperating with the

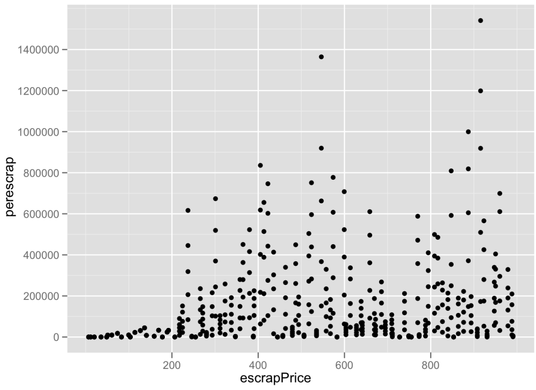
Table 5.2: Figures of (1) Initial money, (2) Tax, (3) E-scrap price, (4) Investment cost, (5) Number of worker agents and (6) Unit size, all plotted against the e-scrap sold to the professional end refiner (PER-e-scrap)



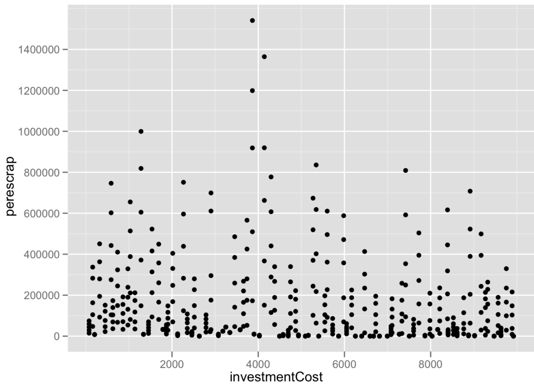
(1) Initial money plotted against e-scrap sold.



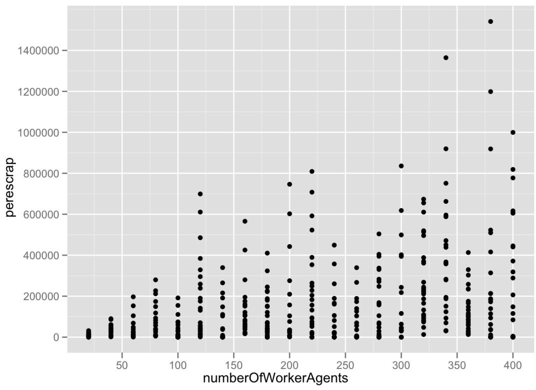
(2) Tax plotted against e-scrap sold.



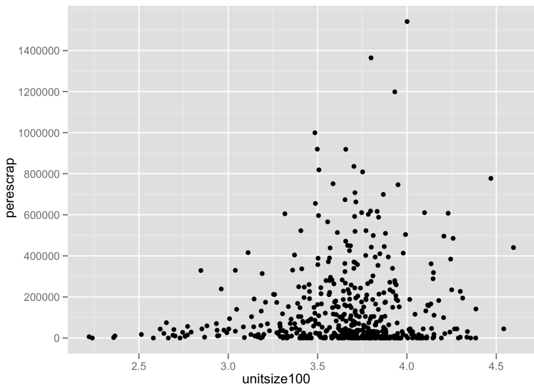
(3) E-scrap price plotted against e-scrap sold.



(4) Investment cost plotted against e-scrap sold.



(5) Number of worker agents plotted against e-scrap sold.



(6) Unit size plotted against e-scrap sold.

professional end refiner. Due to the time limitations in the research only a test experiment of 100 runs was done with 5 repetitions. In this test experiment both economical factors and social factors were tested. The input parameters were in this initial test focussed on the economical factors. Social factors should be tested extensively in the future. The model shows for instance as a result that safe extraction, child employment and the effect of corruption do not change much in different runs and do not cause changes in the results. Also the unit size does not change much. The model does show an effect of the amount of families on the unit size. Less families in the model means that more people know each other as family, and this leads to bigger units.

If we look at the 5 different areas in the t-SNE graph, the model shows that for a very successful cooperation between local recyclers and the professional end refiner a high starting capital, a high e-scrap price, a low tax and a low investment cost cause the best results. If we further look at what has the highest impact of these, graphs (table 5.2) show that a high initial money and a high e-scrap price are more consistently causing high e-scrap selling.

These economic factors seem to overshadow smaller economic factors in the model like the container cost. Since the social factors were not tested to the extent that the economic factors were tested, we can't compare them now. For future work, the inclusion of more social factors to test, such as the risk a boss may take, or the effects of corruption, child employment, safe extraction and patronage can be varied. This could lead to a new understanding of the model.

Chapter 6

Discussion and conclusion

In this chapter we discuss the results and the research done through this thesis on three levels. The case study and experiments itself are the subject of section 6.1. Section 6.2 deals with the modelling process and the MAIA framework. Finally, a conclusion is given for the whole of the research in section 6.3.

6.1 On the results of the experiments in the case study

The e-waste problem is a field in which agent-based modelling is new. The functions in the system are unknown. Also from an agent-perspective, we knew little about what the important factors in the system were. This was a first attempt to capture an e-waste sector in an agent based model. The inclusion of institutional analysis allowed us to look at the system from a social perspective. It made the complexity of the system visible and pointed out what the difficulties were for understanding the system. These difficulties, such as understanding how an agent reacts on corruption or trust, proved to be equally difficult to model. Inevitably, during the literature study, the conceptualization, the implementation and the experimentation, many choices have been made. Nevertheless, through this attempt in modelling a complex system and the efforts in mapping the social characteristics of the sector, a new pathway is explored that deals with social systems modelling.

The subsections that follow discuss the results with respect to the e-waste sector itself. The next section 6.2 goes deeper in the modelling process.

6.1.1 About the recycling sector in Bangalore

Although both economical and social factors were modelled, the outcomes of the experiment pointed towards economical factors mainly. The model shows that in the case of financially unfavourable settings, the model either ends quickly or stays largely informal. The highest amount of formal units in a run was around 30%. The informal sector, by avoiding extra costs in the formal sector, is more stable and able to survive longer. If circumstances are economically favourable to become formal (low tax, low investment cost, high e-scrap price, high starting capital), they are likely to do so. But in the end it seems to steer at an early collapse of the model. One could argue that this means the results show that for the recycling units staying informal economically is best. However, we have to be aware that it was modelled that recycling units will choose for the cheapest or the most profitable option. The agents didn't have a long term vision in the model. This may have accounted to the end results.

6.1.2 Regarding crystal and UPMR scenarios

Looking at the three areas with the highest e-scrap-selling (1, 2 and 4), we can see that in these three cases the starting capital of the workers was high. This could indicate that for a venture like crystal the Unit Boss needs to have high capital to take the risk.

There are very few long term successful runs with a significant number of units doing crystal. The best input parameters seem to be: low taxes, low investment cost, and a price for e-scrap handling that is relatively higher. The pay out time, corruption and the container cost didn't seem to have much effect in the model. This is contrary to what was expected, considering that these are very relevant point in the real world. It could be that variables in the model overshadowed these factors: for instance if the e-scrap handling fee is high enough, a recycling unit will have no problem with the container cost. It could also mean that some factors were not defined strong enough in the model.

6.2 Regarding agent-based modelling the e-waste sector

6.2.1 Points for improvement in the experimentation

During the experimentation, there are learning points that need to be looked at in follow-up work.

Data in and output design

The data output design could be improved. The data is split over 3 tables. To extract some of the more intricate relations in the model, the data needs to be queried from multiple tables, taking more time. Furthermore, a more comprehensive choice of input parameters could have shown more of the social characteristic. The parameters were chosen too much on the practical and financial side. This is unfortunate, as the possibility to test the social characteristics was one of the interesting features of the model. During the experiment design, more tests can be based on the institutions in the model. The capability to implement and test institutions should not be confined to the modelling part only. Varying the parameters of the institutions could have given us different insights in the social complexity of the system.

LHS

The use of Latin Hypercube Sampling provides a statistically evenly distributed set of values over multiple parameters. Because the LHS scatters the values over the parameter space, the comparison of results over multiple parameters is made more difficult. Though this fortifies the validity of the testing process, it is more difficult to handle the data and visualise it. Options for visualising should have been investigated before using LHS.

t-SNE

The comparison of many different parameters through pattern recognition proved to be useful, given the many parameters to test and the use of LHS for the input parameters. By using t-SNE to first make a map of runs based on a desired result (e-scrap sold to Professional End Refiner) and then plotting several graphs for separate parameters and comparing these 'manually', we can try to still get an understanding of the factors influencing the model.

An improved model design could even increase the use of a t-SNE distribution. Because no factors were developed that influenced choices on refurbished parts and waste, the calculation of the t-SNE distribution probably was leaning more on the e-scrap selling, gold selling and computer buying data. The patterns on the t-SNE distribution would become more comprehensive when more different outcomes were used in calculation.

6.2.2 MAIA and the modelling of institutions

The MAIA framework is a helpful tool for conceptualizing a system and identifying important institutions and functions. It gives a different perspective on a system through the layered structure and the intricate relations that can be defined within the model. One of the strongest points is that it *allows* a researcher or modeller to use it in the best possible way. With the flexibility of MAIA, the quality of the model is more defined by the abilities of the researcher than the framework.

Due to the size of the framework, and the possibilities, it may have a steep learning curve. Also, the application of the MAIA framework is not trivial. A good understanding of the system is needed, and a feeling for social systems and institutions is required to adequately answer the details in the framework.

One of the difficulties in MAIA is the translation of institutions into a program with logical operators and numeric values. While the whole design phase is an exercise in *literally* defining the system, a semi-numeric approach, or a focus on the (computer) logic that will be used in the model, would greatly help the transition towards a computer model. A suggested option would be that the literal definitions serve as the raw template in the conceptual design and approach the system from a social science background, and the detailed design would reflect even more on the underlying mechanics and translation into formulas, functions and operators. This way MAIA would not only serves as a framework, but as a binding factor between two different worlds of science.

6.2.3 On institutions that were included in the model

It is difficult to capture the complexity of the real world in a model. Per definition, we simplify the rules to model. Finding the right balance between practical simplification and complicatedness that is still realistic is a challenge. Below the complexities of the real life institutions are mentioned.

Government registration

The government registration had an important function in the model. It facilitates the informal recycling units becoming formal. In the government registration we assumed that the government is directly available and approachable. This is not likely so in the real world. Getting a permit from the government to become a formal company can be a lot of work and may cost a lot of time to do for an informal recycler. This is an aspect that recyclers also keep in mind when given the decision to become formal.

Corruption

This may not have been defined as strongly as in reality. This is also a very complex and psychological institution: the way corruption influences decision making should be thoroughly investigated to recommend a better way of implementation. We stumbled upon questions like: when will a corrupt agent ask more money and when less? It may depend on friendship relations, contempt, mood or aptitude. To model corruption is not as straightforward as simply asking a different price for a product.

Safe extraction

The use of this institution was underdeveloped. The choice that Unit Bosses made to do safe extraction or not was only programmed to occur when the Unit Boss was formal and if he was fined. A more comprehensive form of decision making, such as a 'morality' of the Unit Boss or some other indicator could have made this institution more pronounced in the model. This however brings the difficulty of how to model something like 'morality', and how can you influence it? When diving deeper into these aspects of complex behaviour, it becomes imperative to gather information on how these aspects function.

Child employment

Child employment in the model was confined, through the fixed number of worker agents. I would become interesting to see what would happen if children were 'abundantly' available, and whether something like morality in the system as discussed above would be strong enough to avoid child employment.

6.2.4 On institutions that were not included in the model

The inclusion of institutions is a very interesting option for ABM, and could be used more. At the start of the research there were institutions defined that finally didn't make it due to the difficulty to program, the size of the model and time constraints. In this section we'll discuss these, exploring the possibilities of a more comprehensive model.

Trust

Trust (and distrust) is an institution that was found in the literature to be present in the system. However, during the model design it was left out, with the view that it would be more interesting to perceive the outcomes of the model and define trust from the outcomes rather than programming it. During the test experiment performed we did not find a suitable method for defining trust through the parameters that we used. This should be one of the points to be included in the model design in future work.

Patronage

Patronage is a highly complex institution. During the model design we had difficulty defining how patronage could be practically implemented. It would require intricate definition of the relations between bosses and their employees. We now assumed it could mean something as simple as 'employees cannot leave their job on their own accord'.

6.2.5 Other model functions

Buying of old computers

As we could see in chapter 5 section 5.3.1, the Unit Bosses spend a lot of money in the first tick to buy old computers, but don't recover from their loss of money. Though they are programmed to keep some money aside for the payment of their workers, it seems that they still buy more computers than they can afford considering their employees (unit size). A suggestion for improvement of this function is to let the boss calculate the amount of computers he could process during the coming tick, and let him buy only that amount of computers from the World Market.

Negotiations

On closer inspection during verification, it was noted that negotiations may have been modelled differently from the real world. In the model, we programmed the buying and selling of products to be more of an agreement than an negotiation. For instance, when one agent offers a price, and the seller agrees with the bid, the deal is made. However, the way deals are made is presumably different in India, especially for small enterprises and self employed workers. Since the coming of the mobile phone, power came to many of the poor people, who could phone up multiple buyers and compare prices for their products. This is certainly true for farmers in India, see for instance Stone (2010). If we would model negotiations in such a way that unit bosses have more freedom in choosing the best price for their product, there may be more flexibility and a more bottom up approach. The incorporation of such a system would most likely improve the model and add a new dimension.

Besides these functions that became apparent during the modelling process, there are many more functions that could be improved. The assumptions that were made earlier are all valid starting points for new discussions. There are many options for future work: from optimizing the current model to investigating the possibility of modelling more complex social and institutional functions into the equation.

6.3 Conclusion

This model, from the perspective of agent based modelling research, has been a new attempt at incorporating social characteristics in a model. By having defined institutions and roles, the model has set itself apart from the models made through the general method of agent based modelling. The results of the model, due to the single test that was performed and the lack of an iteration in the final steps during the design and implementation, were unfortunately inconclusive: the use of institutions was not properly reflected in the results, and the social characteristics not tested. At the same time, the exploration of the system during the model design gave us a glimpse of the complexity that we are dealing with. Below a stepwise view is given on what we learn and can conclude from this modelling exercise: from this research back to Industrial Ecology.

A recommendation for follow up work On the level of the modelling the informal recycling sector in Bangalore, the steps of detailed design and implementation, as well as the experiment design and data analysis, should have been iterated (at least) once more.

There is especially room for refining aspects of the detailed design, for instance aspects like negotiations between workers, the way bosses make financial choices and the effect of institutions on the decision making. There is also room for improvement in defining the parameters to test: taking into account more of the social characteristics while experimenting - test the institutions in a more pronounced way - will give insights beyond the economical factors now tested.

Answering the research question On the level of understanding the system, acknowledging the fact that despite the institutional character of the model mostly economic factors have been tested, we see that the highest results for cooperation with a professional end refiner are achieved when 4 factors combine: (1) a high starting capital of workers, (2) medium to low tax for formal companies by the government, (3) low investment cost for informal companies to become formal, and (4) a high e-scrap price given by the professional end refiner for the e-scrap. These results in itself seem trivial: that the cooperation with the professional end refiner should be economically relevant to the informal backyard recycler is something we expected - and to a large extent programmed into the decision making. We can translate these results, however, to real life situations to sketch what the results means.

Translation of the results into real situations The necessary high starting capital for workers in the model could indicate that only bigger and financially stable recycling units have enough capabilities to become formal and cooperate with the professional end refiner. At the same time, it needs a low investment cost and low tax. This could for instance mean financial help to become formal by NGOs, government or other businesses, or subsidies by the government. This joint effort of different parties is also what we see in the Crystal project.

Placing the model into perspective of e-waste research For e-waste research in general, the model provides insight in the (financial) needs for informal recycling to change. The model focusses on local change only, and specifically in the choice of doing gold extraction or not. Comparing this with the whole chain that is involved in the e-waste problem, consisting of electronics production and hazardous substances, use of electronics, disposal of old electronics, transport of e-waste, collection, recycling and extraction, this model covers only a small part of the chain. In fact, it only discusses an end-of-pipe solution. It also does not discuss topics on demand and supply of electronics, consumerism, producer responsibility and take back systems. From this perspective the model provides little to no insight on how to integrally deal with the e-waste problem. Also, we only looked at computer waste and neglected all other types of electronics, components and valuable materials besides gold. The model has therefore been specific in it's goal and system boundary.

At the same time, there is potential for the model to help gain an insight into local recycling of backyard recyclers on a larger scale. This research is technically not confined to the Bangalorean e-waste sector, since there are many similar situations in other cities in India and other countries. In fact, much of the system characteristics can be found in sectors in China and West-Africa as well.

Modelling process is in itself a tool for understanding The method of analysing the results through t-SNE allows for the comparison of a multi-dimensional dataset in two-dimensional graphs. Although pattern recognition can be seen a normative approach, it is capable of covering a lot of (unstructured) data. What has been is noticeable, however, is that understanding the system has started with the modelling process itself. The structuring of the system, identifying roles and institutions through MAIA and detailing the actions in the model have been at least as useful as the results for understanding - or identifying - important factors of the system. We could say that the modelling process is a tool in itself for understanding possible factors for change in the recycling sector.

Modelling research in general The use of the MAIA framework as methodology for conceptualizing the recycling system for agent based modelling helped to gain a structured view of the system. It enables modelling complicated functions through the interrelated tables and diagrams. Besides adding a conceptualization step, it introduces institutional analysis to Agent Based Modelling. This model, although not successfully testing the institutions, identified some of these institutions in the system during the conceptualization. A difficulty was the implementation of institutions. Capturing social characteristics in logical parameters remains to be challenging. Future work, with an improved implementation and experiment design, could discuss the effects of institutions on the informal sector in Bangalore, but also reflect on the impact on agent based modelling in general.

Further research could also focus on what the modelling of social aspects add to the understanding of modelling in general. While a computer model works with logical operators, the inclusion of social aspects could be seen as adding an unseen ‘activation energy’, or a threshold to the decision making behaviour. It could thereby hinder rational behaviour. Understanding how social aspects influence rational behaviour would be a benefit to this specific model and modelling research in general.

Complexity The complexity of the system lies in the combination of technical, financial, political, ecological and social aspects, thoroughly intertwined: an informal recycling sector, where backyard recyclers belonging to a marginalized group of people extract precious metals for their livelihood with risk for their own health, in a country where no dedicated regulations exist, and that are given the choice to become formal. The model covers financial aspects of the system, choices regarding becoming formal, and in a very simplified way the technical aspects as well. The ecological effects were deliberately not modelled as it did not fit with the purpose of this particular model. The social aspects were implemented as much as possible, but proved to be the most difficult to model. This is generally an issue in the modelling of complex systems. The model simply affirms the difficulty for understanding the complex social behaviour of the system.

The environmental issues we are dealing with globally and the need for sustainable development are evident. E-waste, being only one topic in the whole of environmental problems, is a considerable problem, not only due to the complicated composition and recycling, the value of materials in the waste stream or the increasing production of electronics globally, but certainly also because of the social impact it has on our society.

The relevance of modelling to Industrial Ecology should be found in the systems perspective being employed in analysis and design of the model. Different disciplines come together, like in the previous mentioned point about complexity. It is imperative that coming efforts increasingly focus on multi-disciplinarity. This research may well be seen as an example for the need of balanced knowledge on all areas of the system to successfully answer environmental problems.

Appendices

Appendix A

MAIA tables and diagrams

A.1 Constitutional structure

Table A.1: Roles

Role	UnitBoss	Segregator	Refurbisher	Extractor	Government
Objective	Profit and/or income	Profit and/or income	Profit and/or income	Profit and/or income	Compliance by companies to the law
Sub-objectives	Have workers, make connections	Create segregated waste streams	Upgrade refurbishable parts to refurbished parts	Extract gold out of connectorsPWBs	Formal registration by all companies
Institutions	Distrust, Honesty, GovernmentRegistration, Corruption, ChildEmployment, SafeExtraction			SafeExtraction	Corruption
Institutional Capabilities	Hire employees, fire employees, buy resources, sell products, pay salary	Segregate computers into refurbishable parts, connectorsPWBs and waste, OR into refurbishable parts, escrap and waste	Change refurbishable parts into refurbished parts	Extract gold from connectorsPWBs with low eficiency (25%)	(1) Fine formal companies that do not follow regulations, (2) can through a Safety Inspection learn which companies are following which laws, and also if they work safe or unsafe, (3) can calculate a fine per felony, according to the weight of the felony, and (4) can remember companies that were fined for a felony
Entry Condition	Age=old, have money for employment	None (any agent)	None (any agent)	None (any agent)	None (any agent)
Physical component ownership	None	None	None	None	None
Information ownership	None	None	None	None	None

Table A.2: Institutions

In the institutions table we find the institutions that were conceptualized for the system. However, not all of these were implemented in the model. Only Safe Extraction, Child Employment, Corruption and Government Registration were implemented. Distrust and Honesty were left out of the model because of the difficulty to model these in the given time. This is an older table, that was used in the initial conceptualization. The ADICO table A.3 shows additional norms and institutions that are structured according to the Attributes, Deontic type, aIm, Condition and Or/else, as is discussed in section 3.3.1.

Institution	Distrust	Honesty	SafeExtraction	ChildEmployment	Corruption	GovernmentRegistration
Deontic type	Prohibition	Permission	Prohibition	Permission	Permission	Obligation
Type	Informal institution	Informal institution	Informal institution	Informal institution	Informal institution	Formal institution
Subject	• Segregator • Refurbisher • Extractor	• Segregator • Refurbisher • Extractor	• Segregator • Refurbisher • Extractor	• Segregator • Refurbisher • Extractor	• Government	• Segregator • Refurbisher • Extractor
Content	Agents that are distrustful don't trust big firms and rather not deal with them. These agents consider big firms as competitors.	Agents that are honest communicate true information about their properties to other agents when they are asked for it. Agents that are not honest are allowed to state a different value for their properties. For instance: about their income, about prices, about types of products, etc.	Agents that do SafeExtraction don't use toxic chemicals, and have safer working conditions. However, the procedure costs more.	The boss allows child employment. Child workers are cheap.	Corrupt agents ask more money than they should for doing things for other non-corrupt agents. Corrupt agents pay less to do things themselves, whether they are dealing with non-corrupt agents or not. (they have connections.)	To be in the formal sector, agents need to be registered at the government. However: this brings more costs (tax, extra investment costs) and the danger of corrupt inspectors and officials.

Table A.3: ADICO table

Name	**Attributes (roles)**	**Deontic Type**	**aIm**	**Condition**	**Or else**	**Type**
Hire norm	Unit boss	Prohibited	Hire employees	The to-be-hired employee is not hired by someone else	-	Informal
Buy old computers norm	Unit boss	Permitted	Buy old computers	The unit boss has segregators in the group and segregators have enough productivity	-	Informal
Buy refurbishable parts norm	Unit boss	Permitted	Buy refurbishable parts	The unit boss has refurbishers in the group and refurbishers have enough productivity	-	Informal
Buy connectorsPWBs norm	Unit boss	Permitted	Buy connectorsPWBs	The unit boss has extractors in the group and extractors have enough productivity	-	Informal
Child employment	Unit boss	Prohibited	Employ children	Registered	Fined by government	Formal

Table A.4: Groups

GroupName	**RecyclingUnit**
Members	All agents that work for one boss at his RecyclingUnit
Institutions	
Physical Components	OldComputers RefurbishableParts RefurbishedParts ConnectorsPWBs Gold Waste E-scrap

A.2 Physical structure

Table A.5: Resources

Physical Component Name	**Properties**	**Type (fenced/open)**	**Behaviors**
Old computers	Weight (kg) Individual price (INR/kg) Auction price (INR/kg)	Fenced	None
Refurbishable parts	Weight (kg) Average price (INR/kg)	Fenced	None
Refurbished parts	Weight (kg) Price (INR/kg)	Fenced	None
Connectors & PWBs	Weight (kg) Average price (INR/kg)	Fenced	None
Gold	Weight (kg) Price (INR/kg)	Fenced	None
Waste	Weight (kg) Price (INR/kg)	Fenced	None
E-scrap	Weight (kg) ProfessionalEndRefinerPrice (INR/kg) Average price (INR/kg)	Fenced	None

A.3 Collective structure

Table A.6: Agents

AgentName	Worker	GovernmentAgent	ProfessionalEndRefinerAgent	WorldMarketAgent
Properties	Age (child/adult) Specialization (Segregation, Refurbishing, Extracting) Productivity (kg/tick) FamilyName (Name: A, B, C, etc) UnitBoss (y/n) Registered (y/n)	InspectionOfficers (number)	Capacity (kg/tick) Money Desired product quality (yield or efficiency) PayOutTime (ticks)	None
Characteristics	Risky Economical	None	None	None
Personal Values Profit and/or income Increase Status Job security	Wants all companies and self-employed people to be registered Registered companies should follow laws and regulations Formal companies should only deal with other Formal companies people and environment should be safe and healthy	Make agreements with formal companies and buy their e-scrap, with a certain product quality	None	
Type	Institutional	Institutional	External	External
Role	Unit boss, Segregator, Refurbisher, Extractor	Government	None	None
Information	None	RegistrationOffice (list) ListOfFines (list)	None	OldComputers (kg) OldComputer price (INR/kg) RefurbishedParts price (INR/kg) Gold price (INR/kg) Waste price (INR/kg)
Physical components	None	None	E-scrap	OldComputers, RefurbishedParts, Gold, Waste
Intrinsic Capability	Able to calculate profit of myself in a particular situation and compare it with (1) a different offer of another agent, or (2) a different possibility that I have in mind.	None	(1) Can learn who are the formal companies in Bangalore, (2) Can learn from the formal companies in Bangalore that he knows what their profit is, and (3) Can calculate what the product quality is of the products that he receives	None
Decision making behaviour	- which workers to hire - whether to fire an employee - which resources to buy with the available of money - negotiation price - decide whether to produce e-scrap or connectorsPWBs - register with the government or not - employ children or not - safe extraction or not - get hired decision - do crystal or not	fine a unit boss or take the bribe	None	None
# agents (model)	200	1	1	1
# agents (reality)	2.000	1	1	

A.4 Operational structure

Table A.7: Action Situations

Situation	Fluctuating prices	Hire workers	Register	Buy products	Crystal project	Treat old computers	Treat refurbishable parts	Treat connectorsPWBs	Sell products	Safety inspection
Roles	WorldMarket	Unit Boss	Unit Boss, Government	Unit Boss	Unit Boss, Professional End Refiner	Segregator, Unit Boss	Refurbisher, Unit Boss	Extractor, Unit Boss	Unit Boss, World Market	Unit Boss, Government
Actions	Prices of products can fluctuate and change in this action situation	• All UnitBosses decide whether they want to hire workers, fire workers or do nothing. • If the UnitBoss chooses to hire, he offers a job, with a certain income. Other WorkerAgents will decide whether they will take the job or not, based on the income. If they do: they become an employee (UnitBoss = No). • If the UnitBoss chooses to fire a worker, he fires a worker that provides the least amount of profit. The fired worker automatically becomes his own UnitBoss (UnitBoss = yes). • A UnitBoss cannot hire workers that are already employed, nor can he hire UnitBosses that have employees.	• All WorkerAgents start unregistered by default. • All UnitBosses can choose to register. They do this if they believe becoming formal is profitable. • If a UnitBoss registers, the Government lists him in at the RegistrationOffice. • If a formal UnitBoss believes it is not profitable being formal, he unregisters, and is removed from the list.	• Buy old computers from WorldMarket • Buy refurbishable parts from other Unit Bosses • Buy connectorsPWBs from other Unit Bosses	• Formal UnitBosses can choose to deal with the ProfessionalEndRefiner • He will consider the possible profit and whether he can pay the salary of his workers during the PayOutTime • If yes, he makes e-scrap out of old computers and sells it to the ProfessionalEndRefiner	Segregators change old computers into refurbishable parts, connectorsPWBs and waste. Employees take the old computers from the recycling unit and give it back after treatment. They receive their salary afterwards.	Refurbishers change refurbishable parts into refurbished parts and waste. Employees take the refurbishable parts from the recycling unit and give it back after treatment. They receive their salary afterwards.	Extractors change connectorsPWBs into gold and waste. Employees take the connectorsPWBs from the recycling unit and give it back after treatment. They receive their salary afterwards.	UnitBosses sell waste, refurbished parts and gold to the World Market.	• The Government goes through his RegistrationOffice (list). He can do inspections on as many UnitBosses as he has InspectionOfficers (number). He chooses them randomly. • He checks the UnitBosses, if they do SafeExtraction or if they have children as employees. • He fines the subjects if they don't do SafeExtraction or if they have ChildEmployment. • The UnitBosses remember how much they were fined the last tick. They use this in their following profit calculation steps.
Costs and benefits		• Benefit for worker: a job and income • Benefit for boss: get employees to do work and possibly more profit	• Benefit for Government: overview of all companies • Possible benefit for companies: easier to make contact with other formal companies	• Getting products for processing	• Benefit for ProfessionalEndRefiner: getting e-scrap, co-operation and profit • Benefit for other companies: earning money for products, possibly having profit • Cost: delayed time for pay out	Benefits: processing the products, giving it value through treatment, to later sell it	Benefits: processing the products, giving it value through treatment, to later sell it	Benefits: processing the products, giving it value through treatment, to later sell it	Benefits: earning money for products, possibly having profit	• Benefit for government: Law enforcement • Cost: fines for non-complying companies
Physical components				Old computers, refurbishable parts, connectorsPWBs	E-scrap	Old computers	Refurbishable parts	ConnectorsPWBs	Refurbished parts, gold, waste	
Institutions		Child employment	Government Registration		Government Registration			SafeExtraction		

A.5 Detailed design

Table A.8: Decision making behaviour

Fluctuating Prices WorldMarket changes it's prices according to formulas

- Change Old computers price according to algorithm
- Change Gold price according to algorithm
- Change Refurbished parts price according to algorithm
- Change Waste price according to algorithm

HireWorkers Unit Bosses can hire or fire workers

- If someone of my family has connectors: look for extractor. If salary affordable, hire. If not, and I am willing to do child labour, search for children. If salary affordable, hire.
- Same happens for refurbishable parts and refurbishers
- Same happens for old computers and segregators
- If my profit has been negative, fire worker with lowest productivity

Register Unit Bosses can choose to register

- All WorkerAgents start unregistered by default
- UnitBosses decide:
  - If my RecyclingUnit is unregistered, and ProfitIfFormal > ProfitIfInformal: Register
  - Government adds RecyclingUnit to List
  - if my RecyclingUnit is registered, and ProfitIfInformal > ProfitIfFormal: Unregister
  - Government removes RecyclingUnit from List

BuyProducts Only UnitBosses can buy products

- if I do CrystalProject, buy e-scrap from other Bosses
  - Price negotiation between buyer and seller
  - Selling party can choose: if I do CrystalProject myself: sell or don't sell
- If I have segregators: buy OldComputers from WorldMarket
  - A RiskyBoss will buy 10% more OldComputers than the sum of the productivity of segregators in his RecyclingUnit
  - An EconomicalBoss will not buy more OldComputers than the sum of the productivity of segregators in his RecyclingUnit
- If I have refurbishers, and if there are other bosses with RefurbishableParts
  - Buy refurbishable parts till it equals sum of the productivity of refurbishers in my RecyclingUnit
  - Price negotiation between buyer and seller
  - Selling party can choose: if I have refurbishers myself: sell or don't sell
- If I have extractors and if there are other bosses with connectorsPWBs
  - Buy connectorsPWBs till it equals sum of the productivity of extractors in my RecyclingUnit
  - Price negotiation between buyer and seller
  - Selling party can choose: if I have extractors myself: sell or don't sell

CrystalProject UnitBosses can make the decision to do the CrystalProject

- If I am formal AND don't do CrystalProject:
  - if ProfitIfCrystalProject > ProfitIfNotCrystalProject
  - Do CrystalProject
- If I am doing CrystalProject:
  - if ProfitIfNotCrystalProject > ProfitIfCrystalProject
  - Don't do CrystalProject
- If I do Crystal, let segregators make e-scrap, refurbishable parts and waste.
- Sell e-scrap to Professional End Refiner
- Pay containerCost per kg
- Receive money after PayOutTime

TreatProducts

- All segregators
  - Turn OldComputers in RecyclingUnit equal to my productivity into RefurbishableParts, connectorsPWBs and Waste
  - Receive salary from Boss
- All refurbishers
  - Turn RefurbishableParts in RecyclingUnit equal to my productivity into RefurbishedParts and waste
  - Receive salary from Boss
- All extractors
  - if SafeExtraction: turn connectorsPWBs equal to my productivity into gold and waste
    - Boss has to pay a sum extra for SafeExtraction (he loses some money)
    - Receive salary from Boss
  - If NoSafeExtraction: turn connectorsPWBs equal to my productivity into gold and waste
    - Receive salary from Boss

SellProducts UnitBosses

- Sell waste to WorldMarket: Receive Money equal to (amount of waste) * (waste price)
- Sell RefurbishedParts to WorldMarket: Receive Money equal to (amount of RefurbishedParts) * (RefurbishedParts price)
- Sell gold to WorldMarket: Receive Money equal to (amount of Gold) * (gold price)

SafetyInspection The Government checks random RecyclingUnits on his RegistrationOffice (list), equal to InspectionOfficers

- If RecyclingUnit has children employed, fine: UnitBoss pays sum of money
- If UnitBoss does not do SafeExtraction, fine: UnitBoss pays sum of money
- The UnitBosses remembers if he was fined, and when. They use this in their following profit calculation steps.

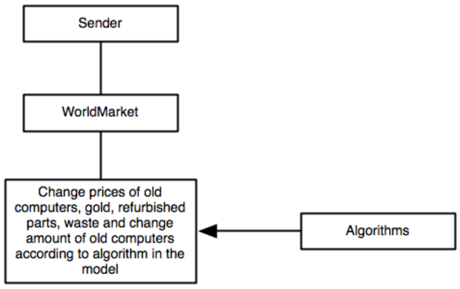


Figure A.1: Action Sequence Diagram of FluctuatingPrices

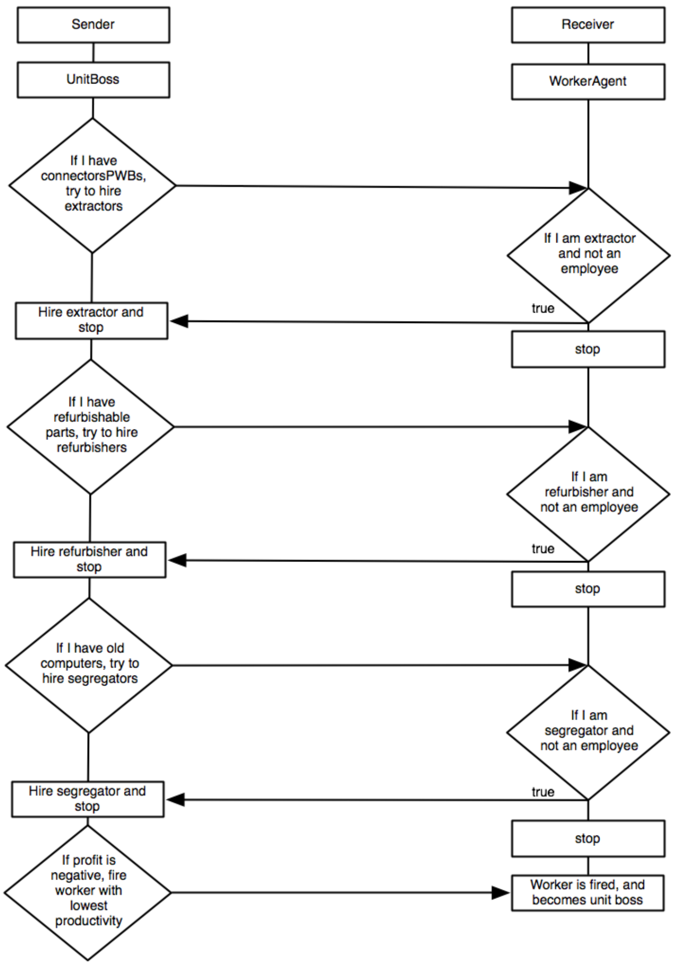


Figure A.2: Action Sequence Diagram of HireWorkers

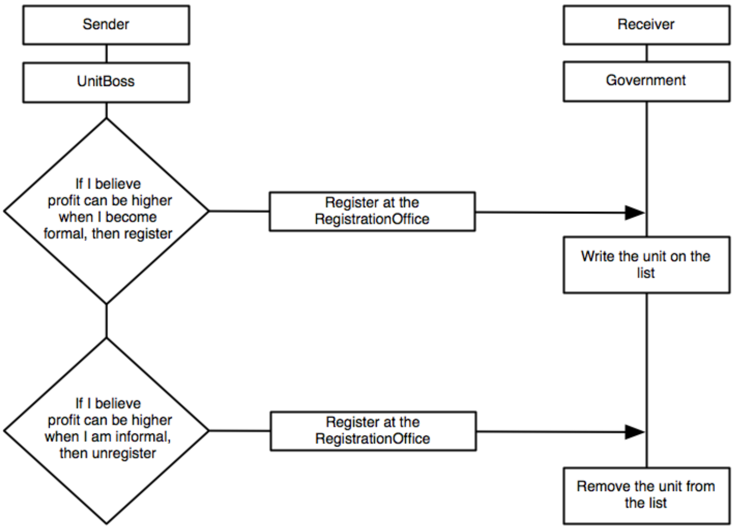


Figure A.3: Action Sequence Diagram of Register

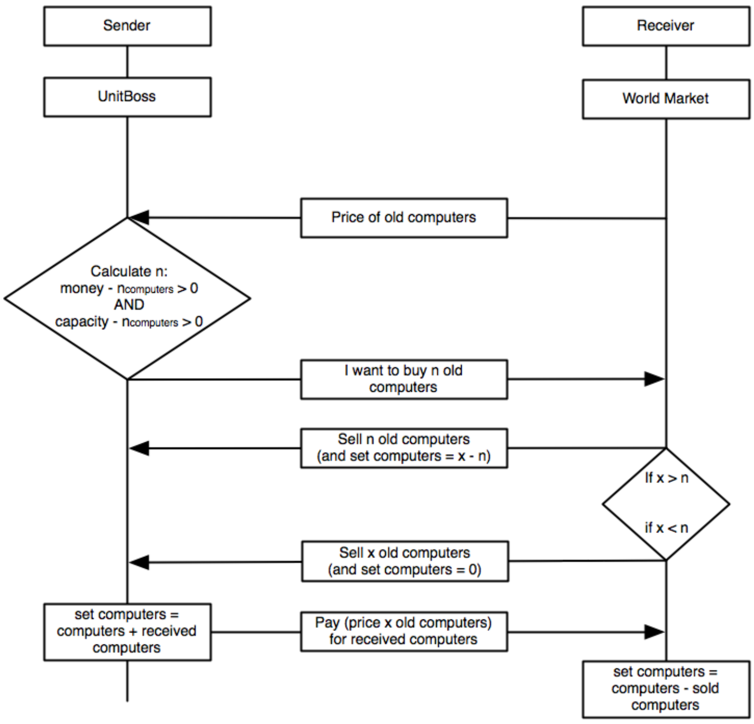


Figure A.4: Action Sequence Diagram of BuyProducts for segregator

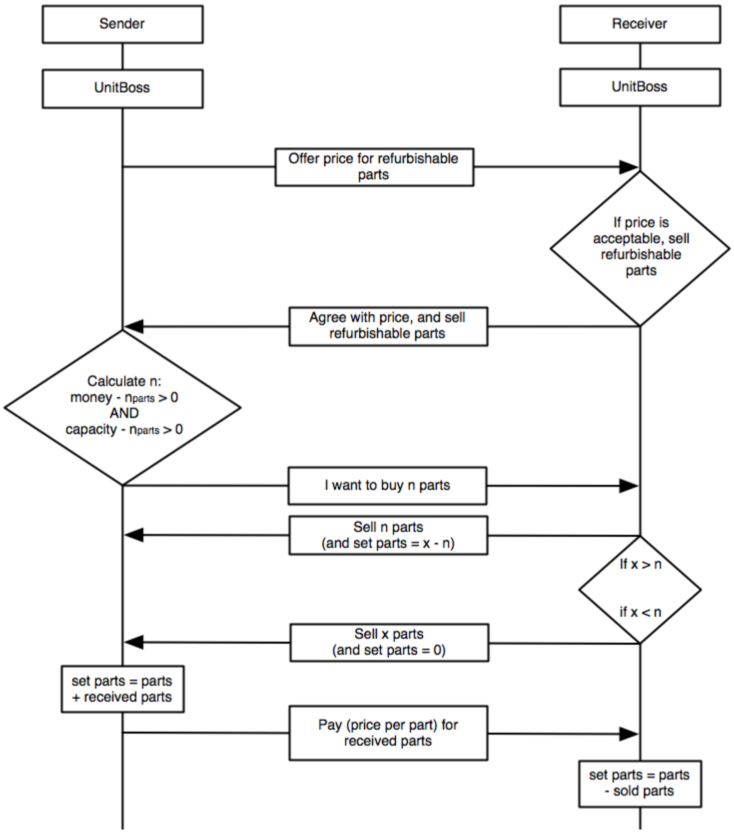


Figure A.5: Action Sequence Diagram of BuyProducts for refurbisher (and extractor)

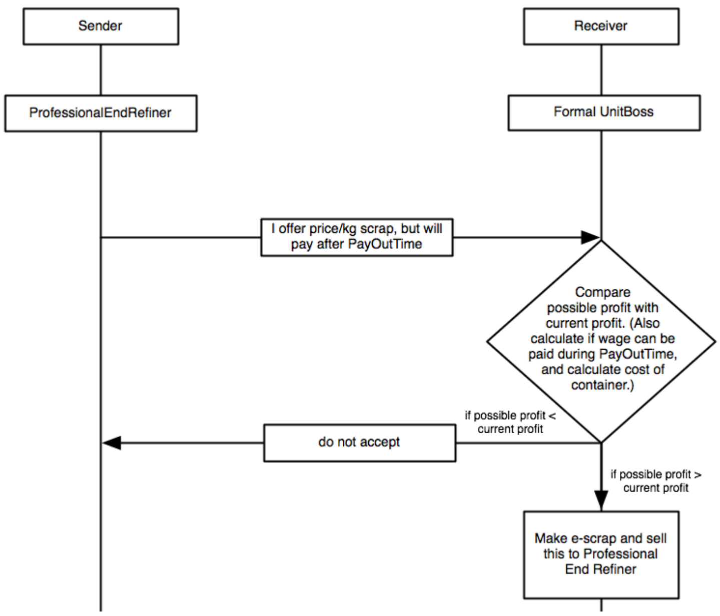


Figure A.6: Action Sequence Diagram of CrystalProject

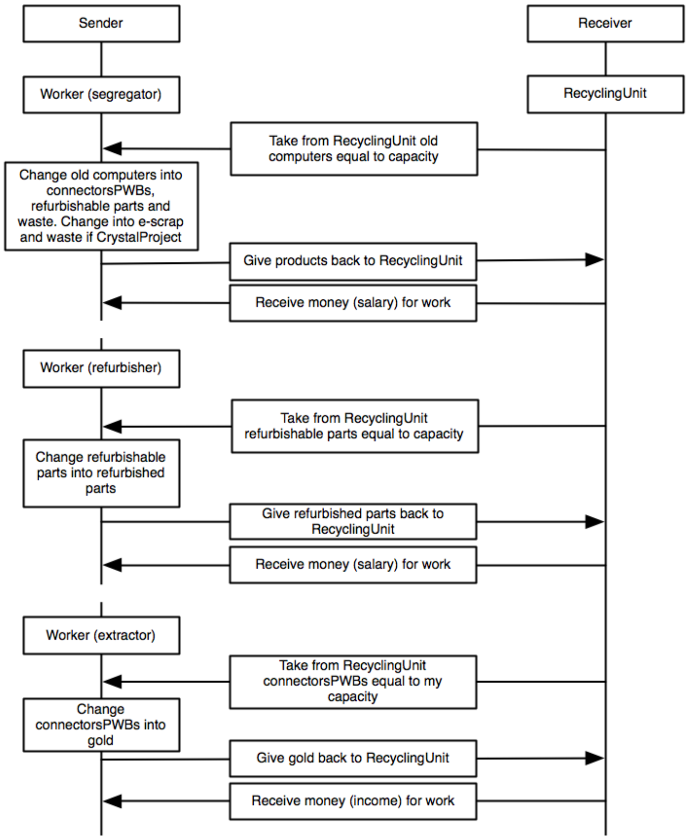


Figure A.7: Action Sequence Diagram of TreatProducts

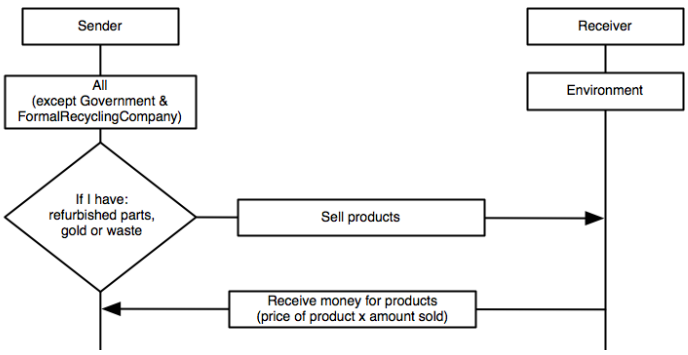


Figure A.8: Action Sequence Diagram of SellProducts

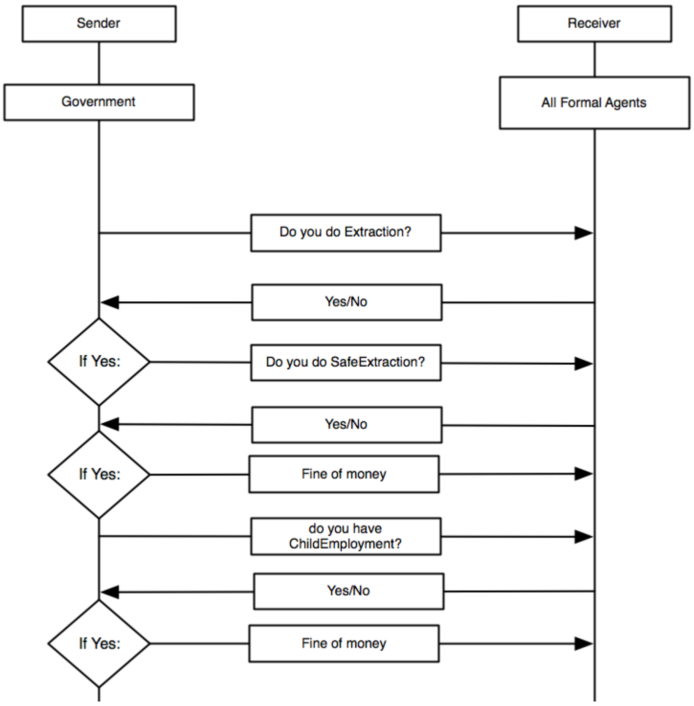


Figure A.9: Action Sequence Diagram of SafetyInspection

Appendix B

Additional graphs of results

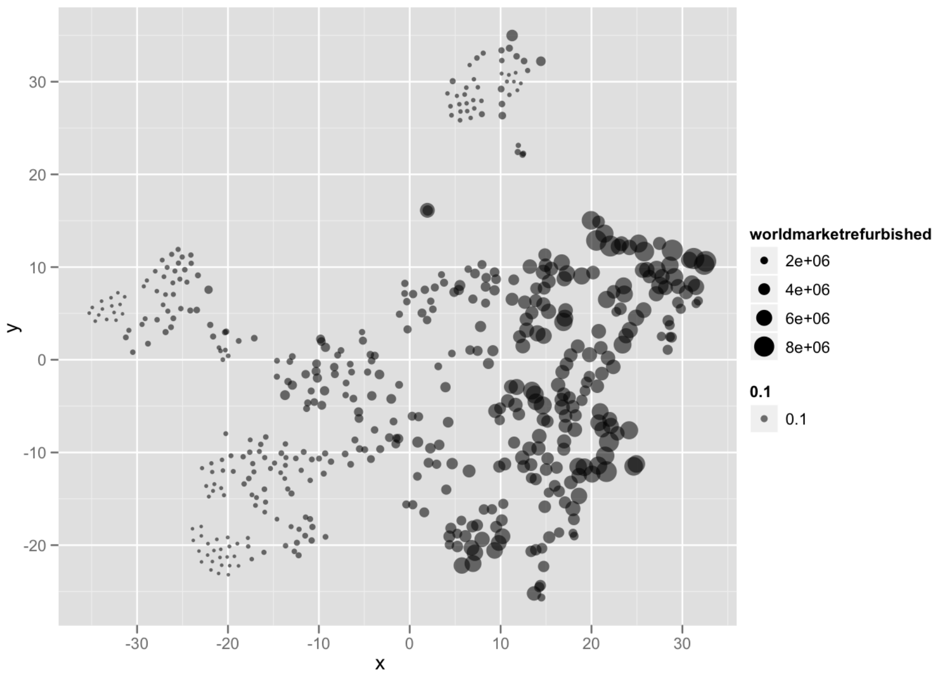


Figure B.1: Refurbished parts sold to World Market, plotted into t-SNE graph.

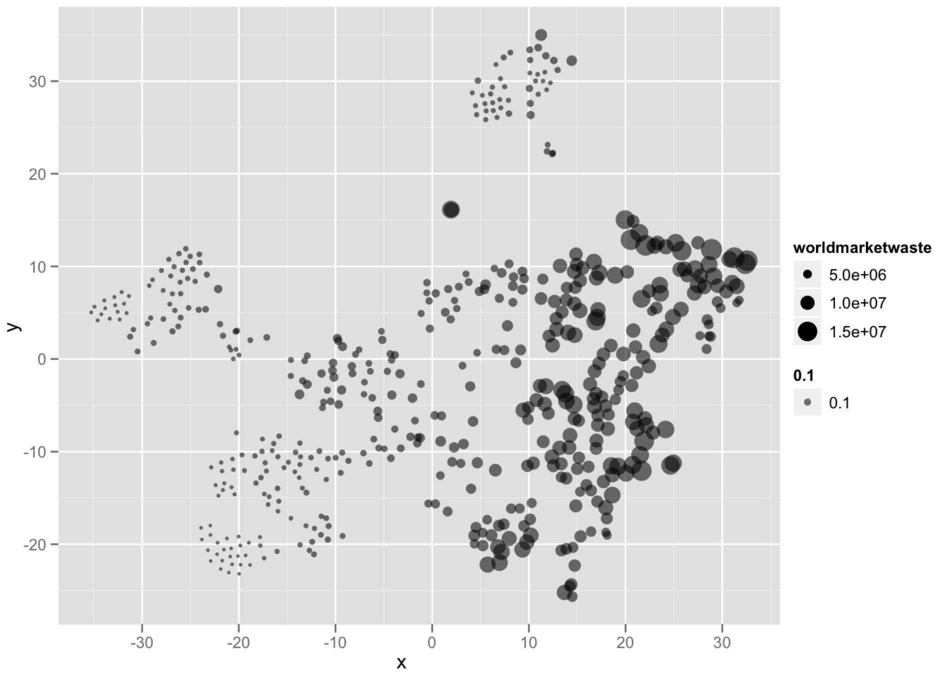


Figure B.2: Waste sold to World Market, plotted into t-SNE graph.

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