Systemic decisions for more sustainable WEEE (Waste Electrical and Electronic Equipment) management in developing countries

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This thesis is dedicated to my lovely Mother, Pili, whose love was my inspiration.
To Jaimito, whose love and companion were my motivation.

Preface & Acknowledgements

Colombia, like all developing countries, has suffered the effects of an unsustainable global development model. The evidence can be found not only in the Latin-American nation's poverty and social degradation, but also in the deterioration of the ecosystem and the pervasive air and water pollution. Throughout my professional career, I have witnessed the deleterious effects of uncontrolled generation and irresponsible disposal of solid waste, including Waste Electrical and Electronic Equipment (WEEE). The lack of awareness, coupled with the rapid increase in consumption of electronic devices, has transformed informal activities, such as recycling, into a source of survival for thousands of people living in poverty. Working with communities has led me to explore the concept of Integrated Solid Waste Management (ISWM) developed by George Tchobanoglous, specifically via a systems approach that primarily focuses on waste management processes. A systems approach, though, implies much more than processes; it requires taking into account different dimensions, stakeholder interests and cause-effect circularity in the short-, medium- and long-terms. Programs designed on the basis of the ISWM may include public awareness and educational strategies; however, for the most part, these aspects have been disjointed of other management elements or, worse yet, not been implemented.

There are several WEEE management guidelines focusing on the implementation of standardized programs, infrastructure and technical solutions in developing countries. Nevertheless, identified negative effects demonstrate that decisions regarding the design of policies and programs must be improved. Decision-Enhancement Studios (DES) that include computer-based simulations as technological tools help to strengthen the systemicity in such processes. In particular, the use of agent-based models and simulation allow policy makers to understand the aggregated behavior of individual decisions of agents on the whole system; for clarity, agents can be consumers, producers or distributors of equipment. Their active participation also increases the knowledge of the system. Likewise, trust among policy makers, which is directly tied to their motivation to cooperated, can be improved using a DES.

This doctoral research has been supported by different organizations, professors, colleagues and friends to which I am very grateful. Professor Rafael Gonzalez advised me throughout the entire process, providing me with key ideas, as well as Systems Engineering tools and instruments to develop the DES design and support the policies designed during the case studies. Professor Claudia Binder helped me secure a grant from the DAAD (German Academic Exchange Service) for a short-term stay at Ludwig-Maximilian University in Munich. Professor Binder also assisted with training in model conceptualization and a framework to describe the contributions of my thesis.

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and the WRF (World Resources Forum); to Empa for financing my two half-year internships and trips through the SRI Project (Sustainable Recycling Industry). Also, I would like to thank all the members of the CARE (Critical Materials and Resource Efficiency) group at Empa for sharing their vast array of experiences in WEEE Management with me and for welcoming me during my visits to Switzerland.

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I was able to implement the agent-based model in NetLogo thanks to the support of the aforementioned Claudia Binder aforementioned and Christian Neuwirth of LMU in Munich; Christof Knoeri of ETH, Mohammad Amandi of KTH in Sweden, and Stefan Holm of the University of Zurich.

I received never-ending inspiration and motivation from members of ELAPDIS (per its acronym in Spanish), Professor Juan Lucena from the Colorado School of Mines, and Professor Markus Schwaninger from the St. Gallen University in Switzerland.

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Acronyms

ABM	Agent-based modeling
A-N	Actor-Network
ANDI	The *Asociación de Industriales de Colombia* per its acronym in Spanish (the Industrial Association of Colombia)
ANT	Actor-Network Theory
CNPML	The *Centro Nacional de Producción Más Limpia* per its acronym in Spanish (the National Cleaner Production Center, Colombia)
Coop4SWEEEM	Cooperation for Sustainable WEEE Management (computer-based simulation)
CPE	*Computadores para educar* per its acronym in Spanish
DES	Decision-Enhancement Studio
DScR	Design Science Research
EEE	Electrical and Electronic Equipment
Empa	The Swiss Federal Laboratory for Material Science and Technology (Switzerland)
FENALCO	The *Federación Nacional de Comerciantes* per its acronym in Spanish (the National Federation of Traders, Colombia)
MADS	*Ministerio de Ambiente y Desarrollo Sostenible* per its acronym in Spanish (The Ministry of Environment and Sustainable Development, Colombia)
NWC	The National WEEE Committee (Colombia)
ODD	Overview, Design concepts, and Details (protocol)
OPP	Obligatory Passage Point
PCP	Post-Consumer Program
SECO	The Swiss State Secretariat of Economic Affairs (Switzerland)
TAM	Technology Acceptance Model
T-T	Technological Tool
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

1.1 The concept of sustainability in solid waste management

The concept of sustainability was first introduced in the area of forestry by H.C. von Carlowitz in 1713 (cited in Hilty and Aebischer, 2015). More recently, it has been linked to “Sustainable Development,” as formalized in the U.N.’s Agenda 21 (U.N., 1993). Furthermore, it has been endorsed in the latest round of global summits and conventions, including Rio+20 in Brazil (2012), the UN Conference of Parties (COP) on climate change in Peru (COP20) in 2014 and in France in 2015 (COP21). At present, several concepts of sustainability coexist, such as corporate sustainability (Marcelino-Sádaba et al., 2015; McManners, 2016), economic sustainability (Martens and Carvalho, 2015) and supplier sustainability (Craig R. Carter and Dale S. Rogers, 2008), among others.

In fact, different organizations have made sustainability part of their corporate and institutional strategies, namely the World Business Council for Sustainable Development (WBCSD), The World Commission on Environment and Development, The Organization for Economic Cooperation and Development (OECD) and The United Nations (UN). These organizations have identified two common characteristics of sustainability: i) a multidimensional approach that integrates social, environmental and economic issues; and, ii) a temporal dimension expressed as “present and future” (U.N., 1993) or “long-term” (Shrivastava, 1995), which implies a cause-effect way of thinking.

As one of the primary causes of global warming, solid waste management (SWM) has recently gained traction at climate change conventions (Christensen et al., 2009; Hilty and Aebischer, 2015; Intergovernmental Panel on Climate Change. Working Group III, 2000). Additionally, environmental problems in urban areas are mainly associated with the degradation of ecosystems and the pollution of air and water, highlighting the need for renewable energy sources in which unsustainable SWM represents both a problem and an opportunity (Hay, L. et al., 2014; Kurdve et al., 2015; Milutinovic, B. et al., 2014; Mirvis et al., 2010). In this sense, the U.N.’s Agenda 21 has already emphasized the extension of solid waste service coverage to all urban and rural areas worldwide (Troschinetz and Mihelcic, 2009). Subsequently, during the Fifth World Urban Forum in Rio de Janeiro in 2010, the management of Waste Electrical and Electronic Equipment(WEEE) assumed its role as a prominent issue within Municipal Solid Waste (MSW) in cities around the world (Wilson et al., 2012). This recognition demonstrates the relevance of WEEE as part of the discussion on urban sustainability, especially in developing countries (Karak et al., 2012; Oyoo et al., 2011). Similarly, during the COP20, the paradigm of Zero Waste was endorsed as a key sustainability strategy (Zero Waste Europe, 2014). Indeed, Heads of State and Government and High Representatives gathered in New York last September (2015) and declared the new Global Sustainable Development Goals (GSDG). The GSDG are constitutive elements of the 2030 Agenda for Sustainable Development entitled “Transforming Our World” (U.N., 2015). The 2030 Agenda includes 17 goals, two of which are specifically aimed at waste management targets (#2:

“Make cities and human settlements inclusive, safe, resilient and sustainable” / # 12 “Ensure sustainable consumption and production patterns”).

Despite these advances, SWM systems have not been consummated in developing countries, resulting in increased public health risks and generating environmental and socio-economic problems (Abu Qdais, 2007; Ezeah and Roberts, 2012; Rathi, 2006; Sharholy et al., 2008). In these countries, institutions that organize territorial planning programs are faced with rapid urbanization and concomitant waste management problems. Moreover, urban planners often make decisions based on economic priorities without consideration of environmental or social variables (Perkoulidis et al., 2011; Zhang et al., 2010; Zurbrügg et al., 2012). To tackle these issues, and simultaneously achieve the objectives set out in the GSDG, studies argue that policy makers and waste management program designers should apply a systems approach, which provides interdisciplinary support involving technical, social, economic, legal, ecological, political and cultural elements (Achillas et al., 2010; Chang et al., 2001; Eriksson et al., 2005; Omran et al., 2009). In the same vein, the concept of transparency has been employed in sustainability to strengthen the participation of stakeholders, thereby addressing two priorities: (i) transparency concerning economic, social and environmental issues, (ii) reporting to stakeholders, actively engaging them and eliciting their feedback in order to *e.g.* improve supply chain processes (Carter and Rogers, 2008).

In addition, an attempt to design more integral solutions for waste management manifested as the theory of integrated solid waste management (ISWM). ISWM focuses on integrating processes (generation, segregation, transfer, collection, treatment, recovery and disposal); it has been widely applied in municipal waste management planning and public policy (Tchobanoglous, 1994; Tchobanoglous et al., 1993). Based on the concept of ISWM, Decision-Support Systems have integrated simulation-based models to study waste generation dynamics (Antanasijevic et al., 2013; Benitez et al., 2008; Maddox et al., 2011), determine landfill allocation (Alves et al., 2009; Antanasijevic et al., 2013; Kollikkathara et al., 2010) and ascertain optimal SWM planning (Yeomans, 2004), among other things.

1.2 WEEE Management in Developing Countries

The European Waste Electrical and Electronic Directive (WEEE Directive) defines Electrical and Electronic Equipment (EEE) as equipment that requires electric currents or electromagnetic fields in order to properly function, as well as equipment for generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1 000 volts for alternating currents and 1 500 volts for direct currents (The European Parliament and The Council on Waste Electrical and Electronic Equipment, 2012). The Directive categorizes WEEE into one of 10 groups: (i) Large household appliances, (ii) Small household appliances, (iii) IT and telecommunications equipment, (iv) Consumer equipment, (v) Lighting equipment (including gas discharge lamps), (vi) Electrical and electronic tools (with the exception of large-scale stationary industrial tools), (vii) Toys, leisure and sports equipment, (viii) Medical devices (with the exception of implanted and infected products), (ix) Monitoring and control instruments and (x)

Automatic dispensers (The European Parliament and The Council on Waste Electrical and Electronic Equipment, 2012).

WEEE has become a pertinent global waste stream due to its high growth rate (Ahluwalia and Nema, 2007). Although this growth rate is especially pronounced in developing countries (Araújo et al., 2012; Herat and Agamuthu, 2012; Ongondo et al., 2011), it is also considerable in the developed world (Premalatha et al., 2013). For example, between 2003 and 2011, 25 of the 50 United States passed WEEE laws (Leigh et al., 2012), and the United States is the largest global generator of Information and Communication Technologies (ICT) waste (Böni et al., 2015). In addition to increasing rates, WEEE is composed of potentially hazardous elements, underscoring the importance of including WEEE strategies in urban sustainability programs (GSMA TM and UNU-IAS, 2015; Przybyla and Pegah, 2007; Widmer et al., 2005).

Hazardous compounds with toxic substances can have public health effects and environmental consequences. These problems are exacerbated in developing countries on account of low-tech recycling and disposal processes, poor operational practices and characteristics inherent to some products and substances upon disposal, as documented in several reports (Duan et al., 2008; Gassara et al., 2011; Hassanvand et al., 2011). Studies performed in Peru, Colombia, China, India, Nigeria and Ghana make it clear that the prevailing—inadequate—recycling operations can engender severe health and environmental effects (Amoyaw-Osei, Y. et al., 2011; Chi et al., 2011; Empa and CNPML, 2008a, 2008b; Espinoza, O. et al., 2008; Ezeah and Roberts, 2012; Sinha-Khetriwal et al., 2005; Thanh and Matsui, 2011; Widmer et al., 2005).

In spite of the hazard presented by some WEEE components, this waste presents an opportunity, for WEEE contains base and precious metals (*e.g.* gold and silver solders), rare earth elements (*e.g.* neodymium in computer hard disks) and other critical raw materials (*e.g.* indium in screens and gallium in mobile phones). These elements can be recovered, yet, in some cases, they are lost in the recycling chain (Herat and Agamuthu, 2012; Reuter and Van Schaik, 2012; Widmer et al., 2005). Developed countries, such as Switzerland (Sinha-Khetriwal et al., 2005), began implementing WEEE collection and recycling programs more than a decade ago. Therefore, the technologies needed to recover valuable materials from WEEE are well-known, and mainly implemented in the industrialized world, while strategies to create citizen awareness about the importance of sorting and recycling waste in developing countries is a much more recent phenomenon.

WEEE Generation Rates and Management Processes in Developing Countries

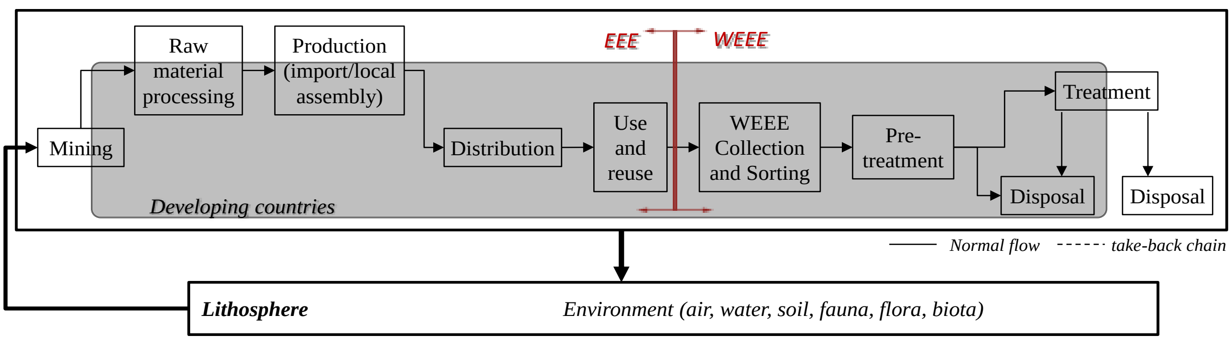
EEE consumption has grown rapidly over the last 5 years in all developing countries. In China, per capita generation (inhabitant per year) of WEEE is around 3.5 kg; in Brazil, around 3.4 kg (Araújo et al., 2012; Swiss e-waste programme and FEAM, 2009); in Colombia, 2.7 kg; and, in Bolivia, around 2.3 kg (Swiss Contact et al., 2009). Recent statistics show that the global quantity of EEE entering the market in 2012 was around 65 million tons and the corresponding WEEE was between 42 and 49 million tons (Böni et al., 2015; GSMA TM and UNU-IAS, 2015). Of the total WEEE generated globally in 2014, roughly 53% was generated in Asia (38%), Africa (5%), Latin

America (9%), and Oceania (1%). WEEE generation in Latin-American countries has been on the rise: in 2009, this figure was rough 2800 kt; in 2014, it spiked to 3900 kt (GSMA TM and UNU-IAS, 2015).

Colombia was the fourth-highest generator in Latin America in absolute terms (roughly 300 kt) in 2014, following Brazil (roughly 1420 kt), Mexico (roughly 910 kt) and Argentina (roughly 310 kt) (GSMA TM, 2015). Taking the example of computers, studies have calculated a global WEEE generation of around 0.3 kg/capita per year; however, in countries such as Mexico, Argentina and Chile, rates are much higher (0.44, 0.49 and 0.42 kg/inhabitant/year, respectively) (Araújo et al., 2012).

A generic scheme of the EEE and WEEE management process cycle in developing countries is shown in Figure 1-1 (below). EEE production in countries such as Colombia refers mainly to equipment imports and, to a lesser degree, the import of (foreign) parts and local (domestic) assembly. Likewise, distribution involves large and small retailers and is divided into new and second-hand (donated, repaired or reconditioned equipment) EEE.

Figure 1-1: Generic WEEE management processes in developing countries. Adapted from (Müller et al., 2014; Streicher-Porte et al., 2009)



Mining activities negatively impact the environment in the form of ecosystem degradation, pollution of natural resources (air, ground and water), in addition to public health problems (Brunner, 2011, 2011). These effects have been largely confirmed in the context of developing countries where informal mining is a pressing issue (Armstrong et al., 2014; Kinyua, 2012). Similarly, the smuggling of low-quality equipment represents a part of imports (production) in developing countries, which increases the amount of WEEE generated given that it must be added to the WEEE exports from the developed world to developing countries. Consequently, urban mining, which is the term for city dwellers' use of WEEE as a material source, has taken on growing importance for material recovery and decreased primary extraction (Simoni et al., 2015).

The use-reuse phase displayed in Figure 1-1 includes both new and used equipment, and the generation of WEEE occurs once EEE is declared obsolete by the consumer. At this juncture, it demands pre-treatment (either repaired or disassembled), with the option of selling or exporting the whole obsolete equipment, breaking it down into parts, disposing of it in sanitary landfills or introducing it into informal recycling processes (this last option is predominant in developing countries).

In order to improve WEEE management, six Latin-American countries have introduced specific legislation; Colombia is one of these six nations. In total, eleven Latin-American countries have begun drafting a regulatory framework (GSMA TM and UNU-IAS, 2015). The majority of these regulations are based on the principle of Extended Producer Responsibility (EPR), which promotes the improvement, in environmental terms, of production and manufacturing systems (Agamuthu and Victor, 2011; Herdiana, D.S. et al., 2014) by placing the responsibility of end-of-life management on producers and distributors. EPR has been extensively applied to EEE in Europe (Khetriwal et al., 2009). According to Lindhqvist (2000), EPR aims to influence production processes in one of two directions (*upstream* or *downstream*): shifting responsibility to *downstream* procedures that involve different actors in collection, recycling and treatment processes; providing *upstream* incentives to producers to incorporate environmental considerations in the design of their products (Herdiana, D.S. et al., 2014), *e.g.* cleaner production or design for recycling (Mayers, 2007).

EPR places the responsibility for equipment on its respective producer(s), including the final disposal of toxic constitutive elements (*e.g.* heavy metals) and the recovery of materials (*e.g.* metals and plastics). Crucially for the case of developing countries, EPR goes beyond the borders of the country in which equipment is produced; responsibility would extend to countries in which equipment is distributed and used. To collect WEEE, producers need communication channels to both consumers and recyclers in order to ensure recycling processes comply with technical and environmental standards. In response to this issue, the reverse logistics chain has emerged a principal strategy, for it entails collection points often located where EEE is sold and at municipal waste collection facilities. Another widely-used structure is the Producer Responsibility Organization (PRO), which employs EPR in a collective scheme of producers, importers and distributors. As of 2007, more than 250 had been established in Europe (Mayers, 2007).

An EPR scheme's success is premised on the identification of relevant actors or stakeholders in the system, in addition to the creation of channels of communication and cooperation. Main (generic) actors or stakeholders at the national level include the environmental authority, the ICT authority, the import/export authority, the industry (producers), distributors and retailers of new and second-hand equipment, recyclers (formal and informal) and, last but certainly not least, consumers. In countries where EPR has been implemented and collective take-back schemes are in place, PRO serves as the bridge between consumers and producers, thus acting as an important stakeholder in its own right.

Two main factors determine the amount of WEEE collected: consumer behavior (Desa et al., 2011; Ongondo and Williams, 2011; Saphores et al., 2012) and physical infrastructure, which, in turn, affects consumer attitudes (which culminate in behavior). Development of physical infrastructure depends on coordination and cooperation among public and private organizations and the existence of a legal framework. It is important to mention that consumers can be households, public (government) or private (industry, schools, universities, etc.) organizations. Common consumer attitudes in WEEE management include: storage of obsolete items at home, transfer to family members, friends or informal recyclers or disposal along with ordinary waste (Fernández P., 2007). Disposal with ordinary waste allows informal waste collectors to glean

WEEE from streets, garbage deposits and landfills (Empa and CNPML, 2010). Factors geared towards boosting consumer participation in formal collection programs include the following (non-exhaustive) list of strategies.

i) The lack of knowledge regarding "best practices" and their positive impact on public health and the environment (Marshall and Farahbakhsh, 2013); the lack of awareness, (Srivastava and Sahu, 2014) stemming from inadequate education and failed transmission of clear information about the possible public health and environmental effects of improper and unsafe WEEE management; the lack of public awareness regarding the responsibility to deliver WEEE to collection points;

ii) Unsatisfied basic needs dictate priorities in each person and/or group (Griskevicius and Kenrick, 2013), not to mention the *Homo economicus* aspect of human beings (Bauman, 2007a, 2007b; Henrich et al., 2005); this is also related to the willingness to pay for formal collection and/or recycling (Marshall and Farahbakhsh, 2013) and the fact that informal recyclers usually pay consumers for WEEE.

iii) At the organizational level, economic considerations drive action, as evidenced by their emphasis on two targets: decreasing taxes on WEEE management (collection service taxes) and reducing cost of EEE purchases (*e.g.* cheaper equipment regardless of quality relative to price).

iv) For both types of consumers (individuals and organizations), physical accessibility is a determinant; this refers to collection point locations, which should be easily accessible for consumers (Srivastava and Sahu, 2014)

As for the second factor (infrastructure), post-consumer strategies have been implemented in some developing countries. However, studies in various countries reveal the inadequate progress of these strategies in urban areas and their virtual inexistence in rural areas (Amoyaw-Osei, Y. et al., 2011; Chi et al., 2011; Empa and CNPML, 2010, 2008a; Espinoza, O. et al., 2008; Ott, 2014; Sinha-Khetriwal et al., 2005).

At this point, other WEEE management actors should be broached. One of the main barriers to implementing collection and management strategies in these countries has been the lack of coordination and cooperation among public organizations and between public and private institutions. The dissemination of regulations and public policies could help achieve necessary stakeholder participation, but this needs to be complemented by control instruments in the hands of the relevant authorities. Furthermore, public policies are usually designed (and passed) by only one authority (generally the environmental authority), despite the fact that the complexity of the system demands inter-sectorial cooperation. In order for such cooperation to be effective, multi-sectorial public policy is required (*e.g.* involving ICT, education and public health authorities).

1.3 Statement of the Problem, Objectives and Research Questions

WEEE Management may be characterized as a typical socio-technical system in that it relies on technical artifacts to achieve material goals; however, it is also strongly affected by several (human) actors' behaviors and decisions. As previously mentioned, the growing population, increasing consumption patterns, and introduction of new technologies in developing countries have brought about the rapid escalation of WEEE quantity.

The main causes of ineffective WEEE management are poor or absent infrastructure in cities, small municipalities and rural areas and deficient coordination and cooperation among actors. The latter, coupled with the first cause, results in meager amounts of WEEE collection via the established network.

Colombia has recently begun to design and implement a national WEEE management system founded on EPR, *i.e.* aimed at forcing producers, importers, distributers and consumers to assume responsibility for the end-of-life management of their technological equipment. To meet this goal, the participation and inclusion of all actors in the entire take-back process is obligatory. In effect, the implementation of this system requires consensual decisions and strategies designed to impact every actor in the reverse supply chain. Additionally, EPR entails the implementation of infrastructure to collect WEEE from consumers with active distributor participation and the design of infrastructure for the transport, storage and treatment of this waste.

The lack of a systems approach in decision-making processes is one of the main hurdles to effective waste management, as evidenced by an analysis of this socio-technical system, an extensive literature review, a case study and the author's own experience. A non-systems-based approach translates into a lack of coordination among stakeholders and results from a failure to design and implement sustainable education strategies. A simulation-based approach may help close the identified gap; as decision-support systems, simulation-based models have been applied in decision-making in waste management, though the "optimization" of processes is suggested, which cannot be expected of socio-technical systems because learning processes for human actors are required to achieve (more) sustainable management.

Taking into account the concepts of sustainability and systems, the present research proposes including four components in a systems approach to decision-making: (i) multiple dimensions of the problem; (ii) targets of the different stakeholders; (iii) processes within WEEE management; and, (iv) circular cause-effects of current decisions in the short-, medium- and long-term. Specific dimensions, actors and stages considered relevant to attain a more systemic decision process are discussed in the development of this research.

Based on the issues described in the previous sections, this doctoral thesis enhances systemicity in decision-making policy designed to increase sustainability in WEEE management—specifically for developing countries—using the design of a Decision-Enhancement Studio (DES). Therefore, this research also contributes to the solution of the principal issues related to policy decisions.

The two main research questions are formulated as follows:

RQ1: How can we design decision enhancement studios to support policy makers in the creation of sustainable WEEE Management programs in developing countries?

RQ2: What are the essential elements needed to enhance systemicity in decision-making for WEEE management?

1.4 Research Methodology and Contributions

The methodology employed to answer the two research questions above implies three facets: philosophy, strategy and techniques.

1.4.1 Research Philosophy

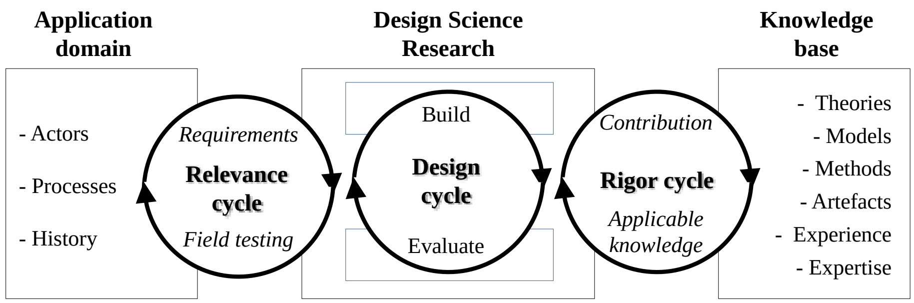
The main goal of this doctoral research is to enhance systemicity in policy-related decision making with an eye towards fostering sustainable WEEE management in developing countries through the design of a decision enhancement studio. From a philosophical point of view, research must account for the nature of the problematic situation. According to Kroes (2012), socio-technical systems refer to "hybrid systems consisting of elements of various kinds, such as natural objects, technical artefacts, human actors and social entities and the rules and laws governing the behavior of human actors and social entities" (Kroes, 2012). Seeing as WEEE management involves the aforementioned elements, it can safely be considered a socio-technical system, above all because it demands technical artifacts to achieve goals such as EEE distribution, WEEE collection and recycling of implementation of public educational strategies designed to boost responsible consumption. WEEE management is also deeply affected by human attitudes and the decisions of several social actors, who play different roles within the management processes (Figure 1-1) and decision-making processes related to planning, designing and implementing programs and public policies.

The socio-technical nature of this research does not reduce the world to pure human knowledge or the empirically-observable and quantitatively-measurable. Rather, the philosophical apparatus used to support this doctoral research is critical realism (Mingers et al., 2013). Thus, in answering the research questions from a holistic and systems-based approach, critical realism is important insofar as it offers a profound understanding of the real world via the recognition and discovery of the system (real world) of each actor that influences the system's dynamics, in addition to accounting for the differences between the actors' perceptual and theoretical lenses (Mingers, 2015; Mingers et al., 2013).

1.4.2 Research Strategy

Engineering can be classified as an applied science, and design is a constitutive part of an engineer's core professional activities (Meijers, 2008). Engineers approach the world as agents of change in an effort to adapt the world to the practical needs of humans by virtue of problem-solving processes (Kroes, 2012; Simon, 1996). This distinguishes them from researchers, who approach reality as spectators, discoverers or theorists in the world (Kroes, 2012). This is coherent with Hevner's Design Science Research (DScR), which improves organizational practice by developing innovative technological solutions, models or methods (Diggelen, 2011; Hevner, A.R., 2007; Hevner, A.R. et al., 2004). In the DScR strategy, knowledge and understanding of the problematic situation's domain, as well as its solution, are achieved in the construction and application of the designed artifact (Hevner, A.R. et al., 2004). Hevner's proposal links relevance and design with rigor as part of the progressive problem-solving process involved in the strategy that constitutes the methodology employed herein (Figure 1-2).

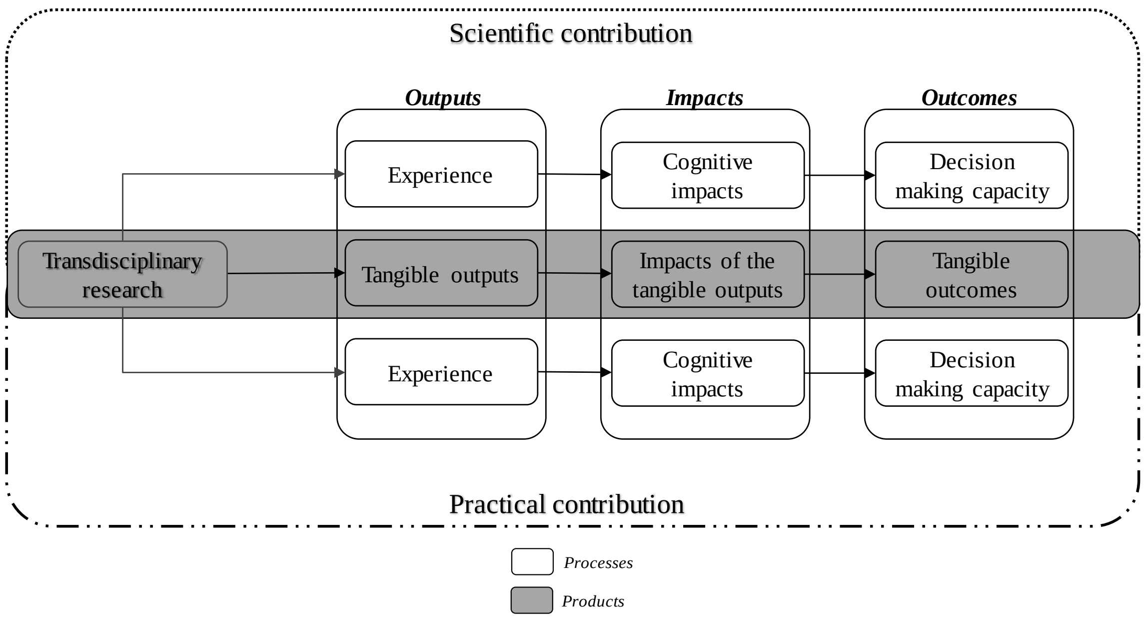
Figure 1-2: Design Science Research cycles. Adapted from (Hevner, A.R., 2007; Hevner, A.R. et al., 2004)



Design in engineering responds mainly to the design cycle in Figure 1-2. However, within DScR, design is not only developed iteratively, but is also tied to the following cycles: the context-based identification of requirements as part of the relevance cycle to define design inputs and, within the cyclical process, field testing of the design, which causes changes in the requirements, the design and the context itself. To support design, applicable knowledge (*e.g.* theories, methods and models) is taken from the knowledge base ("Rigor Cycle" in Figure 1-2) and the design process creates new knowledge that expands the pre-existing knowledge base.

An important element of the DScR is the scientific contribution (see Figure 1-2). Due to the fact that this research tackles a real-world problem, combined with the fact that WEEE management involves several actors inside and outside of academia, understanding the problem requires identifying actor participation for the relevance and design cycles. What is more, the strategy that constitutes the methodology employed herein applied facilitates mutual-learning processes and allows for the creation of solution-oriented knowledge that generates both practical and theoretical results. Together, these characteristics highlight the importance of employing a transdisciplinary approach to the solution of real-world problems (Lang et al., 2007). According to Binder (2015), transdisciplinary projects deliver contributions at the following three levels (see Figure 1-3): outputs (short-term), impacts (medium-term) and outcomes (long-term). Within the outputs, contributions can be tangible, *i.e.* publications, workshops, reports, etc. or intangible, *i.e.* methodological, organizational or social experiences. As for the impacts and outcomes, contributions can be tangible, *i.e.* actions, decisions, plans, etc., or intangible, *i.e.* forms of knowledge (system knowledge, target knowledge or transformation knowledge) or system changes, which might not be easily attributed to the project alone (Binder et al., 2015).

Figure 1-3: Conceptual framework used to structure self-reflection and present contributions. Adapted from (Binder et al., 2015)



Validation was performed throughout the research process using triangulation with multiple instruments. To validate tangible and intangible research contributions (Figure 1-3), the methods applied included textual and photographic reports of workshops and meetings, as well as expert interviews to validate the agent-based model (ABM), experiments to evaluate computer-based simulation and the application of the Technology Acceptance Model (TAM) to validate the decision-enhancement studio, which incorporates a "studio" as the main facilitative environment for decisions and a set of technological tools (Keen and Sol, 2008). Intangible contributions were also validated through the dialogical analysis of documents (products) and open-ended questions in surveys included in the instruments for validating products. The detailed methods applied are described below.

1.4.3 Research Techniques

Critical realism recognizes the existence of different types of objects of knowledge (*i.e.* physical, social and conceptual); as a result, it necessitates a wide range of research methods (Mingers et al., 2013). Developing the relevance-design-rigor cycles in this doctoral research (focused on design), in line with critical realism, meant applying multiple techniques in the form of diverse methods, instruments and tools. These research aspects are outlined in the following paragraphs and described, in-depth, in Chapters 2, 3, 4 and 5. Before proceeding, it is important to clarify that all of the techniques applied were culled from the knowledge base shown in Figure 1-2.

A starting point to gauge the current state of WEEE management in developing countries (application domain), an exploratory multiple-case study was conducted, which helped study current phenomena in a real-world context (Maguire et al., 2010; Yin, 2003a, 2003b). Doing so led to the design requirements (Figure 1-2). The specific case study is embedded, for it includes two units of analysis (Yin, 2003b): the first unit is WEEE management in Colombia (country-level), while the second is WEEE management on the Pontificia Universidad Javeriana's campus in Bogotá, Colombia. This university-level analysis complemented findings related to the country's system. Data collection mainly involved participant observation (Platt, 1983), structured interviews (Briones, 2003) and document review (*i.e.* assessments, studies, and official reports).

From there, Actor-Network Theory (ANT), proposed by Michael Callon (1986) and Bruno Latour (2005), was used to analyze case study data in order to define the artifact's design requirements. ANT is a conceptual framework for exploring socio-technical processes, and it utilizes a set of concepts known as infra-language to look for symmetry between human and non-human actors or *actants* in networks (Correa-Moreira, 2011). This theory has widely applied to studies on the relationship between technology and society. One indicative example is the analysis of the role of the main information system within the National Science and Technology System (Rafael A. Gonzalez, 2010) or the study of the network dynamics of e-government implementation in developing countries (Stanforth, 2006). In human-environment systems, analysis that includes non-human actors is endowed with added relevance given that it identifies the effects of regulatory mechanisms, among other aspects (Scholz and Binder, 2004). In the same vein, ANT proves useful when it comes to understanding the role of laws in the dynamics of complex environmental systems (Méndez-Fajardo and González, 2014). In short, ANT was used, in conjunction with the participation of interviewees, to define historical milestones related to actors, relationships and the dynamics of agreements.

As part of the design cycle (Figure 1-2), the definition of system boundaries was the next step in the design of tools to support decisions within the DES. Consequently, boundaries were defined as the most urgent decision (Keen and Sol, 2008) or the focal subsystem within the problematic situation. This process was based on structured interviews with the relevant actors and took the location and the links with the system as a whole into account. In effect, the previous process enabled workshop participants to reflect on topics that went beyond the limits of the simulated subsystem.

Having gone through the previous steps, the conceptualization of an agent-based model and its implementation as a computer-based simulation were carried out. The ABM was designed using the Overview, Design concepts and Details (ODD) protocol (Grimm et al., 2010; Müller et al., 2013). ABM design took exploratory case study findings and information from the literature review into consideration. Here, it should be mentioned that the empirical data obtained in the case study required the complementary implementation of a survey. The purpose of this survey was to understand consumer behaviors (as part of the WEEE management system); it was duly included in ABM design. The evaluation of the ABM was made using sets of experiments with different scenarios in the model implemented in NetLogo 5.2.0. In order to ensure the best results of the

DES, both the ABM and its implementation as a simulation-based model in NetLogo 5.2 were iteratively validated prior to the DES.

All steps described above were validated and evaluated by triangulation using different instruments, in particular structured interviews with experts, experiments and the dialogical analysis of discussions, questionnaires and documents. Thus, the validation of the DES as the main designed artifact was done with TAM (Davis, 1993; Rigopoulos et al., 2008), expert interviews and experiments. TAM uses the Likert scale, which ranges from "strongly disagree" to "strongly agree" for different constructs related to the artifact to be validated. The detailed questionnaire is described in Chapter 4. Validation forms part of the design cycle (Figure 1-2), though some experts involved in the validation process were concurrently relevant actors in WEEE management, so the specific validation of simulation and of the DES (the artifact) were performed not only for the design cycle, but also for the application domain or relevance cycle in Figure 1-2.

In addition, the weighted sum method used in the design of the multi-criteria decision-making tool has been widely utilized in research related to the decisions field and, therefore, was not individually validated. Nevertheless, the experiments to verify the implementation of ABM also included the evaluation of the relations between the defined criteria and the prioritization of alternatives. Furthermore, a pertinent open-ended question was included in the expert interviews applied before the DES.

Finally, it is important to point out that the experts involved in this research fell into one (or more) of three main fields: WEEE management, agent-based modeling and decision-making sciences.

1.4.4 Research Outline

Firstly, to define this doctoral research's general objective and questions, Chapter 1 explores the key issues in WEEE management within the context of developing countries as part of the relevance assessment. From there, the methodology (in terms of approach, strategy and techniques) is described (rigor cycle).

Secondly, as part of the relevance and design cycle, Chapter 2 explains the exploratory case study structure and main findings through the lens of Actor-Network Theory (ANT).

Chapter 3 presents the design cycle is presented. This chapter develops the DES design as the product of the decision-enhancement studio, the design of the ABM and its implementation as a computer-based simulation and the multi-criteria decision making tool. This Chapter also presents the DES implementation and main findings.

Chapter 4 lays out the validation of the DES and presents the main findings arrived at via the validation instruments.

Chapter 5, the Epilogue, summarizes the contributions made by this doctoral thesis in terms of outputs, impacts and outcomes (see Figure 1-3). Chapter 5 also directly answers the research questions proposed in this section, traces courses of possible future investigation and details reflections related to the methodology employed herein.

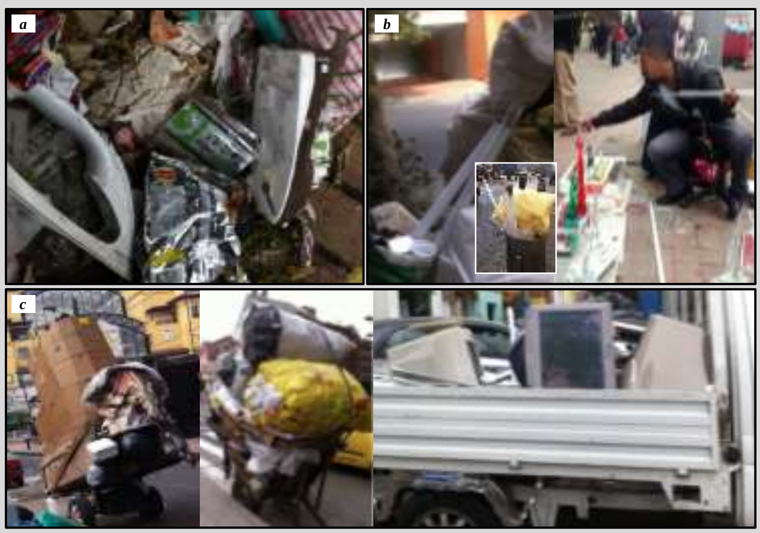
2 Problematic situation: The unsustainable WEEE Management in Developing Countries

2.1 Introduction

Vignette: WEEE Tells Us Stories

Clean, pressed clothes: Strolling through a Bogotá park, appreciating the birds and trees, I found this waste lying on the street (*a* -- Figure 2-1). The image of two families immediately came to mind. The first enjoyed some comfort, as they were able to care for their clothes. Surely, a maternal figure lovingly ironed and added pleasant scents for her children or husband; this loving matron did not know how to properly dispose of her iron after it stopped working, so she discarded it along with ordinary waste. Here, the second family came into play: informal recyclers who earn a scant income for food and therefore have become experts at identifying valuable objects among WEEE. They removed elements with resale value from the iron before continuing on their way, searching for more items of value in all corners of the neighborhood.

Figure 2-1: WEEE scenarios in Colombian streets



Changing light bulbs and ingenuity: Although there are post-consumer programs designed for their collection, bulbs and lamps are commonly found on the streets of Bogotá (*b* -- left side). The most shocking result of such WEEE mismanagement is meeting artists who, in a wonderful display of Colombian ingenuity, create beautiful ornaments by heating tubes and blowing into them. However, they are blind to the presence of mercury and directly absorb the heavy metal (*b* -- right side). Unsatisfied basic necessities mean that informal recycling, an unimaginably arduous task, represents the sole source of survival for more than 13,000 inhabitants in Bogotá. As in the case of the aforementioned artists, I was astonished to observe what were essentially "mobile buildings" made of recyclable materials collected by only one person (*c* -- left side and middle). More than just Colombian idiosyncratic creativity, and caused by myriad reasons, objects take on a profound meaning in Colombia. To give just one example, it is not unusual to find obsolete fridges that have been with a family for more than 30 years, despite functioning exclusively for non-refrigerating purposes, *e.g.* a closet. In the same vein, TVs and computer screens so old that they could be in a museum remain a fundamental part of households. Fortunately, current WEEE collection campaigns have begun to ensure that these objects do not become sources of pollution … however, potential damages to the health of informal recyclers still exist (*c* -- right side).

As described in Chapter 1, although some developing countries have introduced legal frameworks for managing Waste Electrical and Electronic Equipment(WEEE), several studies have cited inadequate recycling operations as prevalent sources of severe health and environmental effects. To tackle these issues, policy makers should design strategies from a systems-based approach that takes the following elements into account: i) different dimensions of the problem; ii) targets of the different stakeholders; iii) processes within WEEE management; and, iv) circular cause-effect relationships stemming from current decisions in both the short-, medium- and long-terms. The failure to rely on a systems approach represents one of the main hurdles to effective waste management; this hurdle is primarily distinguished by a lack of coordination among stakeholders in addition to a lack of design and implementation of sustainable education strategies.

In order to identify the requirements for designing a decision-enhancement studio (DES) to foster systemicity in policy-oriented decision-making in the context of developing countries, this chapter explains the methods utilized for the setting and development of an exploratory case study. Also, in an effort to better understand the context of the research problem, the results obtained from this case study are presented in terms of Actor-Network Theory (ANT). Likewise, the principal findings are discussed to ascertain the requirements for designing more sustainable WEEE management programs.

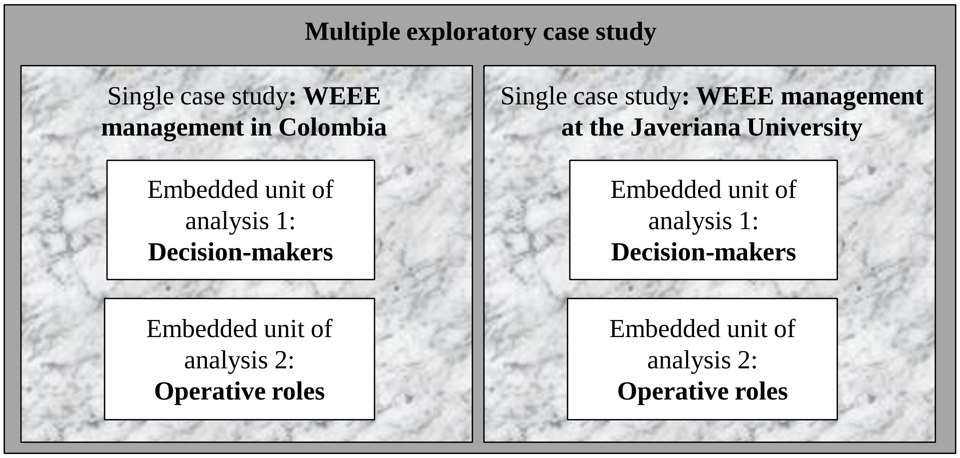
2.2 Case Study Setting and Methods

To study the current state of WEEE management in the context of developing countries, an exploratory multiple-case study (Yin, 2003a, 2003b), composed of two single-cases, was developed, as follows: The WEEE management in Colombia, South America, and the WEEE management at the Pontificia Universidad Javeriana in Bogotá, Colombia. The second study consists of a single-case in the context of Colombia and a single-case at the Pontificia Universidad Javeriana. The Pontificia Universidad Javeriana is located in Bogotá, Colombia's capital and largest city; the campus population can be considered a scale model of a city in a number of aspects: population (the Pontificia Universidad Javeriana's population is roughly 22,000 people), the community's civic behavior (citizens), governmental structure, administrative budget and budget for investment in infrastructure (Armijo de Vega et al., 2008; Bialowas et al., 2006; Jain and Pant, 2010; Maldonado, 2006); in addition, the campus contains natural resource management and waste generation and management dynamics, among other aspects, that frame it as a scale model.

As recommended by Yin's method, the present case study includes the following four components.

First, it is embedded, that is, it includes two units of analysis (Figure 2-2). One is related to decision makers, while the other corresponds to operational roles within the system.

Figure 2-2: Units of analysis in the exploratory case study. Adapted from (Yin, 2003b)



Second, the following questions guided the exploratory case study and helped identify the requirements for designing a DES to support more sustainable WEEE management:

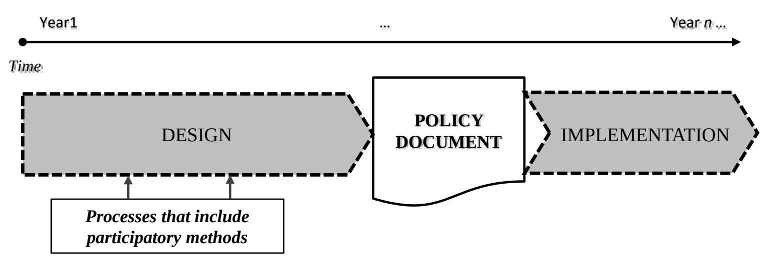
(i) Have decision-makers implemented a systems approach in their decisions?

(ii) Is there an organized operational structure for WEEE management?

(iii) What elements have triggered improvements in WEEE management?

In addition to the review of documents (which included assessments, studies, and reports), decision makers and operative roles related to WEEE Management were incorporated in the participatory policy design in both single-case studies: with regard to the national level, this meant policy design for WEEE management; with regard to the university level, Javeriana's environmental policy included WEEE management. The specific design methods for the two policies are detailed in Appendix C and D.

Figure 2-3: General policy design methodology



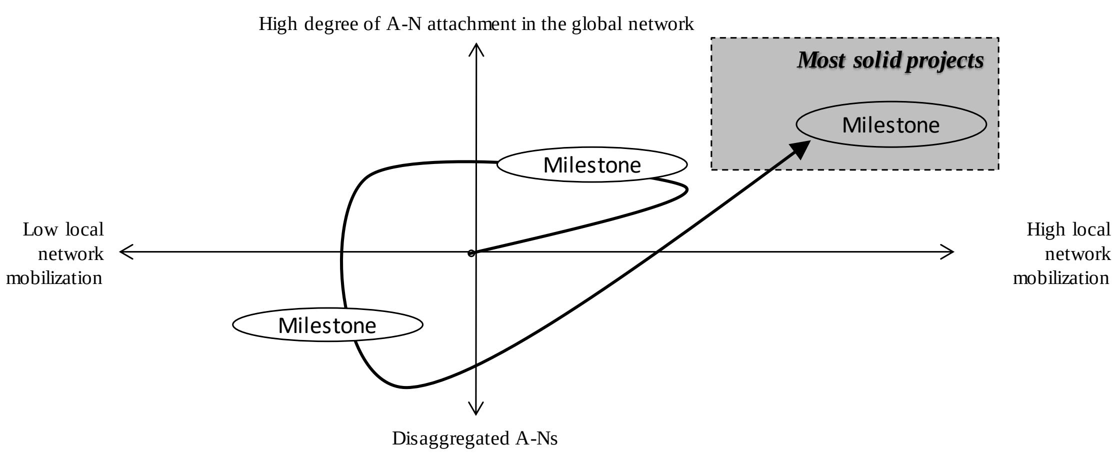
Likewise, actors and processes in committees and technical (operative) groups were observed and assessed via structured interviews; the interviews are detailed in Appendix E. Decision-makers at the Pontificia Universidad Javeriana were not the only ones in charge of managing economic resources at the organizational level, for actors inside University Faculties, *e.g.* deans, directors and even researchers, were also granted this responsibility. Therefore, instead of relying on structured interviews, forms were sent to key figures—past and present deans and department heads—to ascertain the relevant case history and construct a list of milestones later validated by decision-makers.

The third component of this case study consisted of using ANT to interpret the collected data. ANT proved valuable for determining relevant facts, actor-networks (A-N), relationships and agreement dynamics based on historical milestones. In this study, the four constitutive elements of ANT were defined as follows:

- The *Obligatory Point of Passage (OPP)* corresponds to the focal A-N that mobilizes the system by virtue of its power to establish local networks or impose actions on A-Ns in order to meet specific interests.
- The *local network* entails A-Ns with clear interactions that stabilize the system and thus allow for the emergence of milestones.
- The *global network* consists of A-Ns not actively participating in policy decisions despite the fact that they should. A global network also includes A-Ns capable of interfering with the system or impacting the local network when the OPP is weakened. Local network A-Ns can directly interact with global A-Ns.
- *Translation* explains the dynamics between local and global networks by describing the A-N alignment of interests and focusing them on inducing successful action. Translation can be understood in terms of the following "moments" in each milestone: *problematization* or how to become indispensable, *interessement* or how the allies are locked into place, *enrolment* or how to define and coordinate roles and *mobilization* or how the principal A-Ns borrow the force of more passive ones and turn themselves into the representatives or spokespeople of these more passive A-Ns (Callon, 1986a).

The main results of applying ANT are illustrated in the mobilization graph (Figure 2-4). Figure 2-4 helps visually track A-N relationships by presenting a timeline, episodes and milestones as they pertain to, on one hand, the degree of attachment of an A-N in global network and, on the other, the level of local network mobilization. For more information, readers are directed to the results in Section 2.3.2.

Figure 2-4: Graph of A-N mobilization in local and global networks. Adapted from (Méndez-Fajardo and González, 2014; Stanforth, 2006)



As the previous figure illustrates, the *most solid project* is that for which both the highest degree of attachment of A-Ns in the global network and the highest local-network mobilization occurred. Solid projects are ones in which all actors' interests are strongly aligned; as a result, solid projects generate *projects* in the form of programs, strategies, actions, facts or documents.

Finally, from the design's inception, the prior conceptualization of a "system-based approach" for each stakeholder was noted in detailed forms that reported on semantics and were used to demonstrate conceptual changes that took place later as part of the results.

2.3 Case Study Findings

2.3.1 WEEE Management in Colombia

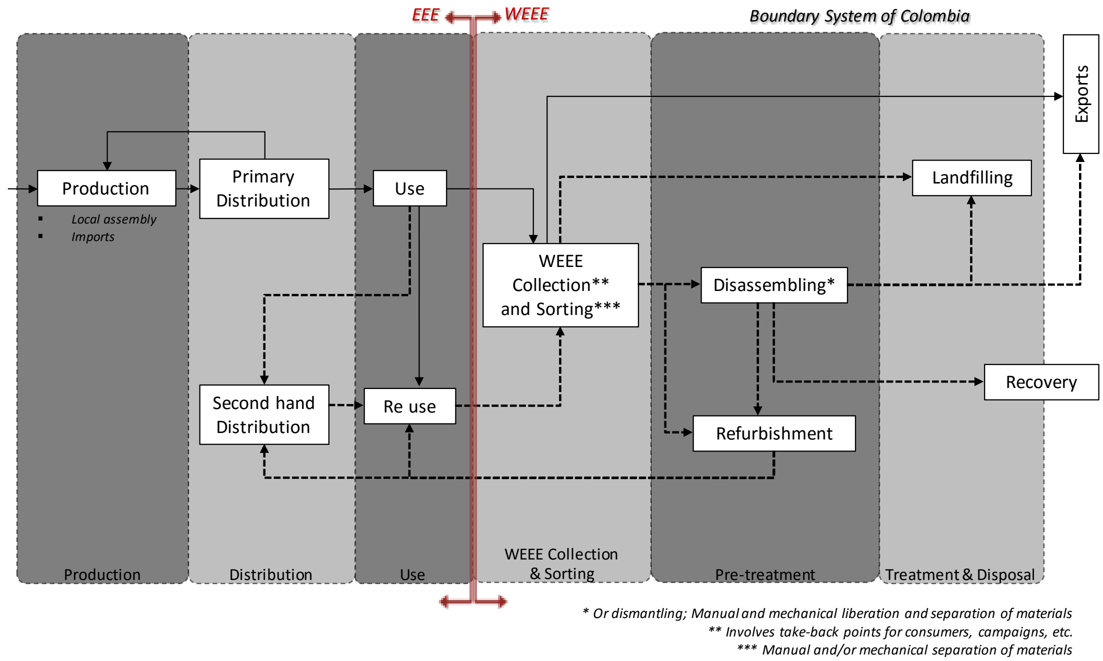
Processes

The total WEEE generated by all world regions in 2014 was 41,800,000 tons, of which 53% was generated in developing countries (GSMA TM and UNU-IAS, 2015). Colombia, a developing country, has around 48.5 million inhabitants, 76% of whom live in urban areas (DANE, 2016) where the largest amounts of WEEE are usually generated. Assessments indicate that in 2013, the generation of WEEE in Colombia was around 120,000 tons. WEEE generated in the country includes large household appliances (24%), IT and telecommunications equipment (17%), consumer equipment (38%), lighting equipment (13%) and batteries (8%) (Pronet, 2013).

The per capita generation of WEEE in Colombia has increased from 3.7 kg/inhabitant in 2009 to 5.3 kg/inhabitant in 2014 (GSMA TM and UNU-IAS, 2015). In order to determine the urban per capita generation of WEEE, it is important to account for the six different socioeconomic levels in the country: low-low (22.2% of the total population), low (41.2%), medium-low (27.1%), medium (6.4%), medium-high (1.9%) and high (1.2%) (Ministerio de Hacienda y Crédito Público et al., 2005).

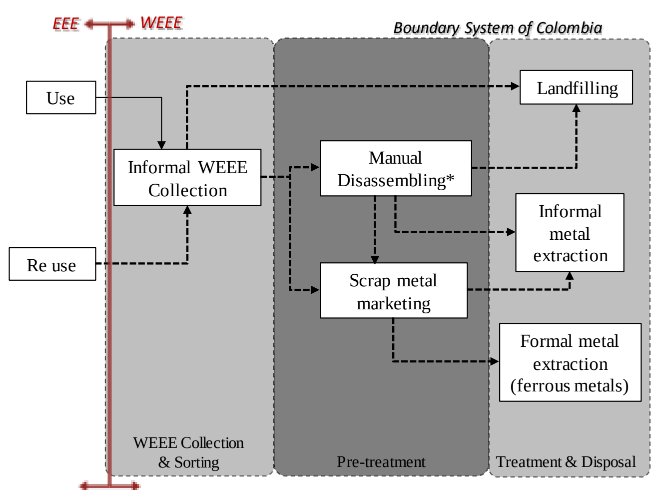
Generic processes related to WEEE management are shown in Figure 2-5. In the figure, production refers to international manufacturers and importers of EEE, as well as local (national) assemblers, which make up less than 10% of the total. Primary distribution refers to the sale of the new equipment—imported or locally assembled directly by the companies that produce them, or by large and small distribution chains. When obsolete EEE is discarded, it becomes WEEE. Some materials obtained in the pre-treatment stage are recovered locally or disposed of in local (regional) landfills, while some fractions resulting from WEEE treatment are exported and further processed for metal and plastic recovery. Moreover, disassembling, also called dismantling or manual processing, aims at separating devices and their parts (*e.g.* CD drives, memory cards, etc.) for subsequent material recovery (*e.g.* metals, plastics etc.).

Figure 2-5: Generic WEEE management processes in Colombia



Previous processes only included the formal system, *i.e.* processes authorized by the environmental authority. In Colombia, as part of the collection and sorting processes, post-consumer programs have been implemented for computers, batteries, lighting equipment and mobile phones. Nevertheless, a high share of obsolete devices is collected and pre-treated by informal workers; in fact, this is a common practice in most waste management activities of developing countries (Chi et al., 2011; Guerrero et al., 2013). Informal recyclers dismantle WEEE by pounding the objects against the ground, for example, which increases potential health risks to recyclers, not to leads to deleterious environmental effects due to the toxic elements contained in EEE (Empa and CNPML, 2010; León, 2010; Streicher-Porte et al., 2005; Widmer et al., 2005). The informal sector also recovers some metals. Figure 2-6 displays the informal processes as a sub-system.

Figure 2-6: Informal WEEE management processes in Colombia



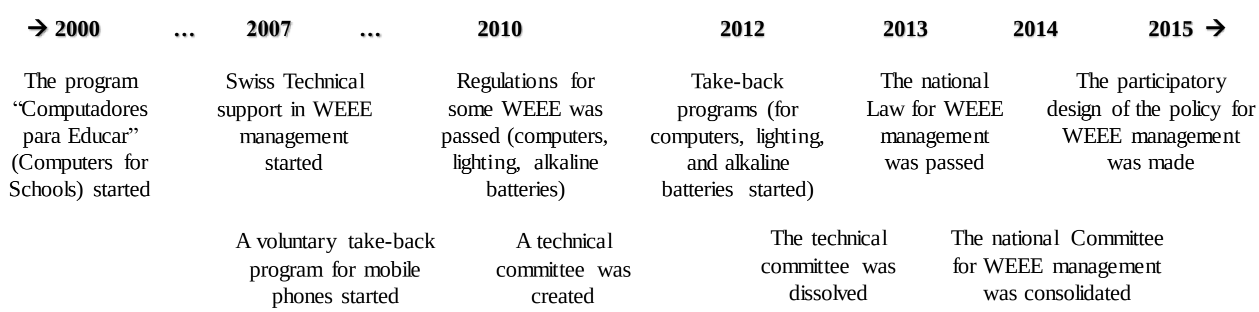
Actors

Generic actors involved in WEEE management in Colombia can be classified as follows: producers, distributors, consumers, recyclers (formal and informal) and the Government at national, regional, local levels. Recyclers usually play the supplementary role of collectors. A National WEEE Committee (NWC) was created in 2014 to advise in matters related to policy decisions and follow-up policies, strategies and programs. As promulgated by the Law 1672/13, the NWC must establish the mechanisms for negotiating with the private sector; identify sources of financial support; and, support research and related technological innovations. The NWC is made up of associations that include groups of producers (ANDI – The *Asociación de Industriales de Colombia* and CCIT – *Cámara Colombiana de Telecomunicaciones,* or Colombian Chamber of Informatics and Telecommunications) and distributors (FENALCO – the *Federación Nacional de Comerciantes*), as well as the *Ministerio de Ambiente y Desarrollo Sostenible* (MADS), the *Ministerio de Protección Social* (Ministry of Health and Social Protection), the *Ministerio de TICSs* (Ministry of Communication and Information Technologies), and the *Ministerio de Comercio, Industria y turismo* (Ministry of Commerce, Industry and Tourism). To round out the committee, two delegates from authorized WEEE recyclers, two advisers and one representative from the *Centro Nacional de Producción Más Limpia* – CNPML (the National Cleaner Production Center) were added. Last, but not least, the NWC counts on the support of international experts.

Past Actions and Current Necessities

According to the interviews, the historical evolution of WEEE management in Colombia (described in Figure 2-7) really did not begin until 2000, when the "Computers for Schools" program was inaugurated (*Computadores para Educar* in Spanish - CPE). CPE focuses on EEE refurbishment activities and seeks to provide donated computers to schools in order to help bridge the digital divide (Marthaler, Christian, 2008).

Figure 2-7: General WEEE management timeline in Colombia



Taking into account these past facts and their results, as well as the latest regulations, WEEE management components were prioritized by the stakeholders interviewed on the basis of what is needed in the short- (1 year), medium- (between 1 and 4 years) and long- (more than 4 years) term to improve Colombia's WEEE management (Table 2-1). It is important to highlight that this prioritization helped identify the most important decisions to be made later in the DES designed in this doctoral research. That is, their prioritization does not represent the real non-linear relationships between causes and effects observed in the case study.

Table 2-1: WEEE management components needed in Colombia per NWC member prioritization (short-, medium- and long-term)

Elements of WEEE Management to Strengthen or Implement
Strengthen strategies to increase take-back of WEEE from users: awareness, education, incentives and sanctions
Strengthen the role of educational institutions in Colombian education and research (high schools and universities)
Formalize informal / semi-formal recycling
Implement citizen-oriented strategies for environmental education and WEEE awareness
Strengthen strategies related to producers and marketers in the form of penalties for non-participation in take-back
Implement take-back (collection) points and strategies related to market chains; from providers to end users
Reduce WEEE linked to responsible consumption of EEE (generate less WEEE)
Design and implement new recycling plants
Strengthen producer incentive systems to promote recycling (cleaner production, responsible design, eco-design, etc.)
Strengthen the role of producer and marketer guilds
Design and implement selective routes for WEEE collection (public or private)
Implement economic/tax-based incentives for collecting / recycling / disassembling / refurbishing businesses in order to increase their technological capabilities

An important finding was that the most urgent action (in the short-term) for improving current WEEE management in Colombia consisted of designing and implementing strategies aimed at increasing WEEE consumer collection rates. Complementarily, educational and awareness programs were shown to be relevant, representing the second and fourth priorities in Table 2-1. In addition, informality in recycling (including informal collection) was found to be a serious issue; this aspect was related to consumer behavior.

Furthermore, a list of causes and observed effects related to current WEEE management in Colombia was prioritized by NWC members and the generic actors who attended activities of the participatory policy design (among them the Swiss experts and academic scholars). This prioritization is shown in Table 2-2, along with the structural or most dependent causes. Structural analysis based on the matrix of influences - MICMAC (Godet, 1993) was used; see Appendix C for more information.

Table 2-2: Prioritization of structural (or most dependent) causes

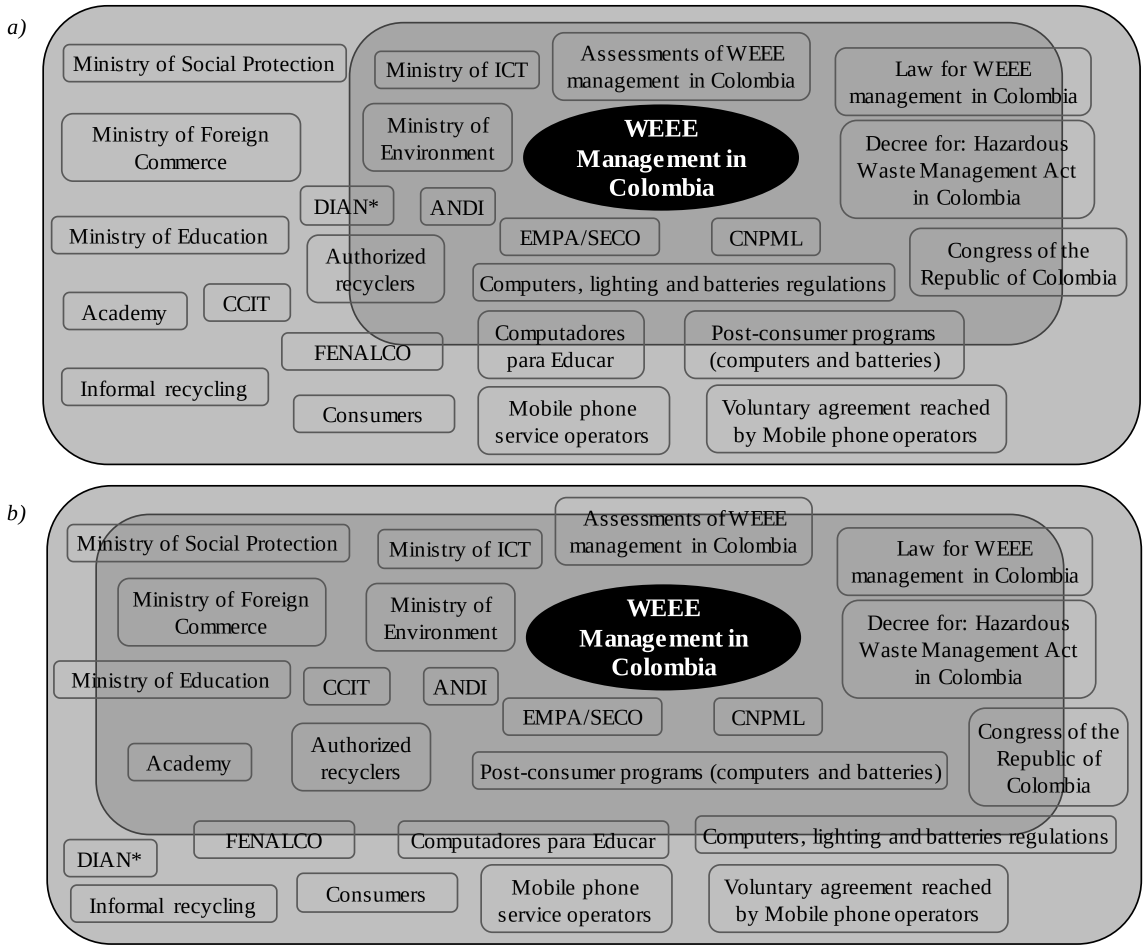
Causes of Insufficient and Inefficient WEEE Management in Colombia
Poor inter-institutional coordination
Poor regulatory framework for legal implementation
Lack of ongoing training of public staff
Poor cooperation among (public and private) institutions
Poor integration of WEEE management in national educational programs
Insufficient monitoring-control by the Environmental Authority with regard to formal and informal sectors
Lack of Information Systems to support monitoring and control activities
Poor general dissemination of information (related to the differentiated WEEE management) to consumers (including the obligation to deliver WEEE to the formal system)
Poor monitoring of the Extended Producer Responsibility to implement post-consumer programs

2.3.2 Actor-Networks and Mobilization

Colombia's WEEE Management

Laws, Acts and Policies were the main mechanisms to tackle previous causes, effects and necessities (see Tables 2.1 and 2.2). Figure 2-8 shows local (shaded area) and global networks in terms of Law 1672/2013 and the participatory design of the national policy (2014-2015) within the timeline (Figure 2-7 above). It should be noted that, as ANT (Latour, 2005) states, the term actor-network (A-N) encompasses not only human but also non-human actors, such as documents and laws.

Figure 2-8: Local and global networks in Colombia's WEEE management system (*National Direction of Taxes and Customs of Colombia). [a) 2013; b) 2015]

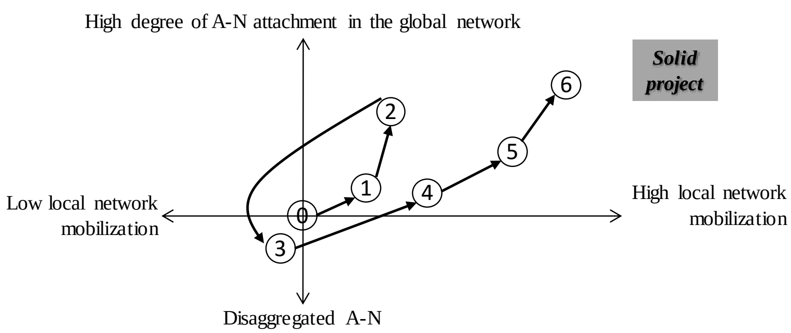


Explicit relationships or links between A-Ns are not displayed in Figure 2-8, for their complexity would render the graph incomprehensible. Furthermore, relationships change, have different strengths, include feedback loops and result in high interaction density. For instance, the local network involves A-Ns that have participated in all relevant moments (detailed below), but the global network includes actors not actively participating in current decisions, despite the fact that they should be. To name just two examples: consumers and the *Ministerio de Educación* (Ministry of Education), which influences education related to consumer behavior. Although all A-Ns involved in the NWC have taken part in the local network, the Educational Authority has not sent any representatives yet.

The MADS has participated throughout the entire timeline of WEEE management in Colombia; likewise, it has convened other actors, published regulations and laws and supported assessments and studies (see Timeline in Figure 2-7 above). In light of this active participation, and due to the fact that any project or action an A-N wants to realize must be approved by this institution, it can be labeled the system's OPP.

Based on a review of interviews and documents, the milestones (or mobilization moments) in the evolution of Colombian WEEE management, in addition to the A-Ns involved in each milestone, were identified as shown in Figure 2-9. The starting point (Milestone *0* in Figure 2-9) was the creation of the CPE program in 2000. Subsequent years have witnessed parallel episodes. On one hand, private companies have increased their interest in computer donations, spurred by the younger generation's push to provide IT access and the positive environmental impact of reducing the disposal of still usable computers. On the other, since companies previously were not financially responsible for the management of this waste, they had an economic interest in their efforts for the first time. Additionally, their engagement also served marketing purposes and resulted in a decrease of tax payment (a tax break earned by virtue of their engagement in corporate social responsibility).

Figure 2-9: Mobilization of actors in local and global networks within Colombia's WEEE management



Milestone	General Description
0	Computers for Schools program was created
1	The Switzerland - Colombia cooperation started
2	Computer and mobile-phone working groups started
3	Regulations for computers and lighting were passed
4	The post-consumer programs *EcoComputo, Lumina* and *Pilas con el Ambiente* were implemented
5	The national law for WEEE management was passed
6	Increased involvement of stakeholders in the participatory design of national policy on WEEE management

In parallel, the government started to design regulations for hazardous waste management under pressure to comply with international agreements, *e.g.* the Basel Convention (1992) or the Kyoto Protocol (1997) and domestic laws, *e.g.* the National Environmental and Natural Resources Management Law (1993). As a result, the Hazardous Waste Management Act was passed in 2005, generating further pressure on the industry. In 2007, an agreement between Switzerland and Colombia was signed (Milestone *1* in Figure 2-9), with the participation of the most relevant A-N. Note that local network mobilization increased as a factor of the *interessement* or attraction of interests: the *interessement* was, on one hand (for the OPP), prevention of environmental impacts, compliance with the hazardous waste law and international sustainability requirements; on the other (for Empa/SECO, the Swiss representatives), it was geared towards supporting developing countries in WEEE management. This Swiss initiative, which started in China, India and South Africa as the "Swiss e-Waste Program," was extended to Colombia and Peru starting in 2007. During the first two years of this collaboration, local network mobilization of the A-N and global network attachment increased. Together, such increases facilitated the creation of the computer and mobile phone working groups (Milestone *2* in Figure 2-9) and EEE and WEEE management assessments. The latter achievement, the assessments, still resonates as important technical documents that support decision making.

In 2009, the local network members conducted a “study tour” to observe WEEE management in Switzerland in order to obtain primary information on the design of WEEE strategies for Colombia. Pursuant to the “study tour,” the working groups entered an internal crisis caused by members’ divergent particular interests, which attenuated global network A-N aggregation and local network mobilization (see Figure 2-9). However, out this crisis, a crucial step was taken: the OPP decided to pass regulations (2010) so as to achieve a mandatory collection of computers and lighting equipment (Milestone *3* in Figure 2-9).

Through a shift in the leadership of the producer representation to ANDI, the composition of the local network changed and mobilization and participation increased. Three post-consumer programs (PCP) for collecting computer (*EcoComputo*), lighting (*Lumina*) and alkaline batteries (*Pilas con el Ambiente*) waste emerged as a result of these efforts (Milestone *4* in Figure 2-9). The *interessement* to achieve this milestone stemmed from two primary (interrelated) motivations: computer producers and importers wanted to comply with the law and to avoid penalties. The economic opportunity presented to authorized recyclers, representing savings for producers, also played a role. On account of the lack of regulation, experience from the second working group (mobile phones) resulted in a weak voluntary agreement by some mobile phone service providers to implement collection points for consumer equipment (phone service subscribers), which would then be passed along to authorized recyclers.

The National WEEE Management Law was passed in 2013 (Milestone *5* in Figure 2-9), and the National WEEE Committee was established in 2014. In conjunction, the creation of the committee and the passing of this 2013 Law were the culmination of a process begun in 2010 by local A-Ns. Implementation of regulations, and related Acts, since 2010 have demonstrated the importance of legislation in terms of achieving increased WEEE collection rates. PCP dynamics have proved helpful as a learning process to avoid failures in complete system implementation (all WEEE EU categories).

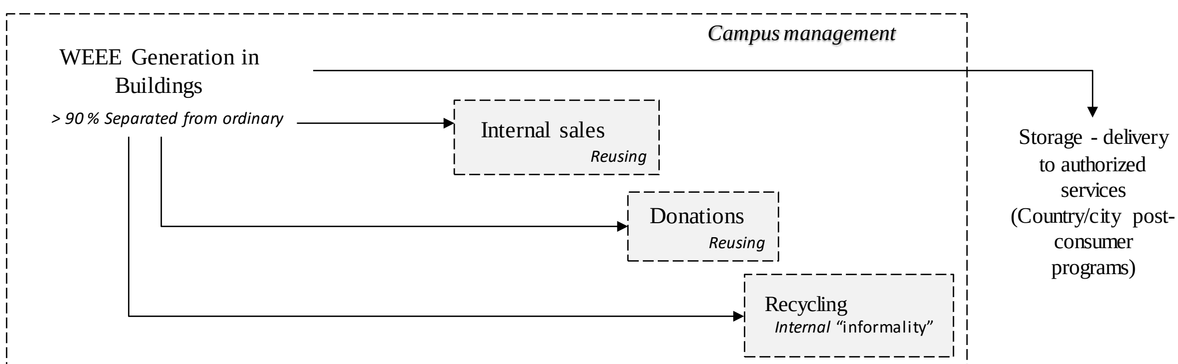
At present, the MADS, with the support of the CNPML, Empa/SECO and the Pontificia Universidad Javeriana, is designing the instruments and regulations needed to implement the Law and a control system. The NWC has been a part of this process, mainly as pertains to policy design (Milestone *6* in Figure 2-9), which has become the *most solid project* (see Figure 2-9). Their involvement seeks to align the interests and motivations of the rest of the actors in local and global networks (A-N *enrolment*); likewise, their involvement looks to help achieve a more sustainable implementation of the chosen strategies. The use of participatory methodologies to identify the causes and effects of the current, insufficient WEEE management system in Colombia, as well as the relationship among causes, definition of structural causes and design of strategies and action plan as part of the policy, have increased the confidence and motivation of A-Ns, which, in turn, has strengthened global network attachment to (see Figure 2-9).

2.3.3 University Campus as City Model

Within the WEEE management system at the city or country level (see Figure 2-5 - Colombia's WEEE management processes), a university plays the role of consumer. Nevertheless, as the second single-case study, the Pontificia Universidad Javeriana exploratory case study was focused on interior processes and actors (decision-makers and operative roles); in and of itself, these constitute a subsystem with additional elements of a WEEE system that encompass much more than consumption.

The Pontificia Universidad Javeriana has two campuses. The main campus is in Bogotá; this campus was the context of this single-case study. The second is located in Cali. The Bogotá campus has a population of around 22,000 people, with students accounting for 71% of the total and scholars/professors for 17%. Waste management, including WEEE, is led by the Campus Administration Office (CAO), which manages campus investments in infrastructure and coordinates the logistics of all administrative processes; the CAO also handles WEEE on a daily basis in the form of specific elements that entail infrastructure, processes and human resources. Although there are no reliable data regarding waste generation, the management processes are clearly delineated (Figure 2-10). Such processes include separation of consumer equipment (TVs, photographs and audio equipment in particular), ITC equipment, lighting equipment and large equipment from laboratories (*e.g.* ovens or refrigerators). Equipment that still works is either sold to the administrative staff or donated to regional social projects (especially computers).

Figure 2-10: General WEEE management processes on the Javeriana Campus. Adapted from (Méndez-Fajardo and González, 2014).



A-Ns actively involved in local and global networks are shown in Table 2-3. The OPP is the Campus Administration Office (CAO). The CAO is responsible for designing, building and maintaining infrastructure investments. The head of this office is the primary decision-maker in terms of planning, designing and implementing SWM infrastructure, in addition to developing related programs and campaigns.

Table 2-3: Actor-Networks Actively Involved in Solid Waste Management (including WEEE) at the Pontificia Universidad Javeriana (Méndez-Fajardo and González, 2014).

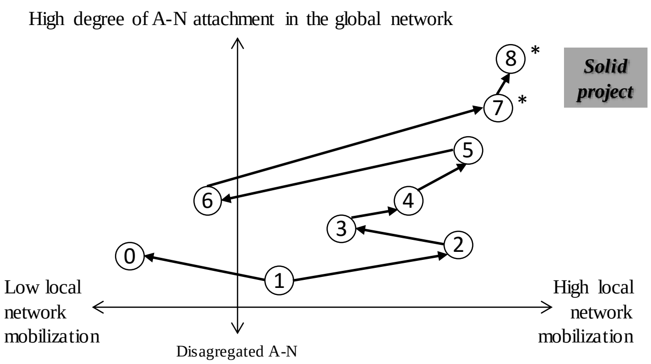
Actor-Network (A-N)	**Units/Faculties/Groups Involved**
Campus Administration Office (CAO)	-
Department of Ecology and Territory (DET)	-
Environmental Administration Group (EAG)	CAO and administrative employees from the primary hazardous waste generators*
The Environmental Committee (EC)	CAO, SFE**, SFES***
Vice-president of the Welfare Office, which is responsible for the Healthy University Program (HUP)	-
University Environmental Group (UEG)	CAO, SFE**, SFES***, SFAD**** and Academic Dean of the Environmental Sciences Faculty
Plans for SWM (ordinary and hazardous waste)	EC
Environmental Management System (EMS) document	CAO, SFES ***
Safety protocols for hazardous waste management within the Sciences Faculty	CAO, SFES***, Administrative Staff from the Sciences Faculty

* Sciences, Medicine, Odontology, Engineering, Arts, Architecture & Design Faculties, as well as the University Hospital; ** Scholars from the Engineering Faculty; *** Scholars from the Environmental Sciences Faculty; **** Scholars from the Architecture & Design Faculty

In addition to the A-Ns identified in the table above, two A-Ns emerged as relevant to WEEE management: (1) employees as the primary consumers/generators of WEEE on the campus; (2) University Purchasing and Supplies Direction (UPSD), which is responsible for EEE purchases. In this respect, Faculties would become crucial if WEEE management were refocused on responsible consumption. The UPSD would also take on added significance due to its role in responsible consumption insofar as they were related to concepts such as green supply, brands with green labels, etc.

The moments of translation at the university are shown in Figure 2-11, and the complete description is included in Appendix A.

Figure 2-11: Mobilization of actors in local and global networks within the Javeriana's WEEE management (Méndez-Fajardo and González, 2014).



Episode	General Description
0	Prior to the passage fo the National Medical Waste Management Act
1	First formal protocol for the management of hazardous waste on the campus (compliance with act in episode 0)
2	Campus Environmental Management System created
3	Campaign for collecting obsolete mobile phones and related accessories
4	University Recycling Program in Bogota (PRIES per its acronym in Spanish)
5	Massive virtual environmental survey
6	Implementation of the post-consumer program for alkaline batteries (*Pilas con el Ambiente*)
7 *	Javeriana University's Ecological and Environmental Policy is developed
8 *	Javeriana University creates an Environmental Management Committee to implement the policy in episode 7

** These milestones (Nov. 2015, 2016) were achieved after the single-case publication (Dec. 2014)*

Mobilization of A-Ns through the moments of translation displayed above began after the National Healthcare Waste Management Law was passed in 2000 (Milestone *0* in Figure 2-11). Of particular importance were the necessary adaptions of the physical infrastructure in the Sciences Faculty building and the protocol for hazardous waste management (Milestone *1* in Figure 2-11). To wit, all milestones emerged from this law's requirements, whether directly or indirectly. For instance, the campaign to collect obsolete mobile phones and accessories in 2008 (Milestone *3* in Figure 2-11) and the leadership of the University Recycling Program initiative (PRIES per its acronym in Spanish) in Bogotá (Milestone *4* in Figure 2-11) emerged for two main reasons: the hazardous waste management legal requirements (2005) and the formalization of informal recyclers in Bogotá (2010). For the milestones described, these regulations were crucial in that they aligned the interests of the OPP and relevant A-Ns within the system.

Similar to the situation observed at the country level, there were important networks of informal collection and recycling on the campus, which involve, for the most part, security staff, cleaning staff, laboratory staff and secretarial staff, all of whom collect not only WEEE but also paper, cardboard and plastics from offices and sell it off campus.

Finally, a fact worth highlighting is the move towards a more systems-based approach achieved by the policy's approval and subsequent operation (Milestone *8* in Figure 2-11) on both of the Javeriana's campuses (Bogotá and Cali), especially given that it represented the first time something of this nature happened at the Pontificia Universidad Javeriana.

2.4 Discussion and Design Requirements

To reiterate, the questions proposed for this case study were:

(i) Have decision-makers implemented a systems approach in their decisions?

(ii) Is there an organized operational structure for WEEE management?

(iii) What elements have triggered improvements in WEEE management?

To more thoroughly answer these three questions, the elements of a systems approach (presented in Section 2.1) should be recalled: i) different dimensions of the problem; ii) targets of the different stakeholders; iii) processes within WEEE management; and, iv) circular cause-effect relationships stemming from current decisions in both the short-, medium- and long-terms.

The first question refers to the decision-maker's approach. Although the main decision-makers incorporated different dimensions and (occasionally) different actors, programs and strategies regarding WEEE management, they failed to account for a multi-causal analysis, multiple management stages and knowledge gleaned from past experiences in an explicitly methodological way. Regulations, laws and guidelines include keywords chosen to foster more systemic actions. In spite of this, two main situations emerged. First, the content of the documents has not been implemented (as was the case for Milestone *2* at the Pontificia Universidad Javeriana; see Figure 2-11), so they have been relegated to unimplemented-yet-documented ideas. Second, some implemented strategies did not include systemic design; thus, only partial solutions have emerged to address the structural causes of the problems to date. Take, for example, the focus of some recycling programs on physical waste collection artifacts, such as bins, to the detriment of educational strategies and continuous information campaigns vital to fostering consumer participation. Situations of this nature were observed in Colombian cities and the Pontificia Universidad Javeriana. In consequence, trashcans are frequently filled with mixed waste, making the recycling processes inefficient. Further confirmation of the non-systems-based approach in decisions is attested by the lack of reliable data on waste generation and the increasing levels of informal activities in collection and recycling.

Decision making did not follow a systemic process at the country or university levels. In the latter case, the main motivation was the authority's requirement for compliance with the laws, such that decisions were made with an emphasis on short-term solutions. What is more, decisions usually flowed from the campus administration area (to the exclusion of other areas), and decisions looked to address daily problems. There was no systematic defined set of criteria to facilitate the prioritization of issues that require investments, *e.g.* infrastructure development, educational campaigns or natural resource management (water, energy, ecosystems). Nonetheless, some successful projects were initiated, attributable to interest from scholars; however, these scholars have not been actively involved in decision-making. Yet, there are positive signs: due to the recently passed environmental policy, various scholars will be brought in to the decision-making process as advisers for the new environmental committee charged with designing and implementing future strategies.

At the country level, informal recycling, discarded WEEE in public areas and sanitary landfills, low rates of WEEE collection, low consumer participation, high levels of smuggling and low EEE quality in markets collectively demonstrate the absence of a systems-based approach to decision-making. A primary cause is rooted in the inadequate cooperation among relevant actors, *i.e.* the lack of coordination among public and private organizations and even within the public sector.

The second question addresses the organizational structure needed for WEEE management. The operational structure, albeit extant, proved insufficient for effective WEEE management in the country and university cases. This research has shown that the most important operational roles in waste management for the two single-cases (*e.g.* the environmental authority at the national level or the logistics director at the Pontificia Universidad Javeriana) have several responsibilities, even outside of the waste management field. Moreover, the lack of information systems, to name one example, available to support decision-making and related activities represents one of the most conspicuous weaknesses of the management system. This lack resulted in a veritable dearth of information regarding waste generation (amount of WEEE generated), generators (actors generating waste) and flows, among other aspects. That being said, one sign of progress is that, at the outset of this exploratory study, neither Colombia nor the Pontificia Universidad Javeriana had a related policy, which has been remedied today.

The third question proposes the identification of elements that have triggered improvements in the WEEE management in each context. In addition to the need to comply with public laws, the particular interests of relevant actors have motivated the OPP in each system (the MADS in Colombia and the CAO at the Pontificia Universidad Javeriana) to promote the design and implementation of strategies considered milestones (Figures 2.9 and 2.11). Since positioning and marketing are key for equipment producers or large consumers, such as universities, both Corporate Social Responsibility and Corporate Environmental Responsibility, usually measured through project impact, have come to form a pivotal step in improving waste management.

Looking specifically at the university case study in which education is the University's *raison d'être*, decision-makers are interested in turning the campus itself into the subject of education. Beyond external requirements imposed by local, regional or national environmental authorities, in-house motivation, *e.g.* boosting Corporate Social Responsibility and increasing the university's positioning both nationally and internationally, prompted the primary decision makers to support policy design activities. Therefore, the latest actions regarding waste management are not merely a reaction to requirements, but rather are part of a strategy crafted to strengthen Corporate Social Responsibility. Of note are Milestones *5* and *6* (Figure 2-11), which emerged as preventive strategies. The massive e-survey (Milestone *5* in Figure 2-11) was part of the participatory design to elicit appropriation of the policy by the actors to design the university's environmental policy (for detailed results, see Appendix D). Moreover, this non-authority-driven strategy may also be applied to the implementation of the PCP for batteries (Milestone *6* in Figure 2-11). It must be granted that Milestone *6* was aligned with Colombia's WEEE Management Law, given that the battery program increased the awareness of responsible consumption in the university community.

More than five years elapsed between the first attempt to design and pass a policy related to WEEE management (at the national level) or environmental management (at the university level) and the realization of this goal. The introduction of a facilitator to methodologically guide discussion and dialogue among actors catalyzed both processes. At the university, this was apparent due to the environmental policy legalized in November 2015 and, in the final step, the national WEEE policy currently under review by the MADS's legal arm. The following understanding about the alignment of actors' interests in the two contexts could help shape similar projects: a policy should be made public as the framework for designing subsequent laws and regulations (which, in turn, guide the law's implementation). However, in Colombia, the WEEE Management Law was passed in 2013, whereas more successful policy design only came about in

2014 and 2015, around the same time as the design of the regulation that included legally-binding annual collection rates for producers. In this legislative context, calls to attend policy design activities were led by the MADS (the OPP at the national level), the same actor actually designing the corresponding regulations. This effectively prompted actor mobilization and made it easier to achieve the required participation.

Lastly, additional elements were observed during the policy design that should be taken into account for sustainable WEEE management implementation: i) the same person should represent actors in local networks throughout the entire process; ii) this representative should be interested in the topic, rather than view it as an obligation; and, iii) as non-human A-Ns, there should be detailed reports of all strategies designed and implemented, along with key elements (actors, actions, type of WEEE, failures, successes, possible future problems and consequences, among other) and complementary strategies, a *de facto* acknowledgment of the fact that achieving project sustainability requires time and resources.

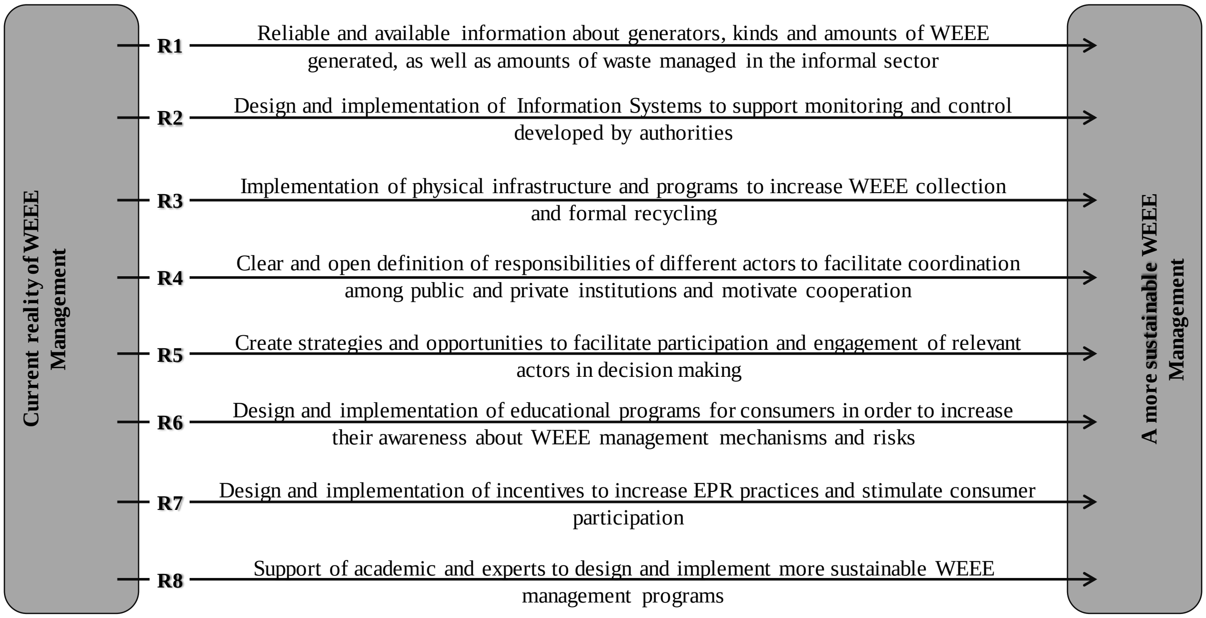
2.4.1 Design Requirements

The answers presented above depict the current state of WEEE management in developing countries. Clearly, there is noticeable contrast between the current state of affairs and a sustainable system. As demonstrated by the interviews and literature review, a more sustainable system would eradicate WEEE in public areas or sanitary landfills, do away with informal recycling, achieve high rates of consumer participation in PCPs and develop regulations and infrastructure to handle all WEEE categories and combat low-quality EEE on the market. An ideal system of this nature would also reinforce formal recycling via the implementation of infrastructure in an effort to recover valuable materials in the country.

The gap between the current system explored in the case study and more sustainable systems is explained in terms of design requirements, illustrated in Figure 2-12 below.

The implementation of all listed requirements would ensure WEEE management was on a more sustainable path. Requirements include information (IT) infrastructure-related aspects (R1 and R2), as well as physical infrastructure (R3); others are associated with human activities, such as education, participation, cooperation and decision making (R4 - R8).

Figure 2-12: Design requirements for more sustainable WEEE management



Public policies are advantageous when bringing together these requirements to form the basis for strategy and program development; however, the design of sustainable policies means requirements such as participation (R5 and R7) and cooperation (R4) cannot be overlooked.

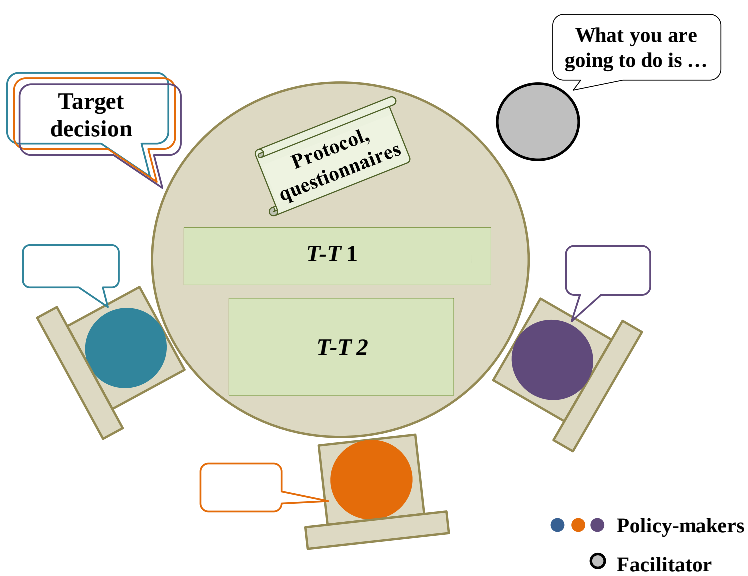
In light of this doctoral research's focus on the achievement of more systemic decision-making processes, the design will not broach all requirements. In other words, the decision-enhancement studio (DES) developed herein included three main elements: people (decision-makers and facilitator), processes that guided the *studio* as the main facilitative environment for decisions and a set of technological tools that integrated technological tools and protocols (Keen and Sol, 2008). Thus, requirements explicitly incorporated into the design of the DES (see Chapter 3) are as follows: R5 and R8 are related to general DES goals, while R3, R4, and R7 are related to specific technological tools goals.

3 The Decision-Enhancement Studio: Towards More Sustainable WEEE Management

3.1 Sustainability and Decision Making

As described in Chapter 1, global agreements on sustainable development have affirmed the relevance WEEE management. The effects of such management are more impactful in developing countries. The exploratory two-case study presented in Chapter 2 revealed the absence of a systems approach in decision-making. This absence emerged as the main structural cause of unsustainable WEEE management in Colombia. In an effort to implement a systems-based approach (or a process closer to a systems-based approach) to waste management, Decision Support Systems (DSS) have been integrated into the simulation-based models, for an integrated approach serves, for example, to guide decision making regarding landfill allocation (Alves et al., 2009; Antanasijevic et al., 2013; Kollikkathara et al., 2010). Further still, this integration allows for a conceptualization of the role of computers within decision making in order to better understand and thereby improve the decision-making process. However, decision enhancement studios take this one step further, given that they serve as a management lens through which it is possible to significantly enhance executive decision making via a fusion of human skills and technology. DESs apply this fusion to areas that combine people, processes and technology, and in which, generally speaking, the impact on decision making has to date been quite limited (Keen, 2011; Keen and Sol, 2008). The present doctoral thesis engages people, processes and technology using a *Decision-Enhancement Studio* (DES), designing a DES that accounts for relevant actors in WEEE management in Colombia, the facilitator (people), the *studio*—the main facilitative environment for decisions guided by a protocol (processes)—and tools such as a computer-based simulation, a multi-criteria decision table (technological tools, T-T) and questionnaires (see Figure 3-1).

Figure 3-1: The decision enhancement studio (DES)



As detailed below, the DES*'s* goal is broader than the T-T's goals. The T-T consists of an agent-based model (ABM) implemented as a computer-based simulation using NetLogo, a multi-criteria decision table implemented in Excel Microsoft Office and a questionnaire included in the DES guideline.

This chapter describes the design of the *studio* and the T-Ts and outlines the DES's implementation. In Chapter 4, the results of this DES, in addition to its validation, are discussed.

3.2 The Decision-Enhancement Service, DES

When defining the DES*'s* goals, it is important to review the types of decisions proposed by Keen and Sol (2008), who argued for six categories:

i) *Urgent decisions* significantly affect customer relationships, market strategy or corporate financing, etc.

ii) *Consequential decisions* have a range of "adequacy," in which there is room for error, time to make adjustments and limited downside risk. Here, the DES contributes to the transformation of the decision-making process.

iii) *Non-avoidable decisions* are ones whose contributions consist of encouraging involvement that leads to commitment, and, in turn, help avoid delays and/or purely "political" decisions imposed by some stakeholders

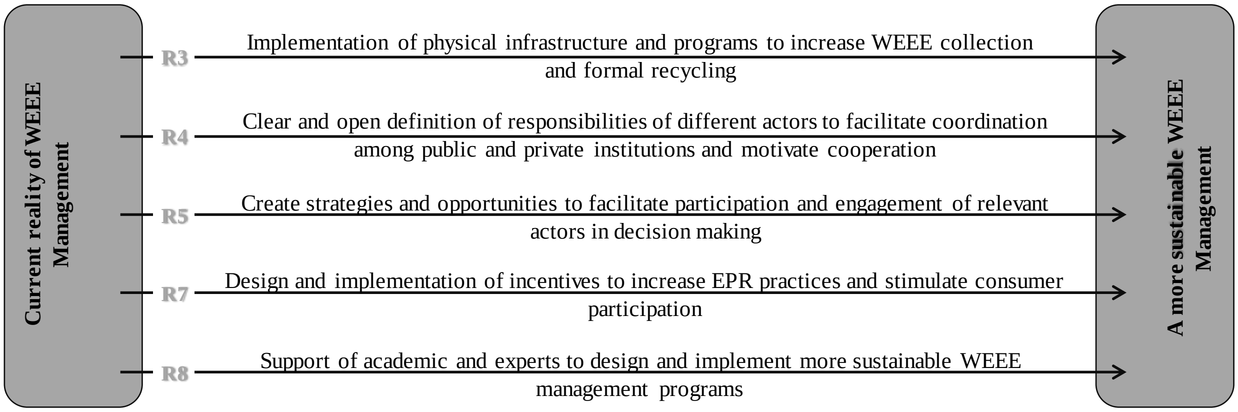
iv) *Non-reversible decisions* are decisions where some parties are not comfortable committing to a decision, even though said parties are aware of the decision's importance and consequences. Therefore, these decisions often form the basis of decision avoidance.

v) *Packed with uncertainty decisions* mean the DES should include simulations to make a recommendation or consensual forecast, in particular via rapid "what if?" visualization and analysis.

vi) *Wicked decisions* emerge from a conflict of values and the difficulty of making trade-offs. In these scenarios, the DES provides a forum for building a mutual understanding of views, shared scenario evaluation and collaborative efforts to reach an agreement with a commitment to "follow-on" action. Thus, the main contribution of this decision is, as in consequential decisions, to improve the process.

The DES has, as a general goal, answering the research questions posed by this doctoral thesis, whereas the goals of the T-T are more specific and tailored to the structural causes of insufficient and inefficient WEEE management in Colombia. Per the results of the exploratory case study (Chapter 2), requirements responsible for driving the design of the DES are R5 and R8 (DES's goals), while R3, R4, and R7 are responsible for driving the more specific T-T goals.

Figure 3-2: Requirements used for designing the decision-enhancement studio



In other words, the DES*'s* goal was directly related to the definition of a systems approach: cultivating an environment in which different points of view (actors) are shared, learning about WEEE management processes so as to add different dimensions to the discussion and raising awareness of the circular cause-effects underlying current decisions with regard to short-, medium- and long-term decisions. Thus, the DES´s goal was formulated as follows: "Decide on aspects that affect sustainability in WEEE management in Colombia". Per the six types of decisions previously outlined, this represents a *wicked* decision, whereas the T-T goal, identified by the relevant actors, was to answer the following question: "How can consumer behavior be influenced?" This corresponds to an *urgent* decision.

The DES*'s* general structure can be broken down into four main parts (Table 3-1), although it was one four-hour-long meeting with a coffee break.

Table 3-1: General DES Structure

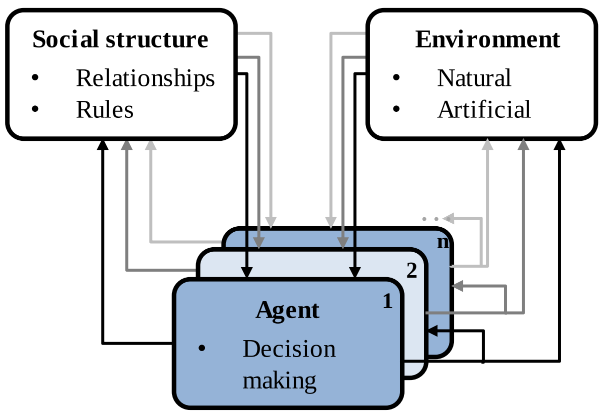
Description of key concepts	20 mins
Description of general and specific goals	
Explanation of the *studio*'s methodology	20 mins
Development of the *studio*	
Individual decision making (groups of 2 or 3 people)	
Using Coop4SWEEM	60 mins
Analyzing the Multi-criteria decision tool	40 mins
Group decision making	50 mins
Questionnaire, TAM validation and general suggestions	15 mins

As part of the T-Ts, an ABM was designed and implemented as a computer-based simulation (see Section 3.3), in addition to the development of a multi-criteria decision table using the weighted sum method and implemented in Excel (see Section 3.4). Section 3.5 details the DES setup.

3.3 *Coop4SWEEEM*: The Agent-Based Model and Simulation

Agent-based modeling may be defined as a computational method that allows for the creation and analysis of models, as well as model experimentation; these models are made up of agents that interact in the decision-making process decisions within an "environment" (Gilbert, 2007). Agent-based modeling helps discover possible emergent properties from a bottom-up perspective and allows for the representation of phenomena (as do other models, *e.g.* equation-based models). Furthermore, agent-based modeling makes it possible to simulate complex situations with limited information, limited possible responses, limited material resources and limited computational capabilities. Nevertheless, the effectiveness of ABMs largely depends on agent organization and coordination roles within the model (Dam et al., 2012; Nikolic and Kasmire, 2013). A generic ABM structure is shown in Figure 3-3.

Figure 3-3: Generic ABM structure. Adapted from (Knoeri et al., 2010)



In order to design the ABM, the Overview, Design concepts and Details protocol (ODD) proposed by Volker Grimm in 2006 was used. The ODD protocol established a standard for describing ABMs (Grimm et al., 2010; Grimm, V. et al., 2006) and has been widely used in the scientific community (Müller et al., 2013). The ODD protocol's general structure (see Table 3-2) was adapted to design an ABM dubbed *Coop4SWEEEM* (Cooperation for Sustainable WEEE Management).

Table 3-2: ODD structure for the design of *Coop4SWEEEM* (Grimm et al., 2010; Müller et al., 2013)

3.3.1. Overview	Purpose
	Entities, state variables and scales
	Processes overview and scheduling
3.3.2. Design concepts	Basic principles
	Individual decision making and sensing
	Interaction, collectives and heterogeneity
	Stochasticity
	Emergence and observation
3.3.3. Details (translation of the conceptual ABM into a computer-based simulation)	Implementation details
	Initialization and input data
	Sub-models

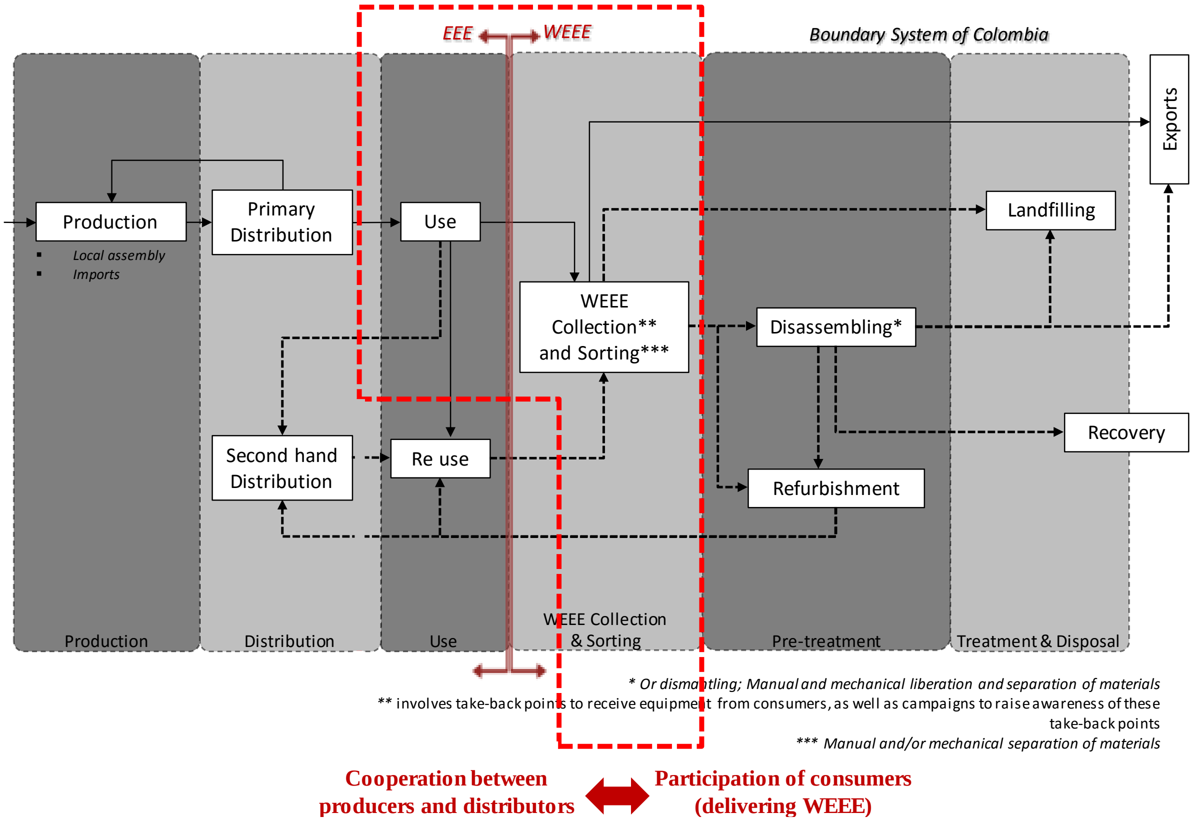
Each item included in Table 3-2 is explained below. Additionally, Section 3.3.3 describes aspects related to the implementation of this ABM in the free software NetLogo 5.2, which is a platform for building and analyzing agent-based models and a staple of agent-based modeling (Wilensky, 1999).

3.3.1 Overview

As part of the ODD protocol (Table 3-2), the "overview" covers the model's purpose, information regarding "entities, state variables and scales," and the description of the "processes overview and scheduling." These three elements are developed below.

ODD starts with a concise summary of the overall purpose for model development. Since the *urgent decision* was defined as "How can consumer behavior be influenced?" the goal of *Coop4SWEEEM* becomes a display of cooperation scenarios between EEE producers and distributors, which is crucial for the implementation and operation of post-consumer programs (PCP). In turn, these PCPs rely on incentives to encourage consumers to return their WEEE through the formal system.

Figure 3-4: Boundaries of WEEE management related to the collection process



Here, two key points should be clarified. Firstly, WEEE refers, for the present purposes, to ICT equipment (or similar), such as mobile phones and computers, for they require different logistics than, say, large appliances, *e.g.* refrigerators. Secondly, neither second-hand distribution/use processes nor recycling (pre-treatment) activities were included in the ABM. These two caveats should make it clear that *Coop4SWEEEM* was designed for policy makers, for those who make decisions about PCPs as part of WEEE management in urban areas.

In the ODD, an entity is considered a distinct or separate object or actor that behaves as a unit and may interact with other entities or be affected by external environmental factors. In this research, entities were agents, and the environment was divided into the two following areas: the "motivation to cooperate area" and the "urban area;" the latter is where PCPs were physically implemented. For their part, agents are a collection of autonomous interacting entities with encapsulated functionality that operate within a computational world, thus allowing for the representation of agent behaviors in light of their past experience(s) (Railsback and Grimm, 2011). The entities utilized in *Coop4SWEEEM* were identified through the case study (see Table 3-3).

Table 3-3: Entities of the *Coop4SWEEEM* ABM

Entity	**Type**	**Description**
Producer	Agent	Represents the producer within WEEE management
Distributor	Agent	Represents the distributor within WEEE management
Consumer	Agent	Represents the consumer within WEEE management
Post-consumer program (PCP)	Agent	Represents the artifact that generates decisions in producers, distributors and consumers within WEEE management
Motivation to cooperate area	Environment	Represents the dynamics of the motivation to cooperate in producers and distributors
Urban Area	Environment	Represents an urban area where the PCPs are implemented and where consumers act

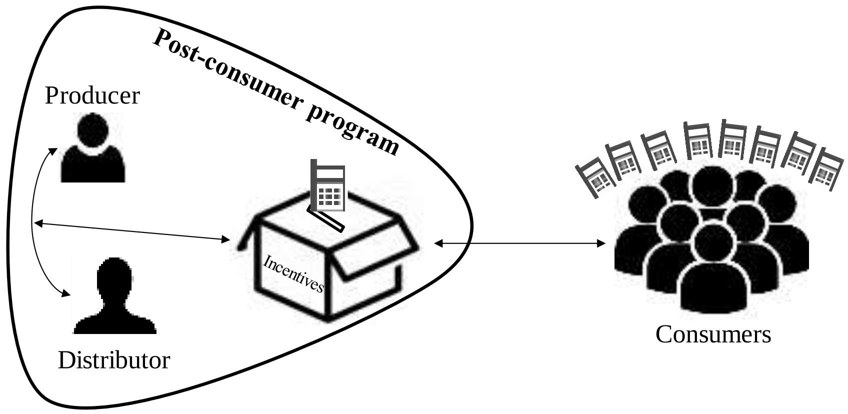
"State variables and scales" are defined by the entities' properties or attributes, as shown in Table 3-4. However, two additional variables are a function of agent actions: potential pollution (expressed as a percentage), a function of the WEEE not returned by consumers via formal systems; and the gap between "motivation to cooperate" in producers and distributors (likewise expressed as a percentage).

Table 3-4: Agent attributes in *Coop4SWEEEM*

Entity	**Attribute**	**Unit**
Producer	Motivation to cooperate	Percentage
	Resources	Units of money
Distributor	Motivation to cooperate	Percentage
Consumer	WEEE	Units
	Main interest	Interest
	Money received	Units of money
Post-consumer program (PCP)	WEEE collected	Units
	Resources bag	Units of money
Motivation to cooperate area	Spatial variable	Coordinates (x, y)
Urban Area	Spatial variable	Coordinates (x, y)

The PCPs included in this design were defined as the "collection strategy," consisting of urns (or boxes) physically placed at EEE points of sale in addition to a variety of incentives aimed at influencing consumers (in an effort to increase the amount of WEEE collected). The PCP represents the triad of producer-distributor-box (see Figure 3-5), in which "producer" and "distributor" represent real (generic) actors. In particular, information diffusion and education strategies were coupled with consumer incentives. The incentives considered in this model were economic and social in nature.

Figure 3-5: Producer, distributor, (PCP) box and consumers in Coop4SWEEEM

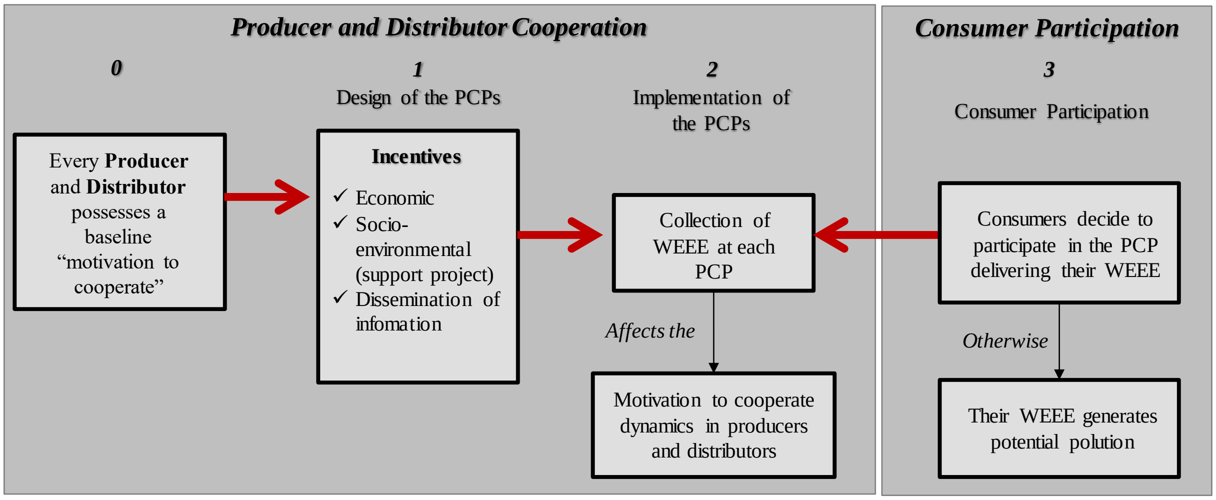


As mentioned, the "environment" was split into two zones (see Table 3-3 above): the first represented the cooperation dynamics between producers and distributors (Sub-model 1) by situating them into the two activity areas in line with their percentage of "motivation to cooperate." The second zone contained consumer dynamics (Sub-model 2) in an urban area.

"Motivation to cooperate" in producers and distributors was defined on the basis of the case study results. It is useful to classify the agents into "more active" or "less active" areas within the larger "motivation to cooperate" areas. Similarly, the primary consumer motivations when deciding whether or not to formally recycle their WEEE were designed using the data obtained in the massive survey of the Pontificia Universidad Javeriana's community, as the Sub-model in Section 3.3.3 below illustrates (see also Appendix F).

As part of the "overview," "general processes" of *Coop4SWEEEM* are shown in Figure 3-6. The current legislative context as pertains to the case study includes regulations for some WEEE. Essentially, these regulations defined an initial percentage of motivation to cooperate in producers and distributors. Under such conditions, the first step was to implement the initial alliance to stimulate cooperation. From there, the next step was to design the two PCPs, beginning with the selection and subsequent implementation of incentives.

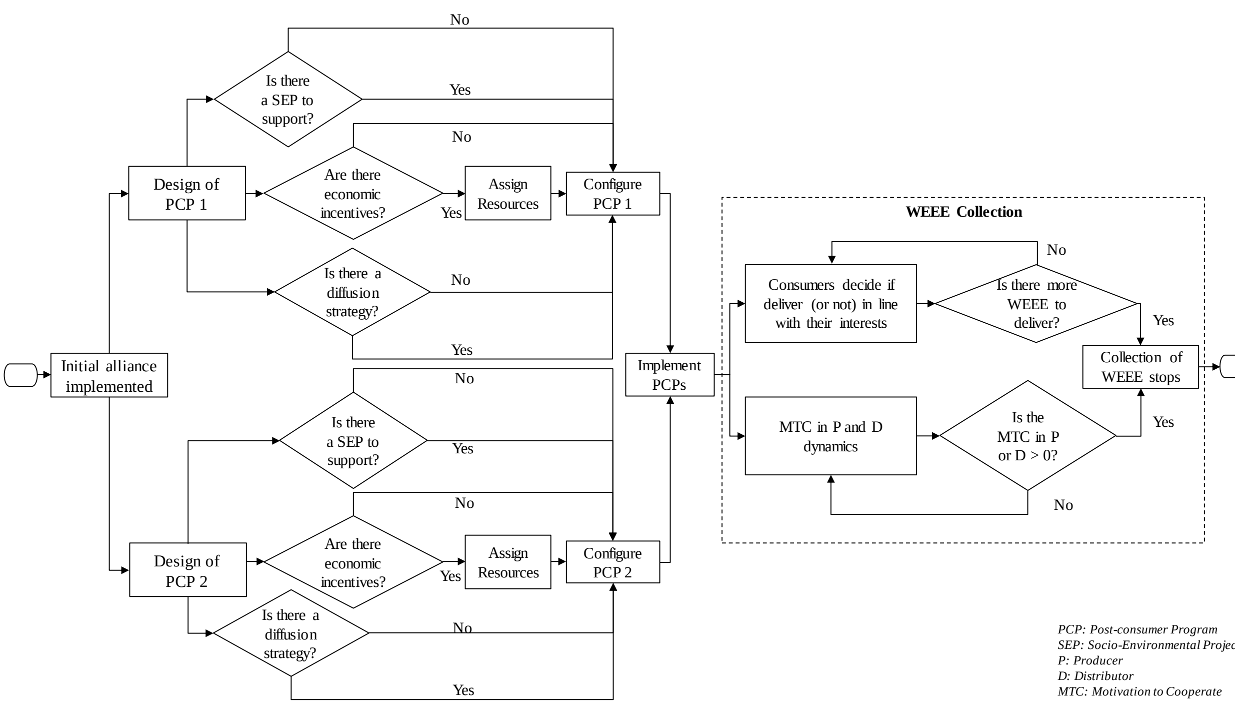
Figure 3-6: General processes of Coop4SWEEEM



The ODD defines "scheduling" as the proper order for executing events in the model. The general schedule corresponds to the previous figure (3.6), yet, within processes two and three, there were specific sub-processes that relied on two different time scales: WEEE delivery dynamics were weekly, as were changes in distributor motives, while producer motives and the amount of WEEE collected via the two PCPs was reviewed annually (in line with current Colombian regulations).

Following the logic displayed in Figure 3-6, the detailed schedule is shown in Figure 3-7.

Figure 3-7: Detailed schedule of Coop4SWEEEM processes



Once the two PCPs were implemented, their physical existence meant consumers could act. After came PCP operation, *i.e.* consumer delivery dynamics went into effect (Figure 3-7). Consumers decided (and continually decide) whether or not to deliver WEEE (measured weekly); distributor motivation to cooperate was measured weekly as a function of the amounts of WEEE collected; and, producer motivation to cooperate was measured annually (conforming to EPR-derived regulations). In parallel, the PCP-Box measured the amount of WEEE collected per week, though amounts were tallied over a year to establish how much each collection point received annually. Similarly, the potential pollution and the gap between the motivation to cooperate in producers and distributors were measured weekly.

Finally, since this model does not include options for consumers to generate additional WEEE (*e.g.* buy new EEE), one situation that may lead this model to cease functioning is consumer failure to deliver WEEE. Another would be if the motivation to cooperate in producers or distributors dropped to zero.

3.3.2 Design Concepts

Design concepts include the description of the theoretical and empirical background, as well as individual decision making and “sensing,” interaction, collectives, heterogeneity, stochastic properties, emergence and observation.

As described in Chapters 1 and 2, the principal theoretical background applied to the development of this ABM is Waste Management addressed from a systems approach and focused on WEEE, for which the Extended Producer Responsibility (EPR) principle (Lindhqvist, 2000) proves the most appropriate by virtue of its widespread use. In this theoretical context, EEE producer and distributor cooperation is needed to achieve, for example, a specific consumer-oriented WEEE collection goal (Kiddee et al., 2013; Widmer et al., 2005). This principle is complemented by the reverse logistics concept; reverse logistics holds that WEEE collected by distributors through consumer delivery is assigned to producers in order to ensure regulatory compliance (Bai and Sarkis, 2013; Chiou et al., 2012; Li and Tee, 2012).

Two different conceptions stem from the theories used to design agents in this research: producers and distributors represent organizations, while consumers represent individuals. To ensure methodological coherence, the approach to the study of their decisions must also be different. On one hand, organizations decide based on the behavioral planned theory (Ajzen, 1991), in which utility and opportunity cost drive agent interest. On the other, behavior curtailment in consumers is based on the value-belief-norm theory (Stern, P.C. et al., 1999). Regardless, economic rationality (Henrich et al., 2005) was used in the design of both agents in light of its utility for understanding the effects of incentives. Decisions in producers and distributors are based on the motivation to cooperate, which was obtained from the case study employing Actor-Network Theory (ANT) (Callon, 1986b; Latour, 2005) (see Chapter 2 for more information). However, the consumer decision model was empirically supported with data obtained in a virtual survey of students, professors, researchers, managerial and administrative staff at the Pontificia Universidad Javeriana in Bogotá. 2139 (84%) registries (within the surveys) were completed, of which 1614 (75.5%) were responded to by inhabitants from Bogotá (Appendix F).

Individual decision making in agents served as the template for the model's cooperation rules (Table 3-5).

Table 3-5: Cooperation elements in *Coop4SWEEEM*

Agent	Required cooperation activity	Primary motivation
Producers	Economically supporting the incentives included in the PCP	Complement to annual collection goals
Distributors	Having a physical space in business places to locate the urn and temporarily store the waste collected	Consumers who deliver WEEE daily became potential customers
Consumers	Delivering WEEE to the PCP	Incentives included in the PCP

"Sensing" in agents depended on the existence of PCPs. Producers and distributors increased or decreased their motivation to cooperate in function of the WEEE received in the PCP Box (as well as accumulated amount collected). Consumers decided to cooperate, *i.e.* deliver WEEE, when PCP Boxes were physically close in the spatial environment that simulated an urban area and as a function of the incentives offered to them—consumers cooperated when incentives coincided with their primary interest (economic remuneration or support of socio-environmental projects or simply stumbling across the PCP).

It is important to point out that there were no learning processes or individual predictions in this initial version of *Coop4SWEEEM*.

ODD protocol defines interaction as the direct and/or indirect (*e.g.* competition for a mediating resource) interactions through which individuals encounter and affect others. Interactions could involve communication, though, in *Coop4SWEEEM,* there was no direct communication (messages) among agents. Since the motivation to cooperate in both producers and distributors, in addition to the consumer's decision to participate, was dependent upon incentives, communication was done via PCPs.

ODD protocol provides two definitions of collectives. For the first, agents can belong to aggregations such as social groups, organizations or human networks; for the second, a separate, explicit type of entity engages in its own actions (Müller et al., 2013; Railsback and Grimm, 2011). Looking at the latter, in *Coop4SWEEEM*, there were four collectives: producers, distributors, PCP boxes and consumers. Agents in this ABM were considered heterogeneous because, as demonstrated in Table 3-4 above, they differed in parameters, preferences and decision-making criteria.

Stochasticity in the ODD protocol refers to determining which processes include randomization. To define the stochasticity in *Coop4SWEEEM*, the spatial information was defined as discrete, as were agent attributes, such as money, resources, WEEE and primary interest. However, motivation to cooperate was defined as continuous. See Table 3-6 below for further description of stochastic properties.

Table 3-6: Stochasticity in *Coop4SWEEEM*

Entity	Stochastic property	Stochasticity
Producers and distributors	Level of motivation to cooperate	Range determined by the analysis of case study data – continuous
	Spatial location within the motivation to cooperate area	Range of (x, y) coordinates showing high or low motivation – discrete
Consumers	Initial spatial location within the represented urban area	Range of (x, y) coordinates within a represented urban area – discrete
	Spatial movement within the represented urban area	Randomized (x, y) coordinates within the entire represented urban area - discrete
		If the PCP includes information diffusion strategies, the randomized movement is directly addressed to the PCP – discrete
PCP Box	Initial spatial location within the represented urban area	Range of (x, y) coordinates within a represented urban area – discrete

Spatial location and movement include randomized movement, which represented the scant or non-existent diffusion of information regarding implemented PCP in the real world—the main reason why consumers have not been apprised of these collection options. Randomized consumer movement was greater in the absence of diffusion of information regarding PCPs. Conversely, when information was spread, consumers (in accordance with their stated preferences) were drawn to the PCP. Further still, the spatial location of the two PCPs was also randomized so as to represent the physical dispersion of these programs in the real world. Also, continuous randomization helped represent differences among agents in terms of their motivation to cooperate (percentage) and, as a result, helped increase heterogeneity in the model.

To define "emergence" in the ODD protocol, the following question must be answered: What key results, outputs or characteristics of the model emerge from individuals? (Müller et al., 2013). With an eye towards improving support and enhancing decision-making in policy makers and authorities, the desired results of emergent properties in *Coop4SWEEEM*, such as higher amounts of WEEE collected and higher cooperation between actors, were made explicit. These characteristics were, in turn, linked to higher sustainability and the prevention of pollution of WEEE management. Thus, emergence in *Coop4SWEEEM* can be said to refer to two categories:

- The dynamics of WEEE collection that emerge from consumer decisions with respect to delivering waste are defined in terms of a comparison of their interests and incentives offered by the PCPs. The flip side of collected WEEE is "potential pollution" (WEEEs not delivered by consumers).
- The dynamics of motivation to cooperate in producers and distributors result from the "satisfaction of individual interests" related to collected WEEE. In addition, the observation of the maximum gap in the motivation to cooperate was interpreted as high-low potential success of the aggregated PCP (of the whole system).

The direct environmental implications of potential pollution must be complemented by the real-world consequences of not delivering WEEE to formal programs. Failing to deliver WEEE to formal programs may engender the following negative effects: i) it may fall into the informal recycling chain, which could harm the health of informal workers and the environment by releasing toxic substances; ii) it may be thrown away or disposed of (by consumers or members of the informal recycling sector) in public areas; see Vignette 2.1.1 in Chapter 2 for more on this point; and, iii) it may be discarded with ordinary waste, ending up in sanitary landfills. This situation would release toxic substances in the waste matrix and pollute natural resources, especially water sources.

The model represents the dynamics of WEEE collection and agent behavior in a single unique design of the PCPs in each run. After runs, for the sake of comparing different scenarios (*i.e.* PCP designs), the results of each possible combination should be observed; using Equation 1, this meant observing a total of fifteen combinations.

Eq. 1 $$C_{i,j} = \frac{i!}{(i - j)!}$$

Where: i is the number of parameters (3 types of incentives, on/off), and j is the number of PCPs.

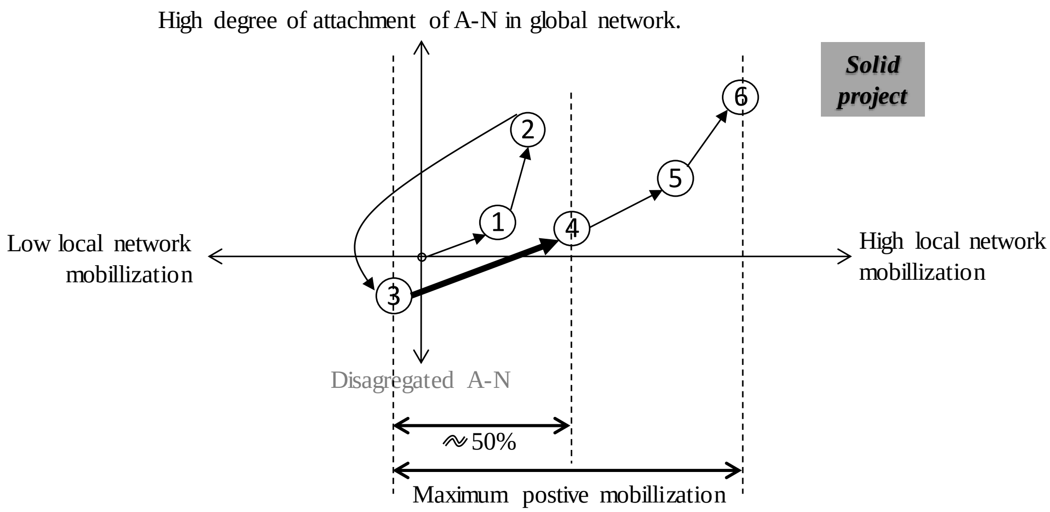
3.3.3 Translating the Conceptual Model into the Computer-based Simulation

To implement the ABM as a computer-simulation tool, the conceptual model must be translated into a computational one. The initialization elements and the following two sub-models facilitate this translation: cooperation between producers and distributors and consumer participation.

In order to define the model world's initial state, and as set forth by the "processes overview" (Figures 3.6 and 3.7 above), the initial alliance for cooperation was implemented, which created two producers and two distributors; in turn, these producers and distributors were linked to two PCPs. Every agent possessed an initial motivation to cooperate and was placed in the corresponding active area (more or less). Then, the initialization called for the design and implementation of the two PCPs. In this model, there was no input data matched to external sources, such as data files, or other models representing processes that changed over time (the ODD's definition of "input data").

The first sub-model is "Cooperation between Producers and Distributors." Analyzing the data obtained in the case study allowed for the modeling of the mobilization of actors into local and global networks. The current normative situation in Colombia, as of 2015, is the existence of regulations for some WEEE generated, in particular computers, light bulbs and batteries (Milestone *3* in Figure 3-8); that is, PCPs are designed (in this model) for collecting the aforementioned WEEE to comply Colombia's regulatory framework (Milestone *4* in Figure 3-8). As Figure 3-8 makes clear, the mobilization of agents to cooperate between these two milestones reached roughly 50% of the maximum positive mobilization. In order to randomly assign the percentage of the initial motivation to cooperate (MTCo in Equation 2 below) as part of the initial agent attributes of these agents, the range was set between 45% and 55%.

Figure 3-8: Actor mobilization in local and global networks in the single-case study of WEEE management in Colombia (see Chapter 2 for further information regarding the case study).



During operation of the PCPs, agents with more than 70% motivation were placed in the more active area (representing the local network in the real world). Furthermore, during this stage, the level of motivation (%) was measured every week (each tick in NetLogo) and adjusted according to the amount of WEEE delivered at each PCP. Change in this variable is called "satisfaction of interests" (in producers and distributors); "satisfaction of interest" dynamics are expressed by the equation 2:

Eq. 2 $$MTC(\%) = MTC_0 \pm IndividualSatisfaction$$

Individual satisfaction is a function of the WEEE collected via the PCP. It differed for producers and distributors:

- For producers, it meant increasing WEEE collected by 1% per year
- Also for producers, it meant either (cumulatively) increasing collected WEEE 5% per year (every 52 ticks in NetLogo): *e.g.* year 1, 5%; year 2, 10%; year 3, 15%; and so on. Or, conversely, reducing collected WEEE by 10% per year when it was under 5% (cumulatively). This rule represents real-world regulatory control (% of WEEE collected annually).
- For distributors, it meant increasing WEEE collected by 2% per year or reducing non-WEEE collected by 0.2% per tick (week).

The simulation stopped when the motivation to cooperate percentage of any producer or distributor reached a value of zero.

The second sub-model is “Consumer Participation.” To characterize this participation, a virtual survey of the Pontificia Universidad Javeriana community was conducted. A total of 2,139 of 2,547 questionnaires were completed. Of these, 1,614 respondents were from Bogotá and fell into the following age ranges: 18 to 22 (43.4%), 22 to 50 (47%), >50 years old (9.6%). 53.3% of consumers prefer to deliver their WEEE to a PCP located in shops and stores where EEE is sold (shops, markets). This population of 53.3% showed other additional interests (*i.e.* motivation to participate) displayed in Table 3-7.

Table 3-7: Consumer distribution according to primary motivation to participate (based on the virtual survey, Appendix F)

Primary Interest	**%***
Receive money (economic incentive)	21.7
Support social/environmental projects	70.8
Finding the box is sufficient (proximity)	3.7
Receive information about the PCP**	3.7

** Of the 53.3% motivated by PCP in stores*

*** Info. regarding what to do with WEEE and the negative impacts prevented by responsible recycling*

Each consumer started the simulation with 5 WEEE devices, and every week (tick), consumers could deliver one WEEE to a PCP-Box. The simulation should allow users to distinguish each consumer when they deliver WEEE. The simulation stopped when the total WEEE held by consumers fell below 5%.

Coop4SWEEEM was implemented using NetLogo software. Table 3-8 summarizes the agents, computational attributes and values defined in the previously described design.

Table 3-8: Agents, computational attributes and values in *Coop4SWEEEM*

Entity	**Attribute**	**Values**
Producer	Motivation to cooperate	0 – 100
	Resources	0 – 100
Distributor	Motivation to cooperate	0 – 100
Consumer	WEEE	0 – 5
	Primary interest	1 - 4
	Money received	0 - 5
Post-consumer program (PCP)	Incentive offered (1 COP per WEEE received)	On-Off
	Social/environmental project to support	On-Off
	Diffusion of information about the PCP and WEEE management	On-Off
	WEEE collected	0 - 805
	Resources bag	Start with 0
		Decreases with each WEEE received
		Increases if producer belonging to the PCP cooperates
Motivation to cooperate area	High activity zone (higher % of motivation to cooperate): x, y coordinates	(-16 to 0), (9 to 16)
	Low activity zone (lower % of motivation to cooperate): x, y coordinates	(0 to 16), (9 to 16)
Urban Area	x, y coordinates	(-16 to 16), (-16 to 8)

The complete NetLogo code is included in Appendix G. In line with the ODD protocol described above, the interface has three main areas (see Figure 3-9 below).

The initialization and input data area includes the design of the two PCPS, each of which has three kinds of incentives that can be turned on or off. Firstly, the PSA-Posc1 (or 2) corresponds to the support of a social/environmental project economically handled by producers. Secondly, the Inc$-Posc1 (or 2) refers to the offer of a direct economic incentive to consumers, such as money in exchange for turning in WEEE or redeemable bonds when buying new EEE. The third and last incentive (DifuPosc1 – or 2) is related to the diffusion of information regarding PCP via media.

Figure 3-9: Coop4SWEEEM interface[1]

The first step in *Coop4SWEEEM*, as previously stated, consisted of implementing the initial cooperation alliance, whose main result was the visualization of producers and distributors (the upper animated area in Figure 3-9). There were two producer-distributor pairs linked to PCPs 1 and 2, respectively. The second step was to design and implement the two PCPs in terms of incentives and then visualize both PCP-Boxes and consumers (the lower animated area in Figure 3-9). There were 161 consumers, 10% of survey respondents in Sub-model 2 (Section 3.3.1.3) described above, adding up to a total of 805 units of WEEE at the simulation's outset.

After carrying out the previous steps, the collection system operation commenced. During this last phase, emergence and observance were continuously displayed in the output area. Consumer dynamics (lower part) and producer-distributor dynamics (upper part) can be seen in the Animation Area in Figure 3-9 (and Figure 3-10). Producer-distributor movement here represents agent motivation to cooperate; the value of this motivation increases or decreases according to the design described in Sub-model 1. For its part, the animation of consumers shows both their randomized movement relative to the location PCP Boxes; color changes correspond to consumer decisions regarding WEEE delivery (Figure 3-10).

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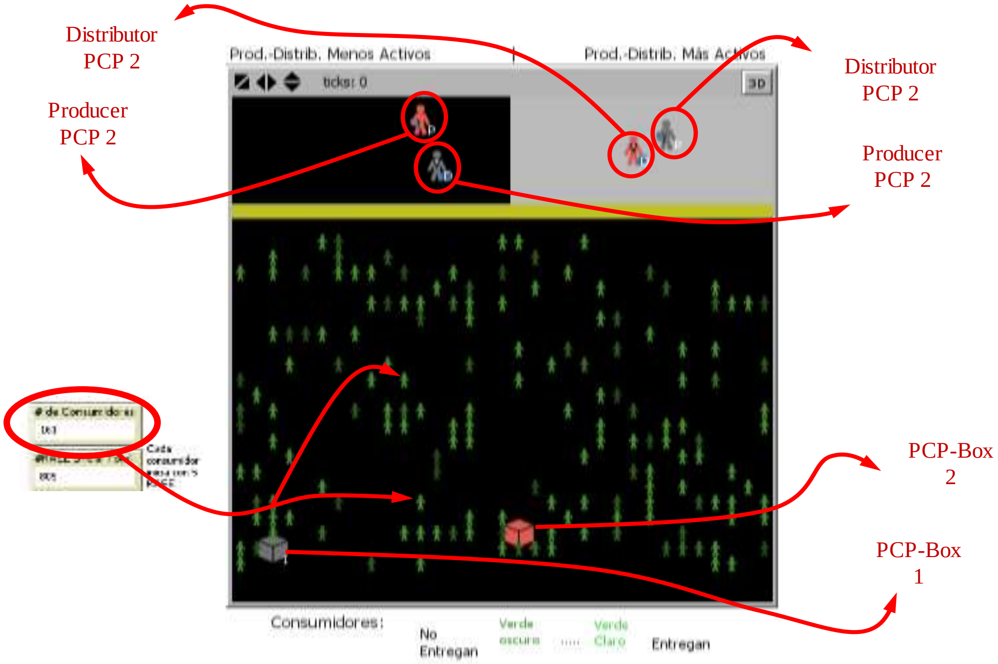
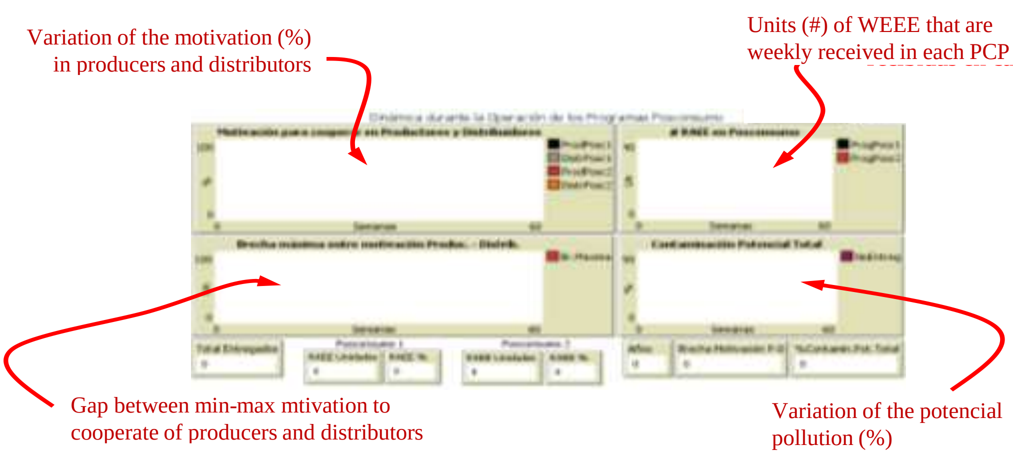
[1] This figure is in Spanish, given that it is a screenshot of the simulation used for the Case Study in Colombia, a Spanish-speaking country

Figure 3-10: Animation Area Details[2]



Turning attention to the graphs in the output area (Figure 3-11), producer and distributor motivation changed in response to consumer delivery of WEEE, as well as potential pollution (%).

Figure 3-11: Visualization of emergence and observation (output area)[3]



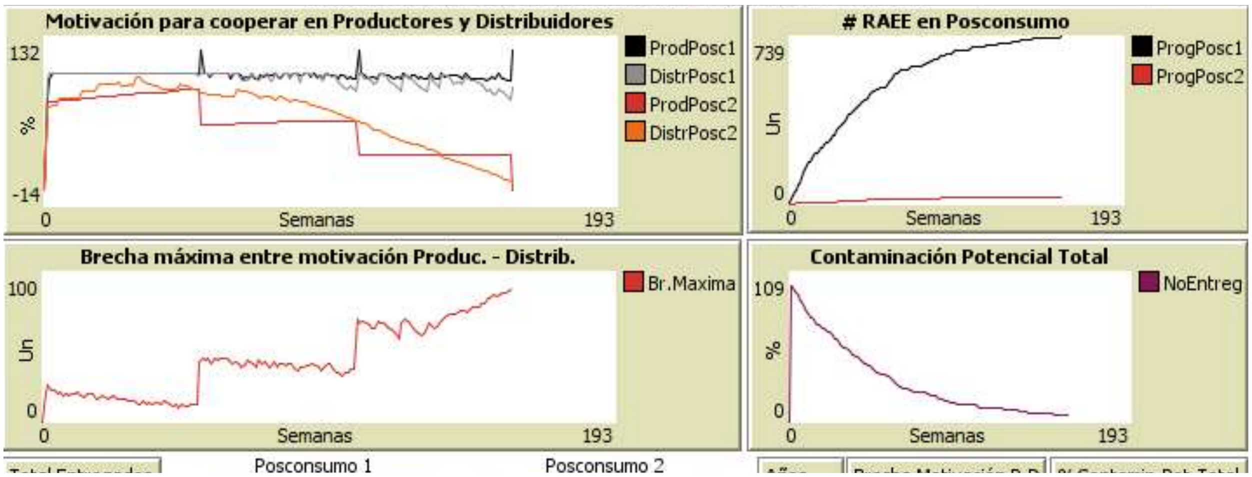
A clear example of how the model works is seen in Figure 3-12. This figure illustrates results of the scenario in which PCP-1 includes consumer incentives and PCP-2 does not include any. For

[2] This figure is in Spanish, given that it is a screenshot of the simulation used for the Case Study in Colombia, a Spanish-speaking country

[3] This figure is in Spanish, given that it is a screenshot of the simulation used for the Case Study in Colombia, a Spanish-speaking country

the sake of clarity, the graphs of the gap in motivation and potential pollution do not show data for each PCP; instead, they portray accumulated data.

Figure 3-12: Example displays for one scenario (final simulated scenarios are shown in part 3.5 below)[4]



At the end of each simulation run, the amount of WEEE collected by each PCP (as units and percentage), in addition to total time (years), final motivation gap and potential pollution were displayed in the output area. These data represent the criteria taken into account for each alternative (scenario) in the multi-criteria tool.

In order to evaluate implementation of the ABM, an experimental design was utilized. Results can be consulted in Appendix G.

3.4 The Multi-Criteria Decision-Making Tool

The multi-criteria decision-making (MCDM) tool consists of a list of alternatives (scenarios simulated in *Coop4SWEEEM*) and criteria used to choose or reject alternatives (a_i). To prioritize alternatives, the weighted sum method was employed (Caterino, 2009; Fishburn, 1967); this method requires a weight (w_i) be assigned to each criterion (j), until 100% is assigned (Equation 3).

Eq. 3 $\sum_j a_{ij} w_{ij}$

Four criteria were defined on basis of the results of the case study and literature review. Firstly, the amount of WEEE collected, the parameter included in policies and regulations as the unit of required producer collection amounts. Secondly, the time elapsed between the simulation's

[4] This figure is in Spanish, given that it is a screenshot of the simulation used for the Case Study in Colombia, a Spanish-speaking country

beginning and end, which represents the number of years needed to collect the WEEE assigned to consumers. Thirdly, there was the final gap between producer and distributor motivation. Fourthly, there was the percentage of potential pollution registered at the end of the simulation.

The weighted sum method was programmed in an Excel spreadsheet (Table 3-9 below); each cell was filled with data obtained from each run of the *Coop4SWEEEM* simulation. Each weight in the table could be changed by decision-makers (DES attendees) in order to generate debate about the importance of including the perspectives of different actors involved in the decision-making process.

Table 3-9: Structure of the multi-criteria decision-making (MCDM) tool

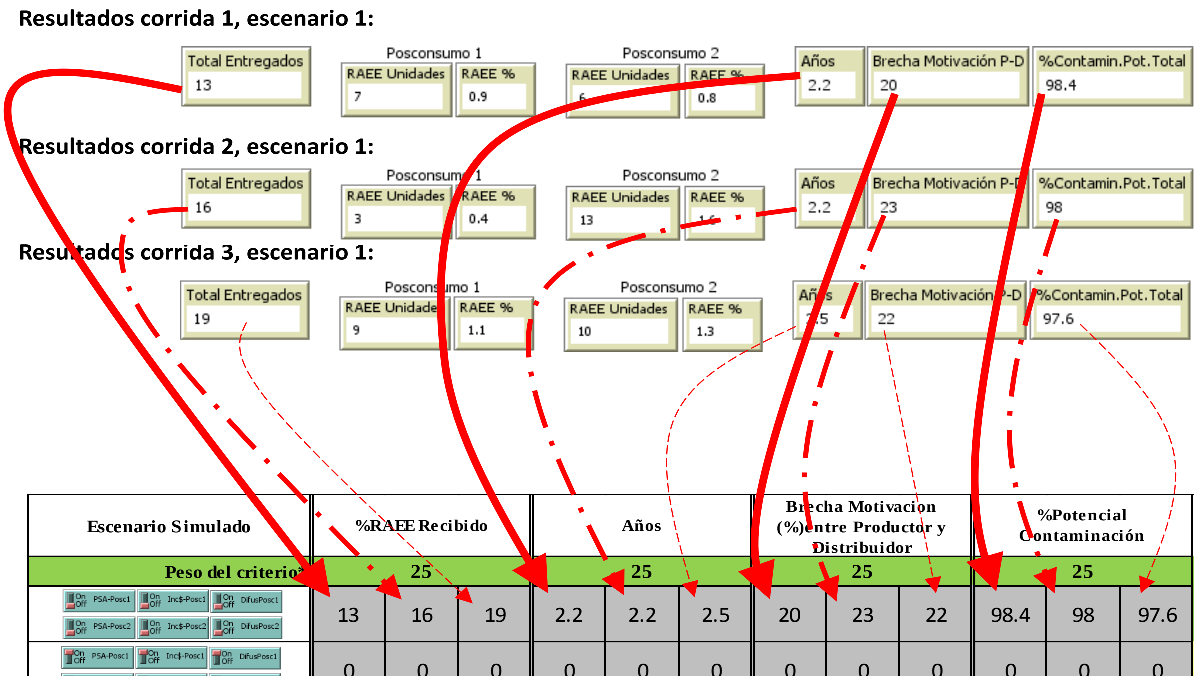
Scenario	Simulated scenario	% WEEE Collected			Years			Motivation gap (%)			Potential pollution (%)			Prioritization
	Criterion weight*	25			25			25			25			*100*
1	**Scenario 1**	50	0	0	1	0	0	20	0	0	40	0	0	0
2	**Scenario 2**	20	0	0	0,2	0	0	50	0	0	20	0	0	0
3	**Scenario 3**	30	0	0	2	0	0	20	0	0	60	0	0	0
4	**Scenario 4**	40	0	0	3	0	0	60	0	0	10	0	0	0
5	**Scenario 5**	50	0	0	6	0	0	90	0	0	50	0	0	0
6	**Scenario 6**	90	0	0	0,4	0	0	2	0	0	5	0	0	0
7	**Scenario 7**	90	0	0	20	0	0	50	0	0	2	0	0	0
8	**Scenario 8**	70	0	0	10	0	0	5	0	0	80	0	0	0

Prioritization scale

The worst **The best**

** The sum of the weights has to be equal to 100. The highest value corresponds to the most important criterion in the decision*

Figure 3-13: Relationship between the two T-Ts (Coop4SWEEEM simulation and MCDM [Excel])[5]



3.5 DES Setup

At first, to engage attendees, a shared understanding of key concepts had to be inculcated. A perfect example is the meaning of *systems approach*. This was defined as an approach that takes the following into account i) social, cultural, economic, politic, technical and environmental dimension; ii) roles within WEEE management (government, producers, distributors, consumers, and formal and informal recyclers); iii) stages of WEEE management in Colombia (production/importation, distribution, use/reuse, collection, pre-treatment, treatment, exportation); and, iv) circular cause-effect relationships stemming from current decisions in the short-, medium- and long-terms. A *post-consumer program* (PCP) was defined as a collection strategy that consists of an urn (a box) physically available at EEE points of sale. A PCP should also offer incentives aimed at influencing consumers, and thereby the amount of WEEE collected.

The third key concept was *cooperation*. In this DES, cooperation refers to the performance of activities that different actors should carry out—together—in order to achieve more sustainable WEEE management. The specific activities required of each actor involved in the simulated collection system, along with the primary motivation of each, are shown in Table 3-10.

[5] This figure is in Spanish, given that it is a screenshot of the simulation used for the Case Study in Colombia, a Spanish-speaking country

Table 3-10: Main cooperation elements in the *Coop4SWEEEM* simulation

Actor	Cooperation activity	Primary motivation
Producers	Economically support the incentives included in the PCP	Complement annual collection goals
Distributors	Having a physical space in the business to place the box and temporarily store collected waste	Consumers that delivered WEEE on a daily basis were potential customers
Consumers	Delivering WEEE to the PCP	PCP incentives

After explaining the definitions of the key concepts presented, DES goals were described. The general objective was to decide on issues that affect sustainability in WEEE management. The three specific objectives were: i) identify aspects that influence cooperation between EEE producers and distributors; ii) visualize producer-distributor cooperation and PCP results implemented in terms of quantity of WEEE collected; and, iii) identify variables that influence consumer dynamics in terms of WEEE delivered.

Next, the tools were described to the group, starting with the individual (groups of 2 or 3 people); to instruct participants in the usage of *Coop4SWEEM*, in the T-T's function and logic, Scenario 1 (of 8 total) was simulated in as shown in Figure 3-14.

Figure 3-14: Scenarios simulated in Coop4SWEEEM within the DES

The multi-criteria table was outlined, as well as the final decision exercise as a whole group. In this table, the eight scenarios run in *Coop4SWEEE* corresponded to the alternatives. In addition, each team observed different simulation results in terms of the criteria included in the complementary decision-making tool.

The last part of the individual decision exercise was guided by information in Table 3-11. The main goal was to elicit discussion of the criteria and their weights as part of the decision-making process. Each team was able to propose different (additional) weight combinations to reflect their own interests and opinions.

Table 3-11: Last individual decision-making exercise within the DES

Simulated scenario	% WEEE Collected	Years	Motivation gap (%)	Potential polution (%)
Criterion weight	**25**	**25**	**25**	**25**
The 2 best alternatives	#	*Explanation of the reasons for choosing each alternative*		
Criterion weight	**100**	**0**	**0**	**0**
The 2 best alternatives	#	*Explanation of the reasons for choosing each alternative*		
Criterion weight	**0**	**100**	**0**	**0**
The 2 best alternatives	#	*Explanation of the reasons for choosing each alternative*		
Criterion weight	**0**	**0**	**100**	**0**
The 2 best alternatives	#	*Explanation of the reasons for choosing each alternative*		
Criterion weight	**0**	**0**	**0**	**100**
The 2 best alternatives	#	*Explanation of the reasons for choosing each alternative*		

The results of the individual phase were shared with the rest of the attendees in order to generate constructive debate to conclude (if possible) with a single group decision regarding PCP design and define the best criteria and weights to make related decisions. In the end, the validation instrument of the Technology Acceptance Model (TAM) was developed by attendees, including a *yes/no* question aimed at verifying whether or not the decision-making process was more systemic than the "traditional" approach. See Chapter 4 for more details related to validation.

3.6 The Decision-Enhancement *Studio* in Action

The DES was developed at the Pontificia Universidad Javeriana on October 25, 2015. The 16 attending institutions, organizations and companies, listed in Table 3-12, represented the main WEEE management decision makers in Colombia who have taken part in the milestones identified in the case study (Chapter 2).

Table 3-12: DES attendees

MADS - *Ministerio de Ambiente y Desarrollo Sostenible*	CI Recyclables SAS - (Authorized WEEE recycler)
ANDI – *Asociación de Industriales de Colombia*	Click on Green - (Authorized WEEE recycler)
WRF - World Resources Forum (Switzerland)	OCADE SAS - (Authorized WEEE recycler)
Empa - Swiss Federal Laboratory for Material Science and Technology (Switzerland)	LITO SAS - (Authorized WEEE recycler)
Red Verde – Post-consumer program (home appliances)	Trade pro escrap SAS - (Authorized WEEE recycler)
CNPML - *Centro Nacional de Producción Más Limpia*	Lasea Soluciones - (Authorized WEEE recycler)
EcoCómputo Corporation - PCP (computers)	Megaserviciosplus SAS - (Authorized WEEE recycler)
Pontificia Universidad Javeriana	Gaia Vitare SAS - (Authorized WEEE recycler)

Protocol development is shown in the pictures below (Figure 3-15). The moderator—the author of this doctoral thesis—explained the main concepts under consideration, such as *systems approach*, *PCP cooperation* and *T-Ts* (Row 1 in Figure 3-15 below).

It is important to highlight that two of the four main PCPs attended the DES: *EcoComputo* was the first PCP implemented (2012) after legal regulations went into effect (2010) and *Red Verde* is the most recent PCP (2014).

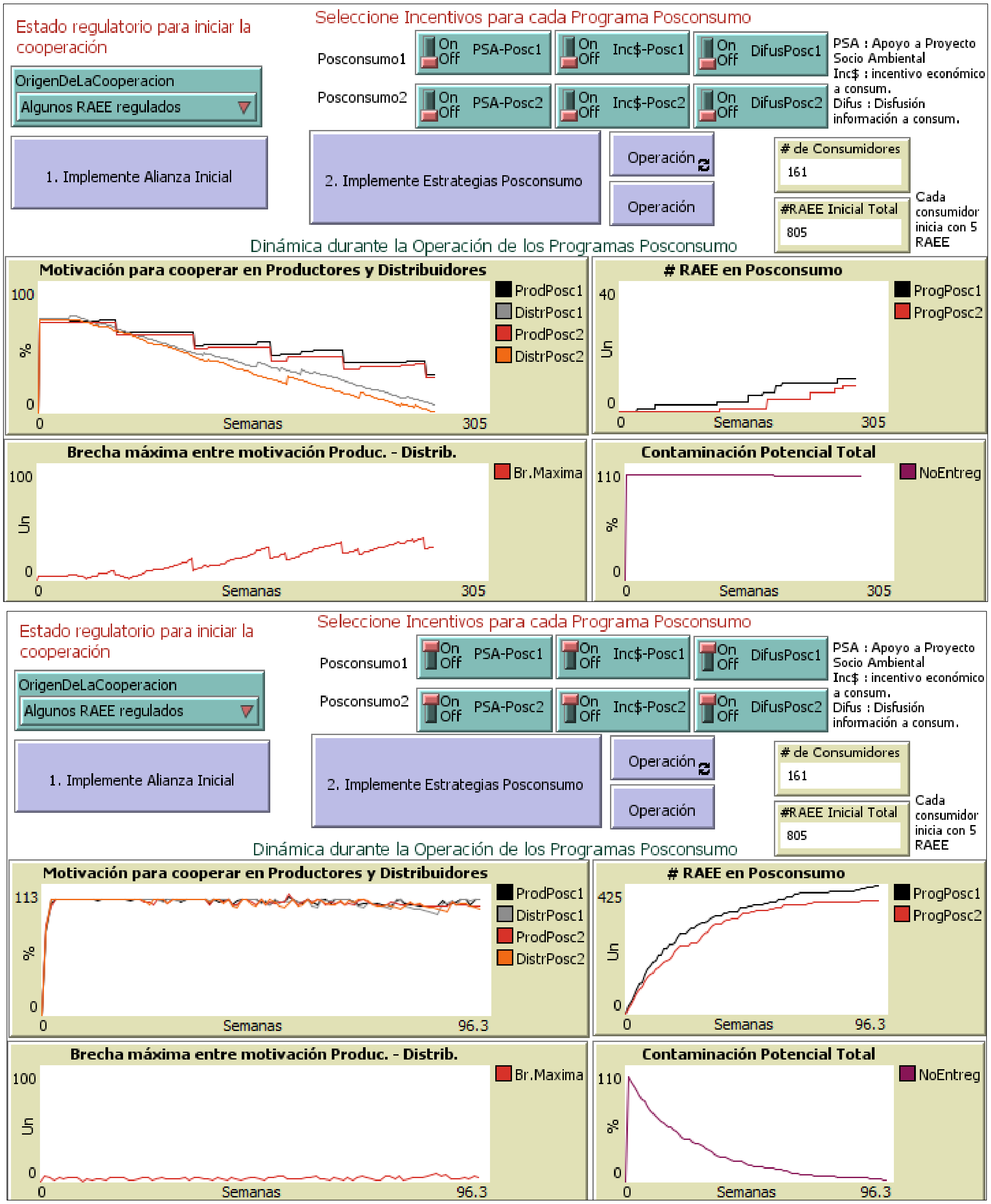
The estimated time needed to develop the DES's agenda (Table 4-1) was fulfilled almost as exactly as planned. However, the use of the simulation for individual decision making took longer than expected, leaving the group decision-making portion of the DES only 30 minutes (Row 4 in Figure 3-15 below). In spite of time pressure, the group managed to discuss the key elements and achieve the DES's goals, which are developed below (see Section 3.6.4).

Figure 3-15: DES development in images

3.6.1 Using Coop4SWEEEM

The eight scenarios included in Figure 3-16 were simulated. The first two (shown in Figure 3-14 above) sought to determine if PCPs should include incentives. All scenarios produced different designs for incentives within the PCPs and concomitant cooperation of producers, distributors and consumers. To illustrate two opposite scenarios, the results of the first two are included in Figures 3.16 and 3.17. A comparison of these two figures leaves no doubt that PCPs with incentives (Scenario 2) achieve greater consumer participation than those without incentives (Scenario 1). It is also worth adding that potential pollution is inversely proportional to consumer participation. Consequently, when the former is lower when the latter is higher, as was the case for Scenario 2.

Figure 3-16: Simulation outputs for scenarios 1 and 2 in Figure 3-14 (above)[6]



Conversely, the motivation to cooperate in producers and distributors plummets rapidly when consumers do not participate. This fact can be observed in the Animation Area (Figure 3-17).

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[6] This figure is in Spanish, given that it is a screenshot of the simulation used for the Case Study in Colombia, a Spanish-speaking country.

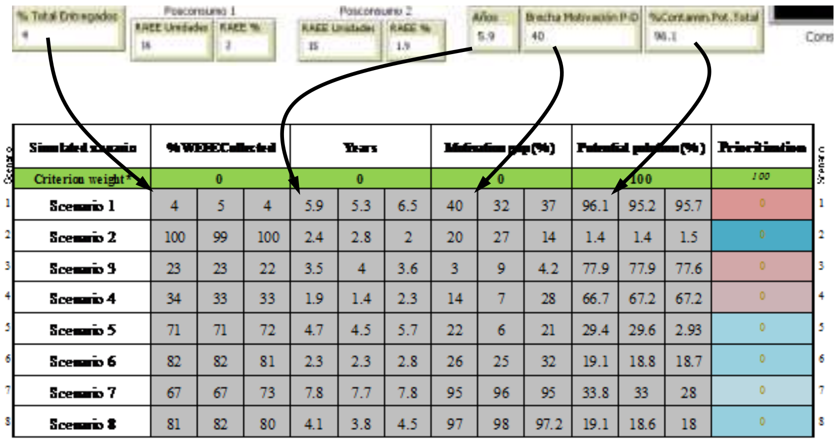
Figure 3-17: Results of simulation of scenarios 1 (left) and 2 (right) in the "Animation Area" of Co-op4SWEEEM[7]

3.6.2 The Multi-Criteria Decision-Making Process

The results of the eight scenarios run in *Coop4SWEEEM* (in triplicate to observe the tendencies) were registered in MCDT as seen in Figure 3-18.

[7] This figure is in Spanish, given that it is a screenshot of the simulation used for the Case Study in Colombia, a Spanish-speaking country.

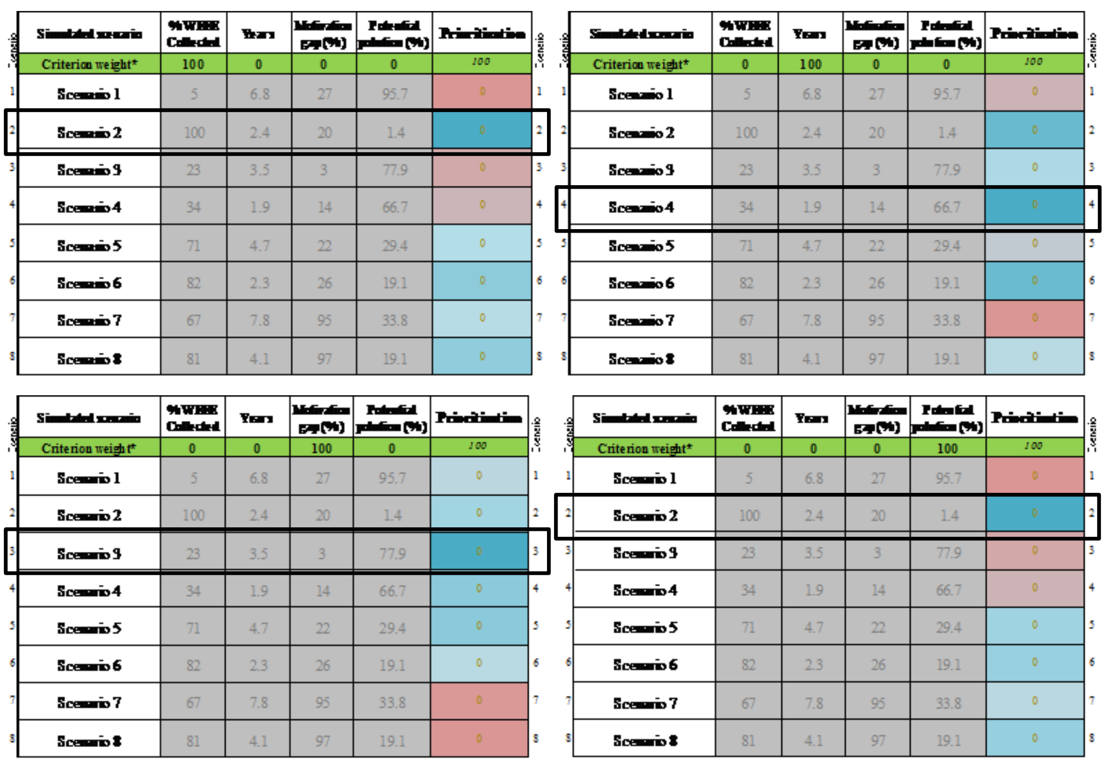
Figure 3-18: Simulation results of the eight scenarios in Coop4SWEEEM[8]



Scenario	Simulated scenario	%WEEE Collected			Years			Motivation gap (%)			Potential pollution (%)			Prioritization	Scenario
	Criterion weight*	0			0			0			100			100	
1	Scenario 1	4	5	4	5.9	5.3	6.5	40	32	37	96.1	95.2	95.7	0	1
2	Scenario 2	100	99	100	2.4	2.8	2	20	27	14	1.4	1.4	1.5	0	2
3	Scenario 3	23	23	22	3.5	4	3.6	3	9	4.2	77.9	77.9	77.6	0	3
4	Scenario 4	34	33	33	1.9	1.4	2.3	14	7	28	66.7	67.2	67.2	0	4
5	Scenario 5	71	71	72	4.7	4.5	5.7	22	6	21	29.4	29.6	2.93	0	5
6	Scenario 6	82	82	81	2.3	2.3	2.8	26	25	32	19.1	18.8	18.7	0	6
7	Scenario 7	67	67	73	7.8	7.7	7.8	95	96	95	33.8	33	28	0	7
8	Scenario 8	81	82	80	4.1	3.8	4.5	97	98	97.2	19.1	18.6	18	0	8

Once the entire table was filled in, each group discussed the changes in prioritization according to the variation of criteria weights, which is displayed in Figure 3-19. The main goal of this step within the DES was to generate reflections regarding the differences between individual points of view. For instance, the amounts of WEEE collected may be the most important criterion for one decision maker, while collecting WEEE in the shortest amount time feasible may be more important for another.

Figure 3-19: Scenario prioritization according to criterion weights



Scenario	Simulated scenario	%WEEE Collected	Years	Motivation gap (%)	Potential pollution (%)	Prioritization	Scenario
	Criterion weight*	100	0	0	0	100	
1	Scenario 1	5	6.8	27	95.7	0	1
2	Scenario 2	100	2.4	20	1.4	0	2
3	Scenario 3	23	3.5	3	77.9	0	3
4	Scenario 4	34	1.9	14	66.7	0	4
5	Scenario 5	71	4.7	22	29.4	0	5
6	Scenario 6	82	2.3	26	19.1	0	6
7	Scenario 7	67	7.8	95	33.8	0	7
8	Scenario 8	81	4.1	97	19.1	0	8

Scenario	Simulated scenario	%WEEE Collected	Years	Motivation gap (%)	Potential pollution (%)	Prioritization	Scenario
	Criterion weight*	0	100	0	0	100	
1	Scenario 1	5	6.8	27	95.7	0	1
2	Scenario 2	100	2.4	20	1.4	0	2
3	Scenario 3	23	3.5	3	77.9	0	3
4	Scenario 4	34	1.9	14	66.7	0	4
5	Scenario 5	71	4.7	22	29.4	0	5
6	Scenario 6	82	2.3	26	19.1	0	6
7	Scenario 7	67	7.8	95	33.8	0	7
8	Scenario 8	81	4.1	97	19.1	0	8

Scenario	Simulated scenario	%WEEE Collected	Years	Motivation gap (%)	Potential pollution (%)	Prioritization	Scenario
	Criterion weight*	0	0	100	0	100	
1	Scenario 1	5	6.8	27	95.7	0	1
2	Scenario 2	100	2.4	20	1.4	0	2
3	Scenario 3	23	3.5	3	77.9	0	3
4	Scenario 4	34	1.9	14	66.7	0	4
5	Scenario 5	71	4.7	22	29.4	0	5
6	Scenario 6	82	2.3	26	19.1	0	6
7	Scenario 7	67	7.8	95	33.8	0	7
8	Scenario 8	81	4.1	97	19.1	0	8

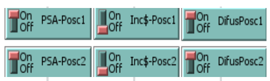
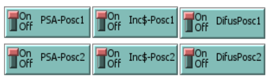
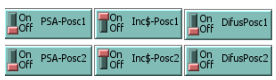
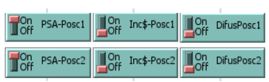
Scenario	Simulated scenario	%WEEE Collected	Years	Motivation gap (%)	Potential pollution (%)	Prioritization	Scenario
	Criterion weight*	0	0	0	100	100	
1	Scenario 1	5	6.8	27	95.7	0	1
2	Scenario 2	100	2.4	20	1.4	0	2
3	Scenario 3	23	3.5	3	77.9	0	3
4	Scenario 4	34	1.9	14	66.7	0	4
5	Scenario 5	71	4.7	22	29.4	0	5
6	Scenario 6	82	2.3	26	19.1	0	6
7	Scenario 7	67	7.8	95	33.8	0	7
8	Scenario 8	81	4.1	97	19.1	0	8

[8] This figure is in Spanish, given that it is a screenshot of the simulation used for the Case Study in Colombia, a Spanish-speaking country.

3.6.3 The Decision

This 9-group individual decision exercise, which formed the basis for full group discussion, culminated in the two following questions: i) based on the previous steps, what elements should be integrated into a post-consumer program (PCP)?; and, ii) which criterion (or criteria) included in the discussion would promote greater sustainability of the proposed strategy, and what should its corresponding weight be? The votes broke down as shown in Table 3-13.

Table 3-13: Results of the voting on the best PCP design

PCP design (scenario)			Voting
6		Include an incentive to support social and environmental projects rather than economic incentives; also include media dissemination of the program	53.80%
2		Include support for socio-environmental projects and an economic incentive; also include media dissemination of the program	30.80%
3		Include an economic incentive	7.70%
5		Include an incentive to support social and environmental projects	7.70%

Looking at each component individually (the two kind of incentives and media dissemination of the program), the incentive to support a social/environmental project and include dissemination received the most votes (92% and 84%, respectively), while the economic incentive garnered 38.5% of votes.

Finally, the criteria were prioritized as follows: amount of collected WEEE (average assigned weight: 49%), time needed for collection (average assigned weight: 29%), percentage of potential environmental pollution (average assigned Weight: 13%) and motivation gap between producers and distributors (average assigned weight: 9%).

3.6.4 Decisions are about Concepts and Interests

In this subsection, select narratives and opinions extracted from notes and records of the results from the last part of the DES are shared here to demonstrate attendees' grasp of the elements of the *systems approach* definition.

a) The representative for *Click on Green*, a formal recycler, said that "the main obstacle to effectively collecting and managing WEEE is the lack of consumer awareness and participation; that's why the current system is unsustainable." The representative went on to add, "to develop strategies to tackle this obstacle and informal recycling, illegal practices and technical deficiencies, the involvement of actors is required".

b) The MADS representative said that, "*homo economicus* must be considered when designing incentives, especially since the informal sector takes advantage of this facet of human beings." Nevertheless, "economic incentives might work at first, but, in the long-term, may become unsustainable. Given that people in the Colombian context always expect money, environmental education should be complementary and continually implemented to guarantee sustainability." The representative for *CI Recyclables SAS*, a formal recycler, echoed the MADS's representative, saying that "the day there isn't any money to buy WEEE, the system will collapse."

c) The MADS representative also proposed that "sustainable WEEE management should include strategies to minimize waste generation instead of solely looking at the collection of already generated waste. Strategies, then, could include, for example, both environmental education for children in schools and young people in universities, and economic incentives for adults."

d) According to the representative of *EcoComputo*, a PCP, "it is necessary to make it clear to consumers that environmentally responsible management comes with a cost, which means it isn't true that only recyclers earn money." In this sense, "when consumers deliver their WEEE to the system, they're actually making a contribution to the protection of the environment, instead of just supporting recycling businesses."

e) The representative for *Lito SAS*, a formal recycler, said that Colombians "are deeply moved by both social causes and social recognition. That is why supporting social/environmental projects is a powerful incentive. Additionally, an interesting complementary incentive could be, for instance, the promotion of *the most responsible consumer of the month* in media."

f) According to the representative of the National Cleaner Production Center, a nationally-recognized expert in WEEE management, "the question should not be about how to avoid program costs, because implementing more sustainable WEEE management programs necessarily entails financial investment. For that reason, the question should refer to where the money is going to come from and where it will go (within the management processes)."

Previous narratives include the four elements of the systems approach proposed in this research (see Table 3-14).

Table 3-14: Elements of the systems approach to WEEE management included in the narratives comprising the last part of the DES

		Narrative					
		a)	b)	c)	d)	e)	f)
Elements to make more systemic decisions to achieve a more sustainable WEEE management	Different dimensions of the problem	Technical, institutional, legal	Economic, cultural	Cultural, economic, social	Environmental, economic, social	Social, cultural, environmental	Economic, logistic
	Different stakeholder targets	Consumers, actors articulation	Consumers, informal recyclers,	Consumers, recyclers, academia	Consumers, recyclers	Consumers, society	" who will give the money …"
	Processes within WEEE management	Collection, recycling	Collection, recycling, management	Generation, collection	Recycling, management	Collection	Collection, management ("…and where …")
	Circular cause-effect relationships stemming from current decisions in both the short-, medium- and long-terms	" … that is why the system is unsustainable … " " … to develop … engagement is required"	".. work in the short term but …" ".. Could become unsustainable" "… continually impemented … " " … the day there is no money …" "… the system will collpase"	" … should include … to minimize …" " … then, the strategies should include … and ..."	" … when conusmers deliver … " "… making a contribution to the environment … supporting recyclers"	" … are deeply moved by …" "	" … to implement more sustainable … it is necessary …"

Furthermore, the discussion of criteria and their weights helps paint other perspectives and, in turn, is conducive to a more systemic understanding of the WEEE management, which is reinforced by the fact that some attendees proposed additional criteria according to their own worldview as follows: socio-economic level and geographical origin (*e.g.* rural, urban) of consumers, additional incentives such as an advance recycling fee and different types of WEEE (large appliances, for example).

Although the producer-distributor motivation gap and potential pollution were the least important criteria for the whole group, two important facts merit highlighting. On one hand, a recycler stated that the motivation to cooperate should be the most important criterion, for there may be significant discrepancies between producers and distributors that limit the system's sustainability. On the other hand, the representative for the producers chose environmental pollution as the main criterion within the DES, which aligned with what was learned during activities prior to this participatory design, in particular the interview (March 2014) and the strategy design (April 2015).

4 The Decision-Enhancement Studio (DES) for More Systemic Decisions

4.1 Introduction

In Chapter 1, the simulation-based approach was proposed as a way to tackle the lack of a systems approach in decision-making processes. In Chapter 2, the results of the case study laid out the requirements needed to achieve more sustainable WEEE management, particularly the requirements needed to design a decision-enhancement studio (DES) that includes people (policy-makers as the decision makers, and the facilitator), processes guiding the DES as the main facilitative environment for decisions, technological-tools (T-T) and protocols.

Chapter 3 presented and discussed the DES design, as well as the results of its implementation. Here, in Chapter 4, the validation is presented. A discussion of validation results supports: i) the design's reliability; ii) the utility of a simulation-based approach as part of the T-Ts; and, iii) provides elements needed to answer the main questions of this doctoral research. For a description of the scientific and practical contributions of this doctoral research, readers are referred to the Epilogue (Chapter 5).

4.2 Instruments for Validating the DES

Design science research (DScR) dictates that research cycles include relevance, design, and rigor (see Section 1.4.2); applying the tenets of DScR, iterative validation processes were developed. In the relevance cycle, requirements were identified and tested with the main actors involved in WEEE management in the case studies. To obtain a conceptual model that sufficiently represented reality, the design cycle relied on a continuous validation not only with real actors in the system, but also with experts.

First and foremost, the conceptual model of the ABM (as part of the T-T), which was structured following the ODD protocol and then implemented with the Software NetLogo, was validated at different moments. Initially, validation was performed pre-DES, which included the evaluation described in Chapter 3. Then, validation was performed "during;" that is, the DES, the ABM and simulation, in addition to other tools, were validated during the development of the DES. This validation employed the technology acceptance model (TAM) instrument, as well as notes and tapes of key moments of process (*e.g.* when each group shared individual results before a whole group discussion of proposed decisions). Finally, validation was performed after the DES: all of the questionnaires, validation instruments and main group discussions were gathered and analyzed in order to identify the concepts and arguments of the actors involved.

Some of the instruments used the Likert scale, which ranges from strongly disagree to strongly agree, as well as a number of Yes/No questions. These were applied to different constructs related to the artifact under validation. The Likert scale was defined as follows: Strongly disagree (1 point), disagree (2 points), neither disagree nor agree (3 points), agree (4 points) and strongly agree (5 points). Results were analyzed by median and interquartile range (IQR) to obtain a more accurate representation of the central tendency and the variability in responses. In addition, analysis focused on the percentage of agree (4) and strongly agree (5) answers given the nature of Likert scale responses, for as Susan Jamieson (2004) argues, intervals between Likert values cannot be considered equal, essentially rendering the mean and standard deviation inappropriate statistics (Jamieson, 2004).

Pre-DES validation focused on *Coop4SWEEEM*; it was developed with five national and international experts from two primary fields: WEEE management and agent-based modeling. The 16 DES attendees evaluated both the DES and T-Ts in line with the TAM.

4.2.1 Instrument for Validating Coop4SWEEEM

The validation of the conceptual agent-based model was used to verify that the simulation was sufficient to elicit the expected discussions within the DES. The constructs, Statements 1 to 13, are shown in Tables 4.1 and 4.2.

Table 4-1: The constructs (and their arguments) included in the validation of the conceptual model and its operationalization

	Statement	**Argument**
	Conceptual model and operationalization	
1	The assumptions and theories that constitute the conceptual model of *COOP4SWEEEM-1.0* allow for the reasonable representation of the model's purpose	Theoretical background is important to properly characterize human decisions in ABM (Feola and Binder, 2010; Grimm et al., 2010; Müller et al., 2013)
2	Agent behaviors reasonably represent reality	This ABM will support decisions by representing possible real cooperative scenarios; hence, the accurate representation of reality is important (Grimm et al., 2010).
3	*COOP4SWEEEM-1.0* allows for the identification of emergent properties defined in the conceptual model	To support policy makers in decision making, the patterns they would like to maximize with the decision is defined as emergence (Koen H. van Dam, 2013)

Specific statements related to the animation and the output data displayed in the simulation were tested with the same ABM and WEEE management experts; see Table 4-2.

Table 4-2: The constructs (and their arguments) included in the validation of the animation and output data of the computer-based simulation

	Statement	Argument
	Animation	Animation is an important communication tool (Nikolic, I. et al., 2013)
4	Animation allows you to identify the moments when producers and distributors are most active, that is, when they are more motivated to cooperate (top of the screen)	In order to successfully implement EPR strategies, producers and distributor cooperation is relevant (Kiddee et al., 2013; Widmer et al., 2005)
5	The animation allows you to identify producers in charge of PCPs with low rates of WEEE collection from consumers (*i.e.* malfunctioning PCP), which is a behavior reflected by low cooperative activity	In a EPR program, the producer is directly responsible for meeting collection goals (Lindhqvist, 2000)
6	The simulation allows you to determine which consumers delivered WEEE and which did not in each simulated scenario	In any waste management program that implies reverse logistics, it is important to analyze consumer behavior (Bai and Sarkis, 2013; Li and Tee, 2012)
	Output data	Proper visualization caveats are important communication goals in a ABM (Nikolic, I. et al., 2013)
7	Changes in producer and distributor motivation to cooperate depend on the dynamics of WEEE returned by consumers	In order to successfully implement EPR strategies, producers and distributor cooperation is relevant (Kiddee et al., 2013; Widmer et al., 2005). Data collected in the exploratory case study, as well as specific papers, were used to design these behaviors
8	Distributor motivation to cooperate depends on the increase in potential customers, which is represented as consumers utilizing the PCP	
9	Changes in producer and distributor motivation to cooperate are evident at different times: for producers annually; for distributors, weekly	
10	The implementation of post-consumer incentive programs generates greater consumer return of WEEE	Incentives are important to motivate consumers participation (Bacot et al., 1994; Griskevicius and Kenrick, 2013; Hernandez and Martin-Cejas, 2005). In addition, economic incentives (Dopfer, 2005; Henrich et al., 2005); socio-economic causes (Kerr et al., 2012) are the main motivations—verified in the massive survey
11	The implementation of economic incentives influences consumers less than incentives in the form of supporting socio-environmental projects (compare scenarios)	
12	The implementation of post-consumer incentive programs to consumers generates less potential pollution than if not offered	

	Statement	Argument
	Animation	Animation is an important communication tool (Nikolic, I. et al., 2013)
13	The implementation of post-consumer incentive programs influences the motivation to cooperate in producers and distributors (circularity of influence)	Causal relationships are relevant in a systems approach (Andrade et al., 2007; Nikolic, I. et al., 2013), especially circular causality: in contrast to systems thinking, conventional thinking assumes single causality, rather than multiple, interrelated causality (Reynolds, 2010)

In the pre-DES evaluations, *Coop4SWEEEM*'s utility with regard to its support of more systemic decisions as part of the DES was tested with the following "yes/no" questions (Table 4-3).

Table 4-3: The constructs (and their arguments) included as "yes/no" questions in the validation of the T-Ts

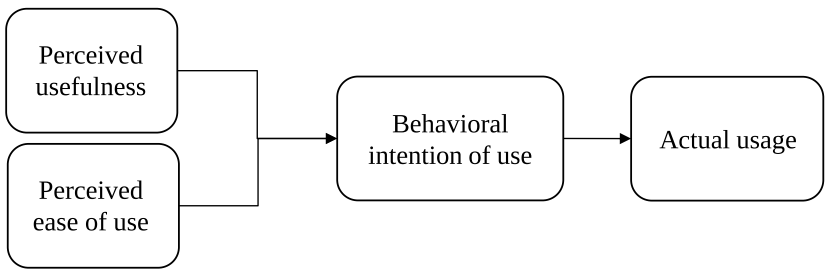
	Y/N Question	Argument
14	In your opinion, does the simulation elicit discussion about more than one process (or stage) within the WEEE management system as regards the decision-making process? (*e.g.* production, generation, collection, pre-treatment, recycling, recovery, final disposal)	To ensure the inclusion of more than one WEEE management process as part of the definition of systems approach in this research
15	In your opinion, does the simulation elicit discussion about more than one dimension within the WEEE management system as regards the decision-making process? (*e.g.* technical, social, cultural, environmental, political, institutional, economic)	To ensure the inclusion of more than one WEEE management dimension as part of the definition of systems approach in this research
16	In your opinion, does the simulation help include the interests of more than one actor within the WEEE management system as regards the decision-making process? (*e.g.* producer, distributor, consumer, recycler, regulator)	To ensure the inclusion of the interests of more than one WEEE management actor as part of the definition of systems approach in this research
17	In your opinion, does the simulation lead to reflection on cause-effect relationships as regards the decision-making process?	To ensure the inclusion of circular cause-effect way of thinking as part of the definition of systems approach in this research
18	In your opinion, does the simulation support the process to assign weights (in the multi-criteria decision table) to the criteria used to choose PCP alternatives (designs)?	To ensure a link between the computer-based simulation and the multi-criteria decision tool

Constructs 14 to 17 are tied to the definition of systems approach to WEEE management proposed in the present doctoral research.

4.2.2 Technology Acceptance Model (TAM)

The extensively incorporated TAM methodology is based on the Theory of Reasoned Action model (Ajzen & Fishbein, 1980, cited in Rigopoulos et al., 2008). A fundamental concept of this theory is that individuals adopt specific behavior if they perceive possible positive outcomes related to its adoption (Rigopoulos et al., 2008). Figure 4-1 visually represents this theory; as far as the DES is concerned, the most important part of the figure is the *behavioral intention of use*.

Figure 4-1: TAM research model (Rigopoulos et al., 2008).



To measure user (read: policy makers) attitudes towards adoption of the DES, TAM was applied as part of this research to validate the DES of the T-Ts (guideline, *Coop4SWEEEM* computer-based simulation, MCDM multi-criteria decision table and questionnaires).

George Rigopoulos, et. al. (2008) used TAM to evaluate user attitudes towards adopting decision support systems. The researcher's methodology supported the following hypotheses:

Table 4-4: Hypotheses supported by the TAM (Rigopoulos et al., 2008)

H1	Perceived usefulness will have a positive relationship to behavioral intention
H2	Perceived ease-of-use will have a strong indirect positive relationship to behavioral intention
H3	Perceived ease-of-use will have a less strong direct positive relationship to behavioral intention
H4	Behavioral intention will have a strong positive relationship to system usage
H5	Perceived usefulness and perceived ease-of-use will have a strong positive relationship to behavioral intention
H6	Perceived usefulness and perceived ease-of-use will have a strong positive relationship to actual usage

The constructs and statements defined to test the hypotheses and validate the DES using Rigopoulos' TAM methodology are presented in Table 4-5.

Table 4-5: TAM constructs**.** Adapted from (Rigopoulos et al., 2008).

	Construct
	Perceived Usefulness
19	With the DES decisions are easier
20	With the DES decisions are more accurate
21	With the DES decision are faster
	Perceived easy-to-use
22	The tools of the DES are easy to use
23	The tools and methodology of the DES are easy to understand
	Behavioral intention to use
24	I think that using the tools of the DES is a good idea
25	I think that using the DES is beneficial for me
26	I have positive perception about using the tools of the DES
	Usage
27	I intend to use the tools of the DES
28	I intend to use the DES instead of the traditional procedure

In addition to Constructs 1 to 13, these TAM statements are measured with the aforementioned Likert scales (strongly disagree, disagree, neither disagree nor agree, agree and strongly agree). As previously discussed, these data are analyzed using the median and IQR, which allows for a more accurate representation of the central tendency and variability in responses (Gonzalez, 2010).

The TAM instrument included a question to determine if the systems approach was used in the DES as part of the decision-making process (Table 4-6).

Table 4-6: "Yes/no" question included in the constructs (and their arguments) for validation of the decision systemicity

29	In your opinion, the decision was made following a more systems-based approach than traditionally done? (*e.g.* it took more than one dimension into account, such as the interests of more than one actor, more than one management phase and the logic of cause-effect)

4.3 Validation Results

4.3.1 *Coop4SWEEEM*

The five experts participating in this portion of the validation represented the following organizations: the *Ministerio de Ambiente y Desarrollo Sostenible* (MADS), the *Centro Nacional de Producción Más Limpia* (CNPML), the Swiss Federal Laboratory for Materials, Technology and Society (Empa) and Los Andes University (in Bogotá, Colombia).

Important adjustments were made to the conceptual design of *Coop4SWEEEM* on the basis of the first two validations. Specifically, as part of the initialization and input data, the diffusion of information was put into effect in order to increase consumer awareness of PCPs. Furthermore, in the Animation Area, the color and size of consumer agents were improved to more clearly indicate which consumers delivered WEEE to the PCPs. The third and final adjustment consisted of displaying the WEEE collected by each PCP instead of the total amount. The first 2 validations—of 5 total—served to modify the model, a sort of pre-validation, before the final three validations were performed (see Table 4-7 below). Due to the low number of evaluators (5 national and international experts), the IQR was not included in this part of the analysis.

After making these adjustments, Constructs 1, 2 and 3 were evaluated with an expert in agent-based modeling. The expert concurred ("strongly agree") that "the assumptions and theories that constitute the conceptual model of *Coop4SWEEEM* allow for the reasonable representation of the model's purpose." Moreover, the expert "strongly agrees" that it "*allows for the identification of emergent properties defined in the conceptual model*." Moreover, the expert agreed with the statement that "Agent behaviors reasonably represent reality."

Table 4-7: Pre-DES validation of *Coop4SWEEEM*

	Construct	SD (1)	D (2)	nAnD (3)	A (4)	SA (5)	Median	%4-5
The animation								
4	The animation allows you to identify the moments when producers and distributors are most active, in terms of a greater motivation to cooperate (top of the screen animation)				2	1	4	100
5	The animation allows you to identify producers who lead the post-consumption program that has low rates of collection of WEEE from consumers (that is malfunctioning PCP), behavior reflected in the low cooperative activity			1	1	1	4	67
6	The simulation allows you to differentiate consumers that deliver WEEE and not in each simulated scenario				1	2	5	100

	Construct	SD (1)	D (2)	nAnD (3)	A (4)	SA (5)	Median	%4-5
The output data								
7	Changes in producer and distributor motivation to cooperate depend on the dynamics of WEEE returned by consumers			1		2	5	67
8	Distributor motivation to cooperate depends on the increase in potential customers, which is represented as consumers utilizing the PCP				1	2	5	100
9	Changes in producer and distributor motivation to cooperate are evident at different times: for producers annually; for distributors, weekly					3	5	100
10	The implementation of post-consumer incentive programs generates greater consumer return of WEEE					3	5	100
11	The implementation of economic incentives influences consumers less than incentives in the form of supporting socio-environmental projects (compare scenarios)				2	1	4	100
12	The implementation of post-consumer incentive programs to consumers generates less potential pollution than if not offered					3	5	100
13	The implementation of post-consumer incentive programs influences the motivation to cooperate in producers and distributors (circularity of in-fluence)			1		2	5	67

SD: Strongly disagree; D: Disagree; nAnD: neither Agree nor Disagree; A: Agree; SA: Strongly agree

As evinced by the high percentage of 4 and 5 answers, signifying “agree” and “strongly agree,” respectively, experts manifested their support of the animation and output data. However, the results of the Constructs 5, 7 and 13, all related to producer and distributor cooperation, had 67% of experts respond with 4 or 5, revealing a relatively less clear judgment regarding these outputs. The three neutral opinions that led to this percentage were assigned by the same expert who, despite the inclusion of a cooperation sub-model in *Coop4SWEEEM*, failed to understand the prior validation, which became patently clear when the expert answered the TAM evaluation as follows: T-Ts were easy to use (“strongly agree) and easy to understand (“agree”).

Moreover, the median of 4 and 5 in all constructs further supports the fact that none of the experts disagreed; in other words, the unambiguous consensus was that the simulation represented the intended behaviors included in the ABM.

Looking at the validation of the model's systemicity, per the definition of systems approach to WEEE management included in this part of the validation (Table 4-8), only Construct 14 failed to obtain 100% positive responses, which proved coherent with the specific goal of the simulation. To remind readers, the specific goal of this simulation was to address the *urgent* decision of "How to influence consumer behavior in order to increase WEEE collected," which refers only to the collection process. However, the DES's goal is broader than that of the T-Ts; the DES aimed to "Decide on aspects that affect sustainability in WEEE management in Colombia." In any case, the low response to Construct 14 is logical and, in fact, along with other aspects, was validated and supported by TAM results.

Table 4-8: Results for yes/no questions included in the pre-DES validation instruments

Question		%Yes
14	In your opinion, does the simulation elicit discussion about more than one process (or stage) within the WEEE management system as regards the decision-making process? (e.g. production, generation, collection, pre-treatment, recycling, recovery, final disposal)	60
15	In your opinion, does the simulation elicit discussion about more than one dimension within the WEEE management system as regards the decision-making process? (e.g. technical, social, cultural, environmental, political, institutional, economic)	100
16	In your opinion, does the simulation help include the interests of more than one actor within the WEEE management system as regards the decision-making process? (e.g. producer, distributor, consumer, recycler, regulator)	100
17	In your opinion, does the simulation lead to reflection on cause-effect relationships as regards the decision-making process?	100
18	In your opinion, does the simulation support the process to assign weights (in the multi-criteria decision table) to the criteria used to choose post-consumer program alternatives (designs)?	100

4.3.2 TAM results

The 16 validations arrived at upon concluding the DES meant it was possible to calculate the IQR, median and percentage of 4 (agree) and 5 (strongly agree) answers; these data were included in the TAM analysis (Table 4-9).

Table 4-9: TAM results

Construct		SD	D	nAnD	A	SA	Median	IQR	% 4 and 5
Perceived Usefulness									
20	With the DES decisions are easier		1	2	8	5	4	-	0.81
21	With the DES decisions are more accurate		2	3	11		4	1.5	0.69
22	With the DES decision are faster		1	5	8	2	4	2	0.63
Perceived ease-of-use									
23	The tools of the DES are easy to use				9	7	4	-	1.00
24	The tools and methodology of the DES are easy to understand		1	1	8	6	4	-	0.88
Behavioral intention to use									
25	I think that using the tools of the DES is a good idea				9	7	4	-	1.00
26	I think that using the DES is beneficial for me				12	4	4	-	1.00
27	I have positive perception about using the tools of the DES			1	11	4	4	-	0.94
Usage									
28	I intend to use the tools of the DES			1	11	4	4	-	0.94
29	I intend to use the DES instead of the traditional procedure			5	6	5	4	1	0.69

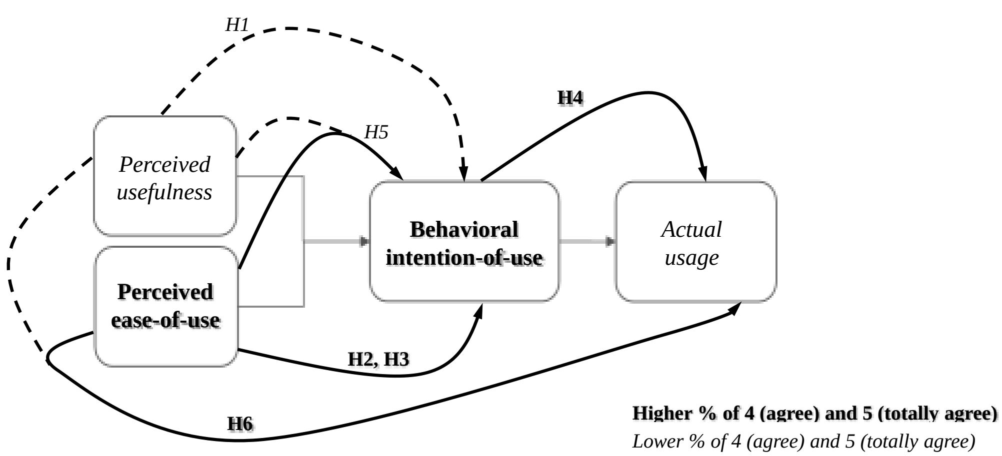
SD: Strongly disagree; D: Disagree; nAnD: neither Agree nor Disagree; A: Agree; SA: Strongly agree

On one hand, the attendees agreed on the perceived ease-of-use and their behavioral intention to use the DES and T-Ts. On the other, some attendees either disagreed or were neutral about the perceived usefulness and usage. At first, the majority of the attendees agreed that making decisions was easier with the DES (Construct 20). Nevertheless, despite a median answer of 4—a sign that the decision was more accurate and faster—both the IQR (1.5 and 2 respectively) and the percentage of 4 and 5 (69 and 63 %, respectively) answers speak to some level of disagreement. According to the opinions expressed by attendees who disagreed or were neutral, this low rating is connected to their perception that the technological tools require users to come from the specific context of WEEE management and/or hail from a metropolitan area.

For the evaluation of Construct 28, which looked at the intent to use the DES and the T-Ts, 94% of answers were positive (“agree” or “strongly agree”), with a median of 4 (“agree”). However, when asked about using the T-Ts instead of the traditional procedure (Construct 29), 31% responded neutrally (neither agree nor disagree). Based on these comments, two principal (potential) barriers can be identified: i) the final decision and tools depend only on the CEO of the company; and, ii) in the context of developing countries, *urgent* decisions require a combination of on-the-spot decision making and traditional processes.

As part of the perceived usefulness, Constructs 21 (DES decision accuracy) and 22 (DES decision speed) obtained the lowest rating in terms of “agree” (4) or “strongly agree” (5). However, according to the model and its supported hypotheses (Table 4-4 above), the results obtained provide strong evidence that the DES efficiently supports the decision-making process by generating behavioral intention of use, despite underwhelming responses to the Constructs about perceived usefulness and actual usage (Figure 4-2).

Figure 4-2: Strong direct or indirect positive relationships according to the hypotheses of TAM. Dashed lines refers to the lowest scores in the TAM results (Table 4-9 above).



In short, attendees considered the decision process developed in the DES to be more systemic than the traditional decision-making process (Table 4-10).

Table 4-10: The final question regarding the systemicity of the decision-making process developed in the DES

	Question	%Yes
29	In your opinion, the decision was made following a more systems-based approach than traditionally done? (e.g. it took more than one dimension into account, such as the interests of more than one actor, more than one management phase and the logic of cause-effect)	100

On balance, the DES allowed policy makers to make more systemic decisions in relation to the aspects that affect sustainability in the WEEE management in Colombia. The DES heightened focus on the design of post-consumer programs and incentives to influence consumer participation. Nevertheless, based on the author of this doctoral research's experience as facilitator (while simultaneously being a researcher) and suggestions made by attendees in the validation forms, two points merit further attention in similar exercises. First, if the time required to implement the DES is less than 4 hours, this should suffice to adequately address 4 scenarios (rather than the eight proposed in Chapter 3). Second, the primary cause of the 5 "neutral" (and 1 "disagree") answers to the Construct referring to decision speed ("the decision was faster") was the delay in understanding how to use the T-Ts. Thus, to streamline this process, instead of explaining the tools pre-DES implementation, the simulation and the multi-criteria decision table should be explained through the development of one complete exercise (simulation and prioritization with the T-Ts).

5 Epilogue

The biggest issue facing management of the Waste Electrical and Electronic Equipment(WEEE) in developing countries is the lack of a systems approach in decision making. The unsustainability of WEEE management systems can be seen in the presence of WEEE discarded in public areas and sanitary landfills, informal recycling, public health hazards, pollution, equipment smuggling, lack of cooperation among stakeholders and low rates of WEEE collection.

Working from the hypothesis that more systemic decision making improves the sustainability of WEEE management systems, this chapter presents answers to the proposed research questions, the contributions of this doctoral research and areas that merit further investigation.

5.1 Findings

Using the Design Science Research (DScR) as methodological strategy, the cycles of relevance, design and rigor were linked as part of the progressive problem solving process.

The first research question (RQ1) posed the following: “How can we design decision-enhancement studios (DES) to support policy-makers in the creation of sustainable WEEE Management programs in developing countries?” First of all, the idea of *designing the design problem* helps designers arrive at deeper understanding of the problematic situation. Likewise, it emphasizes the importance of clearly defining the problem, clearly delimiting the criteria to be used in the evaluation of proposed solutions and clearly defining the solution space.

To facilitate the understanding of the problem situation, Actor-Network Theory (ANT) is recommended to recognize the knowledge gleaned from related experiences, whether successful or not.

Given that a DES engages people (decision makers and the facilitator), processes (protocols and guidelines) and technology (technological tools, or T-T), it is crucial to involve relevant actors that participate in all the design process. Relevant actors were defined in this thesis as policy makers within the WEEE management system.

The DES structure allows designers to tackle two levels of goals: i) the general DES goal; and ii) the specific assigned goals of the T-Ts used in the DES. Due to this two-level goal, the DES accounts for constraints deemed capable of hindering the design of the solution. Example constraints include: the implausible, but required involvement, of all relevant actors (*e.g.* consumers in the case study) or pragmatic requirements, such as the definition of boundaries in the conceptual and computational model used in the technological tools.

Once the understanding and design of the problematic situation has been achieved, the design of the T-Ts becomes a relevant facet of the DES design, notably computer-based simulations in which relevant actors also took part. In general terms, the technological tools aimed to facilitate an understanding of what it means to adopt a “systems-based approach” about a problem situation, which, in turn, was ultimately geared towards sparking dialogue among policy makers. ANT provided the opportunity for understanding the problem and using elements to design the tools. In addition, ANT facilitated the identification of the role played by regulations and laws in terms of aligning relevant actors' interests. Verification of ANT's contributions came in the form of the motivation and active participation of policy makers in the design of the national policy for WEEE management in the country as part of the case study.

In the case of this doctoral research, the goal of the solution arrived at via the proposed design was to highlight the system's effects on the aggregation of individual interests and on the decisions of different actors by showing emergent phenomena. In so doing, the solution stimulates learning processes in decision-makers, which frames an agent-based model (ABM) as the best option. This research further proposes the use of ANT to the design of an ABM; the two naturally prove a productive combination in light of their conceptual similarities, such as parallels between Actor-Networks (A-N) and agents or A-N moments of translation and agent decision making.

To motivate the active participation and thereby obtain better results, a shared common understanding of the most important concepts related to the problem situation and the solution must be attained. In particular, as pertains to the DES designed in this research, the systems approach concept was proposed to policy makers, and duly accepted. Additionally, concepts such as Extended Producer Responsibility (EPR), cooperation and post-consumer programs (PCP) were also accepted during the design activities and in the implementation of the DES.

The second research question focuses on the essential elements that enhance systemicity in decision-making for WEEE management (RQ2: What are the essential elements needed to enhance systemicity in decision-making for WEEE management?). WEEE management is a socio-technical system that relies on technical artifacts to achieve material goals, and it is strongly influenced by human behaviors and the decisions of several social actors. Thus, to strengthen its sustainability a systems approach is required not only for the design of solutions, but also in the identification and structuring of the problem situation. DES design in this doctoral research involved policy makers using a policy design process that operated from a shared understanding of the concept of systems approach. Readers should recall the definition of systems approach in this doctoral research: systemic decision making requires the comprehension of the entire (WEEE management) system and its behavior over time. For that reason, policy makers should include the following elements in the decision-making process:

i) Different dimensions of the problem. Despite the seemingly one-dimensional nature of the problematic situation to which a policy decision is destined, *e.g.* "just" a social issue or "just" an economic one, in the case of the WEEE management, policy makers should include socio-cultural, environmental, technical, economic, institutional and legal dimensions.

ii) Different stakeholders' targets. The whole system is constituted by different stakeholders; in other words, the entire system is made up of a multitude of perspectives. To reach a decision that supports more sustainable strategies, the concepts, knowledge and interests of these different stakeholders cannot be ignored. If, say, the decision is about how to strengthen consumption responsibility in consumers, three different sets of targets must be considered: Consumer targets (Why they use or buy equipment? What do they usually do with the WEEE? What motivations/incentives would get them to participate in PCPs?); producer targets (What criteria are used to design new equipment? What are the goals of media campaigns and marketing strategies? What motivations/incentives would get them to consider strategies related to the waste generated by the equipment they sell? Are responsible consumption strategies actually beneficial for producers?); and environmental authority targets (Are they interested in environmental protection in order to preserve natural resources or to respond to international pressure? Do they have sufficient capacity to support the implementation, monitoring and control of the strategy?).

iii) Processes within WEEE management. The generic stages of waste management are generation, segregation, collection, transfer, treatment, recovery and disposal. However, the systems approach and the nature of the WEEE demand the inclusion of processes that precede WEEE generation, including production, distribution, use and reuse of electrical and electronic equipment, as well as mining to extract raw materials used for the production of this equipment.

iv) Circular cause-effect relationships resulting from current decisions focused on the short- and long-terms. As part of this way of thinking, discussions about past facts, regardless of their success, are key to understanding the motivations of actors and encouraging reflection in policy makers about the possible future effects of current decisions.

Pragmatically speaking, not all aspects of each element described above can be included. Yet, to increase systemicity in decision-making processes, policy makers should include at least some of them the aforementioned four elements. As demonstrated by the validation procedure described in the previous chapter, the DES designed herein helped bring about a systemic process.

5.2 Contributions

Insofar as this research tackles a real-world problem and WEEE management involves several actors inside and outside of academia, understanding the problem situation requires identifying actors' participation not only for the relevance cycle addressed by the research method, but also for the design; the importance of including actor participation was discussed in Chapter 1. Furthermore, the methodological strategy applied facilitated mutual-learning processes and allowed for the creation of solution-oriented knowledge that led to practical and theoretical results. Taken together, these characteristics point to the value of employing a transdisciplinary approach when it comes to solving real-world problems, for this type of approach allows researchers to deliver three levels of contributions: outputs (short-term, immediate contributions), impacts (medium-term, intermediate contributions) and outcomes (long-term contributions). Even though the distinction between outputs, impacts and outcomes was not easy, these distinctions supported reflections on the short-, medium- and long-term effects of decisions. Table 5-1 presents the tangible and intangible outputs of this doctoral research.

Table 5-1: Outputs, or short-term contributions

<table>
<tr><th>Contribution</th><th>Tangible</th><th>Intangible</th></tr>
<tr><td rowspan="6">Outputs (short-term contributions)</td><td>Workshops and reports</td><td>Defining boundaries and participatory policy design methods</td></tr>
<tr><td>Presentations at international conferences and publications</td><td>ANT in the design of ABM</td></tr>
<tr><td>EEE consumer characterization</td><td rowspan="4">Systems approach to WEEE management seen in processes, actors, dimensions and multi-causality (knowledge of the system and transformation of this knowledge into desired knowledge)</td></tr>
<tr><td>Pontificia Universidad Javeriana's Ecological and Environmental Policy</td></tr>
<tr><td>Policy for Integral WEEE management in Colombia</td></tr>
<tr><td>The decision-enhancement studio (DES)</td></tr>
</table>

Tangible outputs were identified as the workshops as part of the participatory policy design and reports on partial workshops and interview results, which were aimed at increasing the interest of actors involved.

In addition, tangible outputs included presentations at relevant conferences (Méndez-Fajardo et al., 2015; S. Méndez-Fajardo et al., 2013; S Méndez-Fajardo et al., 2013; Méndez-Fajardo and Gonzalez, 2014; Ortega R., M. et al., 2013), through which the use of ANT with regard to Colombia's WEEE management, the agent-based model designed and systemic decisions on WEEE management were shared with different scientific communities. In addition, three non-scientific publications formed part of the case study at the university and were published in the monthly university magazine "*Hoy en la Javeriana*" (Mejía, 2013; Méndez-Fajardo, 2013a, 2013b). Looking at scientific publications, a paper (Méndez-Fajardo and González, 2014) and a book chapter (Méndez-Fajardo, et al., 2016 - in press) on the use of ANT in the design of ABMs stemmed from this research. Likewise, the two policies designed were also tangible short-term contributions, not to mention the DES as designed artifact. The DES includes the ABM and *Coop4SWEEEM* simulation, as well as the multi-criteria table.

The virtual survey made it possible to characterize EEE consumers as part of the tangible outputs. Parameters included were related to re-use behaviors, changing and storing equipment, as well as discarding WEEE and motivations to participate in existing and future PCPs.

Turning attention to intangible outputs (see Table 5-1 above), the methodological experience was important in the following moments: the definition of the focal problem to address with the technological tools (the urgent decision); in turn, this defined the boundaries of the system to model and simulate. Both the definition of structural causes and policy strategy design were methodological *and* social experiences. Organizational experience increases the opportunity to bring different actors into the decision-making process, and the continuous interaction of participation built trust among the actors. This latter contribution is categorized here as a social experience because positive interactions build trust.

Impacts and outcomes are included in Table 5-2 below. In the table, tangible impacts refer mainly to the influence of tangible outputs on actions, decisions or plans after the transdisciplinary project. Along with actor participation, changes in language and concepts related to the systems approach on WEEE management and sustainability are the most important tangible impact. The experience of one of the formal recyclers participating in all workshops exemplifies this impact: at the beginning of the second workshop, three months after which the systems approach was initially broached, the formal recycler said that, “in order to illustrate to our friends who could not make it to the first workshop, I would like to hear the explanation of a systems approach again.” During discussion in the same workshop, he highlighted the relevance of “taking into account the ideas geared towards minimizing WEEE generation,” even though, as a recycler, it would be in his best interest to increase WEEE. In the DES (9 months later), he was one of the most active actors, notably asking, “How can these technological tools help us to achieve more sustainable WEE management?” Following the session, he wrote, “Strategies that only consist of economic incentives or dissemination of information are bound to have a very poor effect on the amount of WEEE collected.” Thus, he proposed “the most important criterion to design a post-consumer program should be strengthening environmental awareness in consumers.”

A review of this actor’s initial statements, coupled with his participation, is a testament to the effect of the design process and DES on his decision-making process, which began with the definition of a systems approach as “one that takes different actors into account.”

Table 5-2: Impacts (medium-term contributions) and outcomes (long-term contributions)

Contribution	Tangible	Intangible
Impacts (medium-term contributions)	Transform actors’ concepts	Improved actor understanding of the system and other actors’ viewpoints
	Create Pontificia Universidad Javeriana’s Environmental Committee	
	Develop system knowledge and target knowledge for policy design from a systems-based approach	
Outcomes (long-term contributions)	Fulfillment of the goal of the thesis	Increased decision-making capacity of practitioners and scientists
	Implement the Pontificia Universidad Javeriana’s Environmental Management Plan	
	Implement (future) the decision reached in this doctoral research; future decision-enhancement studios implemented to support different policy decisions	

Looking at the university context, in spite of successful projects born out of scholars’ interests, these scholars have not been actively involved in decision-making. Nevertheless, recent policy has led to a number of scholars forming part of the new environmental committee; the organizational change proposed by the Pontificia Universidad Javeriana’s rector was instrumental in this respect. In 2016, the rector explicitly designated this committee with designing an action plan to implement the policy's strategies, which guarantees the future emergence of new milestones on the path to a more sustainable campus.

An intangible impact of the outputs (Table 5-1) is the cultivation of system knowledge and its application to policy design, not to mention the alignment of target knowledge and a systems approach. The achievement of this intangible impact entailed moments of participation and, perhaps more importantly, the shared concepts of a systems approach. In line with the specific topic for which the policy (*i.e.* decision to be made) was developed, the aspects of each of the four elements are subject to change, though the elements (dimensions, actors' interests, processes and circular cause-effect in time) are not necessarily subject to change.

Intangible impacts refer to cognitive impacts. The DES improved systemic knowledge; moreover, participants may leverage their experience(s) to promote skills such as the deeper understanding of others' viewpoints. This is a key part of achieving more successful decisions in the future and developing more stable and reliable networks.

Beyond the scope of this doctoral thesis, outcomes include the future implementation of the University Environmental Management Plan. There are two ways to enact the tangible outcome of Future (potential) DES implementation. First, the characterization of consumers offers additional attributes of consumers (as agents) and potential new rules in the ABM that can be implemented to simulate alternative PCP properties. In fact, this represents a potential tangible output insofar as the additional DES could support future decisions related to WEEE management at the country level. Second, there is the opportunity to implement the vision at the university level, as well as some of the scenarios discussed within the DES, *e.g.* a pilot project for the design of more effective strategies at the local, regional or national levels.

Last but not least, another output is the author of this work's increased knowledge of WEEE management, decision-making, systems approach, modeling and programming. As a civil engineer—academically speaking, the highest growth discipline—the author was educated in the concepts and tools of systems engineering and social sciences, such as ANT and the development of ABMs. Undoubtedly, these skills will allow the author to lead interdisciplinary projects in other environmental and civil engineering fields aimed at sustainability.

5.3 Reflections on the research strategy and techniques employed herein

Among the multiple influences that have shaped the contemporary systems approach, the soft systems tradition (mores than the hard or the critical traditions) is the closest to a conceptual frame for this doctoral research. In addition to the explicit use of a systems approach in the DES, which was as the main artifact designed, the methodological strategy used in this doctoral research, the Design Science Research (DScR), may also be systemic. Both the strategy and techniques employed herein contain elements of the following systemic strategies: the 'soft systems methodology' (SSM) proposed by Checkland (2001; 1984), or the 'inductive-hypothetical strategy' (IHS) proposed by Sol (Sol, 1982) and based on Churchman's Singerian Inquiry Systems; IHS can be characterized by arriving at an understanding pre-design, whereas DScR stresses understanding through design (Diggelen, 2011). DScR shares the SSM goal of intervening in a problematic situation and embracing divergent views about the definition of the problem itself, which even may not be easily agreed upon (Reynolds, 2010).

In this doctoral research, the DScR also included an important level of researcher participation, as is the case for action research. Yet, researcher participation pales in comparison to the importance of achieving participation by the relevant actors, especially given the time required to conduct interviews, workshops and meetings. Fortunately, however, the exploratory case study in this doctoral research coincided with the actual policy design process, which helped ensure relevant actor participation.

Critical realism, the philosophical approach of this research, relies on a broad range of techniques, and this research was no exception. Some techniques were interpretive (ANT) and some positivist (the Technology-Acceptance Model), yet all had pragmatic goals. In the face of the limitations associated with the dearth of statistical data related to the WEEE management, the methods used herein included participative simulation as action and as a learning strategy. The ABM made this possible, for it represents complexity with limited information, limited material resources and limited computational capabilities.

5.4 Further research

Real-world problems, in this case WEEE management, can be tackled two ways, which can be considered opposing or complementary. One is the preventive approach focused on reducing WEEE generation and, correspondingly, decreasing EEE consumption. The other is the reactive approach, which guides actions towards the responsible collection and treatment of already generated waste.

Responsible consumption involves both approaches. A responsible consumer should decide to buy or reuse equipment based on economic and aesthetic criteria *and* on environmental and ecological criteria, the latter two being related to the minimization of waste generation. A responsible consumer should also make an informed decision regarding WEEE disposal, that is, disposal through formal systems (part of their behavior). Invariably, emotions play a crucial role in consumer decisions. As a result, these decisions are intimately connected to the consumer characterization performed in this doctoral research with the hope of arriving at a profound comprehension of consumers and thereby exploring additional incentives to strengthen the responsible consumption.

When combining the EPR principle and the two types of approach (preventive or reactive), the result is two differing “directions”: the preventive is *upstream*, focusing on green design, design for recycling and cleaner production, and the reactive is *downstream*, focusing on collection and recycling programs and technology recovery. The DES designed in this doctoral research emphasized the latter approach, the downstream direction, in light of the pressing (urgent) decision to address WEEE management in developing countries. However, that does not mean upstream-oriented policies were ignored, for these are required to strengthen a systemic approach to policy design, and the present doctoral research invites future policies aimed at addressing needs beyond the urgent (precisely the philosophy of a preventive approach).

As part of the preventive approach, research that aims to involve policy makers and relevant operational actors related to mining activities should be carried out for, in light of mining's relevance as one of the most significant problems in Colombia (*e.g.* informal recycling) and other developing countries. In fact, urban mining, aimed at incorporating informal recyclers into the formal system, becomes the opportunity to minimize the exploitation of virgin materials needed for EEE production.

Finally, extensions of *Coop4SWEEEM* could be used to examine the differences between collective and individual PCPs, as well as the ways in which the methods of WEEE collection, and subsequent storage, affect distributor motivation (*e.g.* when delays occur). Furthermore, the *Coop4SWEEEM* could be of use in the exploration of the effect of different regulatory scenarios on motivation to cooperate as pertains to sustainability, especially in the case of developing countries.

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Appendix A. Paper: Actor-Network Theory on Waste Management: A University Case Study

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Actor-Network Theory on Waste Management:
A University Case Study

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ABSTRACT

In developing countries, territorial planners are confronted with rapid urbanization and its inherent solid waste management (SWM) which has increased public health risks, and generated environmental and socio-economic problems too. To analyze these issues, a University campus (as a scaled city) was studied applying the Actor-Network Theory to find key elements to take into account for sustainable SWM programs not only in universities but also in cities. To achieve this goal, different actors and relationships between them were identified, as well as their dynamics throughout the SWM history. Some findings were that Environmental City's Authorities requirements have been the main cause of actions related to hazardous waste within the campus, while scholar's interests have initiated non-hazards. Otherwise, documents, operative committees, and scholars involved in milestones, have become as the main support for decision-makers. Researchers also verified that decision have not been made through systematic processes neither from a systems approach.

Keywords: *Actor-Network Theory, Campus, Solid Waste Management (SWM), University, Waste of Electrical and Electronic Equipment (WEEE)*

1. INTRODUCTION

Environmental issues directly related to ineffective Solid Waste Management (SWM) have drawn the attention of researchers looking to analyze the operation of such systems on a global scale (Chang et al., 2011; Ciplak and Barton, 2012). Actions aimed at improving SWM practices, specifically those of developing countries, are negatively affected by resource scarcity, socio-economic inequality and excessive urbanization, among other cultural, social, political and economic aspects (Guerrero et al., 2013; Marshall and Farahbakhsh, 2013). Studies also show that in developing countries SWM decision-makers do not usually include these different dimensions (Achillas et al., 2013; Cheng et al., 2003; Karmperis et al., 2013). As a result, it becomes critical to employ a systems approach in order to overcome obstacles for achieving a more sustainable SWM paradigm (Liu et al., 2011; Marshall and Farahbakhsh, 2013).

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The main processes within SWM include generation, collection, recycling and final disposal. For the last stage, the most common technology in low-middle income countries is the sanitary landfill (Vergara and Tchobanoglous, 2012), where organics and inorganics are deposited, which increase greenhouse emissions (Gassara et al., 2011), as well as the risk of environmental pollution and public health impacts (Lang et al., 2007; Quaghebeur et al., 2013; Rabl et al., 2008).

Public education is usually excluded in the conception, planning, design, implementation and operation of SWM projects (Aini et al., 2002; Longe et al., 2009). In this regard, schools and universities can play a significant role by influencing environmental education and citizen responsibility (Armijo de Vega et al., 2008; Jain and Pant, 2010; Sobreiro and Jabbour, 2007). In addition, campuses can be considered as scale models of a city in all of its dimensions; civic behaviours that are practiced at schools and universities impact the context, tions: (i) Decisions about SWM in the campus have been made through systemic processes? (ii) Decision-makers have applied a systems approach in their decisions? (iii) Is there an organized operative structure for SWM in the campus?, and (iv) Which elements have triggered improvements in the SWM system in the campus?

Data about historical facts in the campus' SWM from 2000 to 2013 were documented through three main methods: participant observation (Platt, 1983), structured interviews (Briones, 2003) and document analysis.

Related to the Actor-Network Theory (ANT), there are four constitutive elements: firstly, the Obligatory Passage Point (OPP) which correspond to the Actor-Networks (A-N) that mobilizes the system and in this case corresponds to the main decision-maker. Secondly, the local network that involves the main A-N identified in relation to the milestones, whereas the global network involves A-N who are able to interfere with the system and even impact culture and behaviour of not only students but also the greater educational community (Armijo de Vega et al., 2008, 2003; Bialowas et al., 2006; Jain and Pant, 2010; Maldonado, 2006). Waste generated on campuses can include ordinary, hazardous, foodservice, construction and demolition waste (CDW), e-waste and office and garden waste (Bialowas et al., 2006).

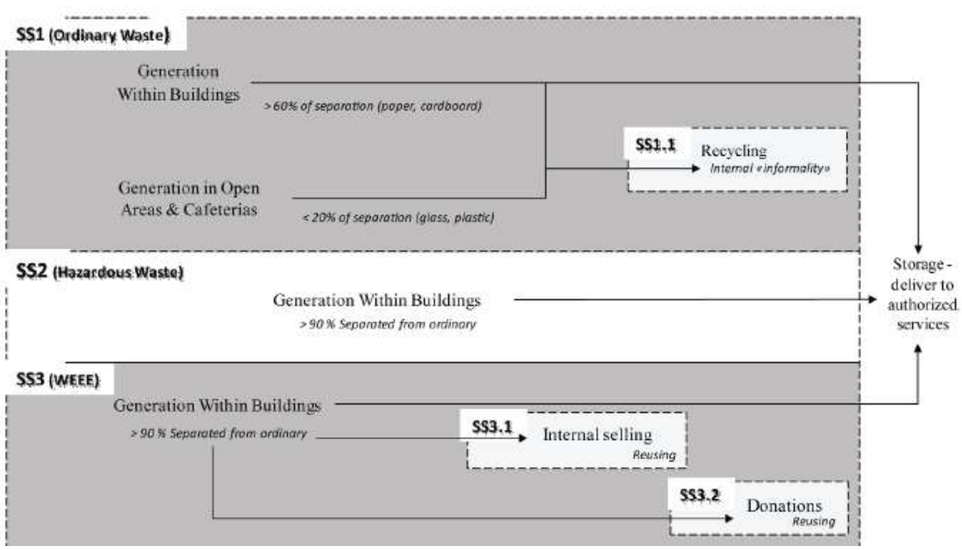
This research is carried out at an university campus as an exploratory single case study which is helpful to study current phenomena in a real world context (Maguire et al., 2010; Yin, 2003a, 2003b). This case is also embedded because it includes two units of analysis (Yin, 2003b) as follows: decision-making roles and operational roles within SWM structure in the campus. These units were analyzed for ordinary waste, hazardous waste, and WEEE (Waste of Electrical and Electronic Equipment). It is important to highlight that embedded single case studies are analytically generalizable to theoretical propositions (Krikke, 2011). As an exploratory case study, and in order to achieve that generalization to SWM systems, this research aims to answer the following ques- the local network when the OPP is weakened. In the same way, A-N in local network are able to interact directly with A-N in the global. The dynamic between local and global networks is also described through "moments of translation" – as the fourth element - which are when the A-N align their interests, focusing them towards the generation of successful action (Callon, 1986; Gonzalez, 2010); these translations constitute the mechanisms through which the networks progressively take form based on power relationships (Stanforth, 2006).

The result is a narrative report, as well as the trajectory of moments of translation that helps to understand the A-N relationships within the SWM system. Finally, in accordance with the composition of dynamics of the Actor-Networks, authors draw conclusions and develop recommendations.

2. SWM IN THE CAMPUS

The university campus, which is located in Bogota, Colombia, concentrates around 22,000

Figure 1. Processes of SWM subsystems in the campus. Subsystem 1 (SS1) for ordinary waste, SS2 for Hazardous, and SS3 for WEEE



people among students (71%), scholars and professors (17%), and administrative staff. The structure of the organization is hierarchically divided into one President, and 5 Vice-Presidents; there are also different Direction Offices, Institutes and Faculties. The SWM is led by a Direction Office and handled daily through a specific system that includes infrastructure, processes, and human resources.

Institutional solid waste is divided mainly into three types: ordinary, hazardous waste (HW) and WEEE. The corresponding management processes are shown in Figure 1, in which each type of waste is represented by a subsystem. These three types of waste are also the main groups in the city and even in the country. Because of that, SWM in the campus interacts with the city and national systems through the compliance of regulations, transactions with recyclers and NGOs who receive e.g. plastics, paper and cardboard, as well as the formal contracts with suppliers of electronic equipment, and public (ordinary waste) and private (hazardous and WEEE) collection services.

Like Figure 1 shows, ordinary waste (plastic, cardboard, glass, paper, organics, among other non-hazardous) is generated within buildings (classrooms, offices, bathrooms) and also in open areas and cafeterias, while hazardous and WEEE only within buildings; hazardous waste comes mainly from laboratories and healthcare facilities, and WEEE from offices and classrooms in which devices like video beams and computers have been installed. At the end of the management processes, all of the recovered waste are stored and delivered to the correspondent service out of the campus.

As with ordinary waste, information about generation of hazardous and WEEE is quite low too. Official decisions about SWM are usually not taken based on real generation data. Despite this, different actions have been developed to promote sustainable SWM in the campus, as well as to reinforce environmental education and responsibility in the university community.

Furthermore, the exploratory case study allowed us to observe a low perception about HW and WEEE, not only in the university community but also among other relevant actors. HW causes particular concern given the concomitant public health and environmental consequences because of the presence of impurities in materials, low-tech production processes, poor operational practices and characteristics inherent to some products and substances upon disposal (Duan et al., 2008). The most troubling HW cases produce severe health and environmental effects, usually as a result of improper disposal (Gassara et al., 2011). The Ministry of Environment in Colombia, in an effort to counter this issue, formulated Law 4741/05 which is the Environmental Policy for Hazardous Waste Management in the Country, as well as Law 1672/13 for WEEE management.

In the campus, HW includes packaging of chemical substances, acids, paints, solvents, and agrochemicals, as well as WEEE from equipment like TVs (plasma and LCD), computers, printers (toners and ink cartridges), faxes, phones, mobile phones, cameras, video beams, copiers, and lighting. Alkaline batteries are not included in the 2002/96 guideline (The European Parliament and The Council on Waste Electrical and Electronic Equipment, 2012); however, they are considered WEEE. As Figure 1 shows, three clear outputs of the WEEE have been created in the campus: internal selling (SS3.1), donation (SS3.2) and delivery to the authorized managers. Internal selling and donations are mainly applied to computers and printers. The first is available to janitors and security personnel who may buy the equipment paying low prices. The second one is developed with high schools in Bogota, in other municipalities, and with regional social organizations.

A common issue found for all of the waste is related to registry of generation rates and specific composition of the three kinds of waste; data related to waste generation is important to design strategies and indicators, but it is usually poor and unreliable (Antanasijevic et al., 2013; Beigl et al., 2008; Lebersorger and Beigl, 2011). For example, for ordinary waste in the campus, official report shows 700 ton in 2011 and 2012, which means a *per capita production* (*pcp*) of 0,09 kg/person/day. This *pcp* is abnormal data, taking into account the amount of people in the campus, as well as the usual rate of *pcp* in Developing Countries: between 0,25 (Bangladesh) or 0,30 (Africa or, Costa Rica), and 1,10 (Thailand) or 1,20 (Tukey) (Guerrero et al., 2013); in addition, studies have reported *pcp* between 0,80 and 1,40 for Latin America and Caribbean Countries (Vergara and Tchobanoglous, 2012), and 0,90 for Bogota (UAESP, 2011). Additional observations verify the existence of one additional subsystem (SS1.1 in Figure 1) related to separation and recovering of recyclable waste. The measurements to characterize ordinary waste generation have been taken in the storage points of the SS1; data from SS1.1 has not been taken into account.

This situation also exists in the city as a whole for the three kinds of waste: the informal sector recovers and recycles waste outside of the authorized systems and does not report related data. In Addition, the sociocultural context that involves illegality, micro-traffic, mafias, and extreme poverty, makes it difficult to get this information.

Finally, universities are not only playing the role of consumers and generators in the city system, but also an educational partner. As generators, they have the obligation of minimizing and delivering the waste to the official systems, and as an educational organization they have the responsibility of building awareness in the university community.

3. ACTOR-NETWORKS (A-N) IN THE SWM IN THE CAMPUS

Table 1 shows the main A-N related specifically to the SWM system.

Two A-N were not identified by the main decision makers: the informal recycling network (SS1.1), and the bins implemented to promote behaviors to increase source separation. It is important to emphasize this fact as a possible explanation regarding the high uncertainty in generation data (which was discussed immediately after Figure 1), as well as the low percentage of source separation in open areas and cafeterias within the campus (Figure 1). This lack of separation is an expected result when the design and implementation of infrastructure

Table 1. Actor-networks within the campus

Actor-Network (A-N)	It Involves
The Campus Administration Office (CAO)	-
The Department of Ecology and Territory (DET)	SFES ***
The Environmental Administration Group (EAG)	CAO and Administrative employees from the main hazardous waste generators*
The Environmental Committee (EC)	CAO, SFE**, SFES***
The Welfare Vice-president office responsible for the program Healthy University (HUP)	-
The University Environmental Group (UEG)	CAO, SFE**, SFES***, SFAD****, and Faculty of Environmental Sciences´ Academic Dean
The plans for SWM (ordinary and hazardous waste)	EC
The Environment Management System (EMS) document	CAO, SFES ***
The safety protocols to manage the hazardous waste at Faculty of Sciences	CAO, SFES***, Administrative Staff from Faculty of Sciences

* Faculties of Sciences, Medicine, Odontology, Engineering, Arts, Architecture & Design, and the University Hospital; ** Scholars from Faculty of Engineering; *** Scholars from Faculty of Environmental Sciences; **** Scholars from Faculty of Architecture and Design

or technologies to minimize environmental impacts are developed without community participation or the support of public education programs. The adoption and the resulting cultural change needed to achieve sustainable infrastructure projects, demands the inclusion of sociocultural and educational activities in all of the phases, in addition to the technical, economic and operational elements (Méndez-Fajardo et al., 2011; Y. Romero et al., 2011).

4. HISTORICAL EVOLUTION OF SWM AT THE CAMPUS

The history of SWM at the university started in 2000, when Law for healthcare waste management in Colombia was published. This policy prompted the design of the safety protocol for hazardous waste management at the Faculty of Science in 2001. This process was led by the administrative employees who are responsible for this topic. The support received from the Campus Administration Office (CAO) was materialized in different constructions to adapt storage places inside the Science building between 2001 and 2003.

Later, between 2005 and 2009, different actions were developed. First, in 2005 the Environmental Committee (EC) was created and was active until 2009. This committee was led by the CAO head involving scholars from the Faculties of Engineering and Environmental Sciences; its goal was to debate ecology and environmental issues in the campus, as well as identifying opportunities to develop preventive actions guided by the EMS document (see Table 1). At this time, different ideas related to SWM were materialized, mainly SWM plans, collection campaigns, training activities, and some constructions (mainly of storage places within buildings and open areas in the campus).

As part of these activities in 2007, a rough version of an Environmental Policy for the campus was written but it was not adopted by university authorities. During 2008, two important outcomes were generated: the design of the plan for ordinary SWM, and a campaign for the collection of mobile phones and accessories, which was supported by companies like Bellmont Trading and Motorola. This campaign was developed along six months and was important to start the environmental education process in the university community. In early 2009, after generating the plan for hazardous SWM, this committee was dissolved by the new head of the CAO.

During 2009 the CAO head developed related actions guided by the SWM plans but without the support of a specific group of experts. In 2010 because of an Environmental Authority requirement and also based on the new public law, the Environmental Administration Group (EAG) was created. The requirement was specifically about hazardous waste management in the campus, mainly toxic elements like mercury and silver which had possibly been generated by the Faculty of Odontology. Because of this, the EAG involved the main hazardous waste generators represented by administrative employees responsible for these elements like laboratory technicians, secretaries who control the cleaning personnel in each faculty, and a university hospital employee. Between 2010 and 2012 several activities related to ordinary and hazardous waste were developed: In 2010, for example, scholars from the Faculty of Environmental Sciences (supported by the CAO) led the University Recycling Program (PRIES because of its name in Spanish) which involves more than 15 public and private universities in Bogota.

More recently, in 2012, the UEG was shaped and led by the Welfare Vice-President and involving scholars from the Faculties of Engineering, Architecture & Design, and Environmental Sciences. This group is mainly focused on the design of an Environmental Policy for the University; however, different actions have emerged from it, like for example one massive survey that involved students, professors, management, and administrative personnel in order to measure their perception about the importance of working on different environmental elements in the campus, including SWM.

The second recent action that involved the UEG was the beginning of the campaign to collect alkaline batteries within the campus. This national campaign is led by the Ministry of Environment and by the Association of Colombian Industry (ANDI).

Along this history, there were several moments of translation between local and global networks in which different milestones were generated: A-N in the global network are able to interfere with the system and even impact the local network when the OPP is weakened. At the same time, A-N in local network are able to consult directly with A-N in the global (Stanforth, 2006). The local network in this case study is composed of heterogeneous A-N as follows: CAO, EAG, EC, the plans for ordinary and hazardous SWM, and the safety protocol for hazardous waste. The global network includes internal A-N like UEG, HUP (see Table 1), and researchers from Faculties of Engineering and Environmental Sciences, as well as external actors like Environmental Authorities, Public Collection Service, Authorized Collection Service (for hazardous waste), and related laws too.

5. MOMENTS OF TRANSLATION

The moments of translation (Table 2 and Figure 2) show that the power relationships within the system are dominated by the Campus Administration Office (CAO), whose role was recognized as the obligatory point of passage (OPP); the head of this office is the main decision-maker in terms of planning, designing and implementing of the SWM infrastructure, as well as the development of related programs and campaigns. This office depends directly on the Administrative Vice-president who manages the budget of the whole organization with the approval of the President, but the justification that the CAOs head submits in the process of planning and executing the budget is the main criteria.

Before Law for healthcare waste management in Colombia *(0)*, there were not remarkable actions about SWM in the campus. The creation of the safety protocol *(A)* pushed also some physical infrastructure adaptations in the campus which increased visibility for this topic. This episode was supported by CAO (economic

Table 2. Episodes within the SWM history in the campus

Episode	General Description
0	Before the publication of the national law for the management of healthcare waste
A	First formal protocol to manage hazardous waste in the campus, created to the compliance of healthcare waste law
B	Generation of the document about the Environmental Management System in the campus
C	Campaign for collecting obsolete mobile phones and accessories
D	The University Recycling Program (PRIES because of its name in Spanish) in Bogotá
E	The massive virtual environmental survey
F	Campaign for collecting alkaline batteries

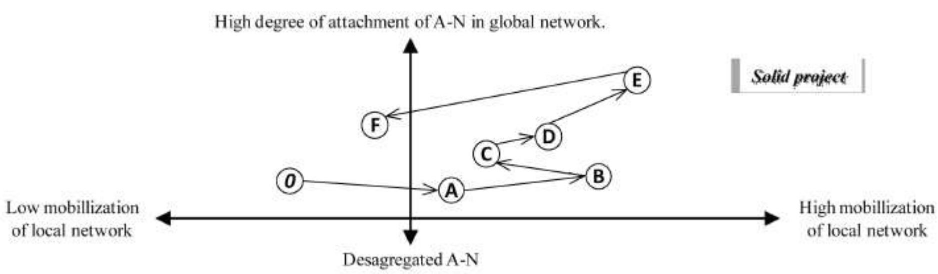
resources) and by scholars from the Faculty of Environmental Sciences, who two years later also led the design of the Environmental Management System for the University *(B)*; this document has become important because it has been included in arguments of the other SWM actions in the campus.

An important milestone within documented history was the work of the EC between 2005 and 2009, time in which important documents were generated like ordinary and hazardous SWM plans, as well as the campaign to collect obsolete mobile phones and accessories in 2008 *(C)*. In this last action, related decisions involved some common A-N to the previous episodes showing also a low local network mobilization.

Two years later (2010) the University became the leader of the PRIES initiative *(D)* involving more than 10 universities in Bogota. This episode was developed by scholars from Environmental Sciences Faculties and strongly supported by the CAO, and was related to some strategies included in both plans for SWM (ordinary and hazardous). This moment also strengthened awareness in the university community and generated important investments in infrastructure like bins, storage places improvement, and re-design of the internal collecting routes of waste. Despite the fact that this was partly due to medium-term effects generated this program of Bogota's universities as a group failed even within the leading university because of the low participation of A-N form the local network.

The last two episodes included in Table 2, both implemented during 2013, have been a result of the alignment of interests of the CAO, the EAG (both of the local network), the JEMG, and some public laws related to WEEE (Waste of Electrical and Electronic Equipment) in the Country. In this regard, episodes *(A)* and *(C)* were motivated by the Environmental Author-

Figure 2. Moments of translation and A-N attachment and mobilization in each episode



ity requirements based on public laws, but as an important contrast, episode *(F)* emerged as a preventive strategy aligned with the recent Law for WEEE Management in the Country in order to avoid future requirement from the authorities, as well as support the spread of this new law within the university community.

In the same sense, episode *(E)* was implemented to identify perception and priorities from the university community not only about waste management, but in relation to different environmental issues which fits more with a systems approach of the campus' management. Survey results were included as one of the main criteria to design the environmental policy for the University which are going to be published in 2015. Based on the 1881 answers, SWM (including responsible consumption), water management, and healthy eating have become the three main issues to attend to.

All of the episodes involved the CAO, which demonstrates its role as the OPP. In the same respect, its continuous participation has generated an important level of appropriation about SWM relevance, which has pushed it to act in a preventive way that anticipates the legal requirements too. However, some communication problems were identified as obstacles for some SWM initiatives which were verified in the dispersion of activities (decentralized and even unknown by CAO). It should be noted, though, that the battery collection national campaign brought into campus was a result of the effective communication between the CAO, the EAG and the JEMG. This effectiveness has been achieved through the participation of the same people in the different committees and groups.

The main external generator of movements in the SWM system at the University has been Environmental Authority through requirements about the compliance of related public policies. Under these norms, committees and important documents and constructions have historically been created and implemented. However, in 2012 several facts helped to start a possible change in this dynamic: on the one hand, the newly appointed Welfare Vice-President has worked in environment and society topics throughout his life not only as a Jesuit but also as professional, professor, and in managerial roles within the university. On the other hand, pre-existent relationships between him and the *persistent* scholars from the Faculties of Environmental Sciences and Engineering, who have participated in the majority of the episodes, generated the JEMG with a real interest from everyone involved. This working group also includes the OPP who has motivated himself to make decisions taking into account environmental variables more strongly than in previous years. Because of this, the latest actions related to SWM have not been a reaction to authority´s requirements, but implemented to apply these new laws in-line with the social responsibility of the organization.

Finally, it is important in the system to assign responsibilities to administrative employees who are really interested on environmental topics. This has been the cause of, for instance, safety protocols becoming useful and being applied in other faculties, as well as becoming key documents for monitoring the activities that put into effect hazardous waste management laws by the EAG.

6. WEEE MANAGEMENT IN THE CAMPUS

The OPP (the CAO) and A-N are shown in Table 1, nevertheless, two new A-N emerged: Firstly, the Faculty's Offices (employees) as main consumer/generators of WEEE within the campus, and secondly, the University Services Direction (USD) which is also important because it is the gateway for equipment, through supply activities. Faculties will become relevant if the WEEE management is refocused on responsible consumption, and USD because part of the responsible consumption could be related to concepts like *green supplying, green labels, green brands,* among others.

As was explained earlier, in consonance with Colombia's WEEE system, there are three outputs for WEEE in the campus (Figure 1). Both subsystem SS3.1 and SS3.2 are related to reusing equipment. The first is comparable with the distribution chains of used, repaired and reconditioned equipment in Colombian cities. In the same way, the second one is similar to the program *Computadores para educar (Computers for educating)*, that receives obsolete computers from industry, reconditions them, and donates them to high schools in the whole country. Reusing computers through these two subsystems involve A-N with two main motivations: in the internal selling (SS3.1) is the economic interest that motivates actions, while in donations (SS3.2) is closing informatics gaps among children population as a social interest which push actions.

Finally, as with ordinary waste management, the rest of WEEE has been delivered to the authorized collection and management system in the city, in which the main A-N are janitors (within the campus), authorized companies, and related public policies that motivate these activities.

7. CONCLUSION

The main findings in the exploratory case study will be presented according to the preliminary questions, as follow:

Decisions about SWM in the campus have been made through systematic processes? Despite the fact that the organization has a clear hierarchical structure, as well as people responsible for the topic, there is no structured-systematic decision-making process. Firstly, the main (external) A-N that has moved the system forward is the environmental authority through the requirement of compliance with related laws. It means that the main decisions have been made because of the direct influence of the Mayor's offices responsible for SWM issues in the city. In the same sense, within campus, successful projects have been born out of interests from scholars who have been involved in active decision-making committees.

In addition, decisions about investment in infrastructure and campaigns within the campus involve not only SWM but also water, energy, ecological resources, building's construction, among other elements. Related to that, there are not systematic criteria to prioritize these several issues.

Decision-makers have applied a systems approach in their decisions? On one side, lack of systems approach for planning the SWM actions in the campus could be verified by observing the unreliable data about generation. Official characterizations (2010, 2011 and 2012) were made in the central storage places but there is an informal flow of recyclable waste that has not been included there. It could mean that designers of SWM strategies have not been taking into account neither informality (SS1.1 in Figure 1) nor the alternatives to prevent the generation or increase recycling/reusing practices based on amount of waste; even when these strategies could decrease the taxes paid for collection and management in the city system.

On other way, an organizational environmental policy does not exist. Internal policies like public policies in a city or country, are needed to conceptualize the organization from a systems approach (Dangi et al., 2009; Manga et al., 2008). It is important to emphasize that a systems approach in this paper involves three main elements: takes into account several dimensions (politic, economic, social, cultural, environmental, etc.), as well as micro and macro levels, e.g. designing policies as a strategy for the macro level in the organization, but involving on it actions and dynamics of the individuals like students, scholars, managers, administrative employees, janitors, and bins.

One successful strategy to involve individuals in the conceiving, designing and implementing stages of SWM programs is the development of opinion participation like the virtual survey. This artifact facilitates not only the approach to the opinions from the community, but also the adaptation of the strategies within them, which is a key element to achieve sustainable projects. Nevertheless, because of the low participation of students, it could be important to experiment several media to invite them, additional to email and university website.

Is there an organized operative structure for SWM in the campus? An operative structure exists; nevertheless, it is not enough to be effective. The study showed that the most important roles in the waste management processes have several responsibilities in addition to SWM. In the same sense, the lack of some information system to support their decisions and related activities is one of the main weaknesses of the system; this results in the lack of information about generation, generators, and flows not only of this waste within the campus but also about equipment purchased yearly by the organization.

The office that is directly responsible for SWM in the campus, designed by the OPP, has the support of the Environmental Administration Group (EAG, Table 1). Nevertheless, EAG has become as a closed group (similar to a syndicate) which blocked the participant observation of the researchers during the last months of this research specifically in the EAG meetings. This effect was caused by misunderstandings about the goals of the recent group UEG (University Environmental Group, Table 1) which demonstrate the importance of clear and effective communication between each A-N.

Which elements have triggered improvements in the SWM system in the campus? The most important external element that has pushed actions is the compliance with public law, while inside elements have been mainly three: Firstly, academic interests of scholars who have garnered the OPP (which is the Campus Administration Office) support to develop related projects in the campus. Secondly, the interest of the OPP in decreasing costs for SWM.

The third motivation is the organization's positioning and marketing related to its environmental responsibility which is measured through projects, strategies and constructions to preserve natural resources.

Education as the main purpose of the University has been included as an explicit goal within the first element, as well as in the third: currently, the OPP is interested in having the campus become an education subject itself. This point is clearer in other different issues like for example *sustainable water management*. One example is the construction of an artificial wetland (2012) for rainwater harvesting to use it in gardening or in washing floors and facades, activities that had been previously done with drinking water. This project was born out of the academic interests of a group of scholars of the Faculty of Engineering in 2005 who involved several students through undergraduate and graduate projects, as well as involving the OPP in the decision-making process in 2010.

Finally, it is important to evaluate the organizational structure related to SWM in order to reinforce it, as well as design and implement strategies for (i) measuring generation and composition of ordinary and hazardous solid waste, (ii) decreasing generation of it, not only the amount of waste delivered through recycling or collecting campaigns – reactive, but also based on a preventive focus that includes i.e. responsible consumption, (iii) WEEE management under both focuses as well (preventive / reactive), (iv) decision-making based on structured guidelines that involve appropriate criteria, as well as on the context (city/country), all of them with educational purposes as well.

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Appendix B. Chapter: Using Actor-Network Theory in Agent-Based Modelling

Using Actor-Network Theory in Agent-Based Modelling

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1.1 Introduction

Design-oriented research usually involves modelling for the purposes of representing, exploring or simulating real-world situations. A widely-used approach is agent-based modelling; agent-based models (ABM) help understand or reveal the effects of collective behavior by representing the rules governing agent decisions and the influence of these decisions on a virtual (or sometimes actual) real-world environment. A number of different theories guide the design of individual agents, their interactions and the environment on which they act, most of which are focused on representing the currently observed situation or are driven by historical data in order to enable calibration and the interpolation of future scenarios. However, these approaches often lack the in-depth reconstruction of historical trajectories or fail to capture the dynamics that have led to collective patterns, whether successful or not. Furthermore, most of these strategies treat agents as human actors or institutions, leaving out non-human actors or treating them as a part of a different category, despite the fact that both human and non-human actors exercise agency, interaction and collective behavior. Thus, the main research question addressed in this chapter is how to extract key elements from historical trajectories in socio-technical systems via the identification of networks of human and non-human actors and their past dynamics such that this information can be used for the design of agent-based modelling and simulation.

Put another way, this chapter proposes the use of Actor-Network Theory (ANT) as an innovative pragmatic approach to the design of agent-based models and simulations with the purpose of supporting policy design or enhancing decision making. Given that ANT stems from a socio-technical tradition, it provides theoretical foundations, insights and guidelines for the exploration and conceptualization of real socio-technical systems with emphasis on intervention. The first part of this chapter introduces the main conceptual elements of ANT and ABM. From there, the chapter proceeds to discusses possible links between ABM and ANT concepts using an exploratory case study in the context of WEEE (Waste of Electrical and Electronic Equipment). Based on the application of ANT in the case study, a methodological framework for integrating ANT and ABM is presented and discussed in the last part of the chapter, along with a brief examination of open issues and concluding remarks.

1.2 Agent-Based Modelling

There is no single, all-encompassing definition for an agent. Agency can be framed within the economic theory of agency (Ross 1973) or the theory of the firm (Jensen & Meckling 1976), from a human social cognitive theory perspective (Bandura 1989). Agency can understood from a computer science perspective, which combines distributed systems and artificial intelligence into the notion of an intelligent software agent usually acting on behalf of a human user (Sycara et al. 1996). This last perspective opens a wide range of possibilities, *i.e.* agents can be simple or complex, autonomous or semiautonomous, homogeneous or heterogeneous. What is more, from the computer science perspective, agents may form small, collaborative teams or a large, self-organizing social system. In simple terms, agents usually represent social actors, such as individual people, collectives, institutions, businesses, countries or any entity with a certain specific goal (Gilbert & Troitzsch 2005; Gilbert 2007; Railsback & Grimm 2011). As such, agents should be unique and autonomous. To be clear, unique implies that an agent may be different from others (as opposed to homogeneous agents, whose behavior is closer to that of automata) and autonomous implies that agents pursue their own objectives, that is, act independently of each other (Railsback & Grimm 2011).

A benefit of this computer-science understanding of agents lies in that it requires the focus to extend beyond the agent itself; as a result, it includes communication and interaction among agents, as well as interaction with an environment. The goal, then, becomes not just the individual design of agents, but to design them as a part of an artificial society (Epstein & Axtell 1996), or to design an agent-based simulation in general (Sanchez & Lucas 2002), which means conceptualizing, designing and implementing ABM and simulations. In ABM, agents interact within an environment, and this interaction denotes the ability to send messages to each other and affect each other's actions. Messages may represent a spoken conversation between real actors or information flows via one agent's observation of another. Agent-to-agent interaction of this nature represents the primary difference with respect to other computational models (Gilbert 2007). Moreover, agent interaction generates emergence or collective patterns that can be visualized in the system's macro level, thereby suggesting that ABM has as a primary goal the study of complex, collective emergent structures or patterns that emerge from simple rules defined at the individual level (Macy & Willer 2002).

ABM allows for the modelling of individual heterogeneity through explicit representations of the rules governing each agent's decisions by situating agents in different places within an environment, *i.e.* the virtual world in which agents act (Gilbert 2007). An ABM, then, is a system composed of individual agents (and the rules governing their simple decisions), the environment (whether geographical-natural or artificial, such as a knowledge space) and the social structure (made up of relationships and rules governing agent interaction)—see Figure 1.1. The effects of collective agent action in relation to the environment and the social structure generate emergent patterns, although such patterns can, in turn, affect the agents individually and even affect their future decision-making akin to the co-evolution of agency and structure in Giddens' Structuration Theory (Fuchs 2003; Knoeri et al. 2010). Therefore, ABM presents two levels (or more) of interactions: system-wide changes and individual adaptations to different external conditions (Railsback & Grimm 2011).

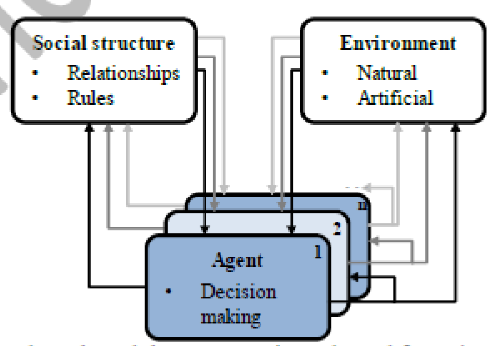

Figure 1.1 Agent-based model representation adapted from (Knoeri et al. 2010)

One of ABM's most salient features is the ontological correspondence between computational agents in the model and real-world actors (Gilbert 2007). This correspondence is associated with the level of similarity between the two, and, when this correspondence is high, ABM is more easily implemented, making the outcomes easier to interpret.

1.2.1 ABM approaches

When setting up the agents and their social structure, we find a number of theories, some of which are rooted in the social sciences, *e.g.* the theory of interpersonal behavior (Triandis 1979) to understand curtailment behaviors such as switching off appliances or driving behaviors in transport systems. Looking at a different time scale, the theory of planned behavior (Ajzen 1991; Feola & Binder 2010) can be used for one-off behaviors, such as heating system installation or refrigerator replacement.

Some ABMs and simulations, such as *SocLab*: "A Framework for the Modelling, Simulation and Analysis of Power in Social Organizations" developed by (Sibertin-Blanc et al. 2013), have used the sociology of "organized action" (Crozier & Friedberg 1983), are also referred to as strategic analysis. Strategic analysis is a theoretical framework for the analysis of the organizational dynamics based on power relations (Sibertin-Blanc et al. 2013). Within the same field, we also have the institutional analysis and development framework proposed by Ostrom (Ostrom 2005), in which individuals are the key driving components of a social system. In Ostrom's theoretical framework, as well as in the framework proposed by Giddens's structuration theory (Held & Thompson 2008), the social context not only encompasses the behavior of individuals, but is also structured by individual interactions. For their part, individual interactions are shaped by institutional settings (Ghorbani et al. 2012).

In addition, there are several theories stemming from the computer science side of ABM. Most notably, Zambonelli and his colleagues (Zambonelli et al. 2003) have proposed a model for multi-agent systems that is based on computational organization: software agents assume different roles (with their own permissions and responsibilities), interact with each other and are modeled separately from the environment in which they interact.

1.2.2 Agent interactions

The simplest interaction among agents consists of data transfer from one agent to another, *e.g.* one agent informs another of its gender and age, enabling the second agent (receiving the information) to make a decision. A more complex interaction would be the exchange of messages whereby an agent composes a message within the confines of a language and another agent interprets it.

Interactions can be included in the ABM as part of the (individual) agent decision-making process and as rules, norms or shared strategies in the social structure.

A similar phenomenon to the decision-making process is agent decision and action according to a reasonable set of rules aimed at optimizing the agent's own utility (seen in many models). Agents, however, may also act irrationally, or randomly, without optimizing their welfare. Some economists assume that individuals are *hyperrational*, that is, they assume people always select optimal courses of action. Yet, when real-world actors, such as policy makers, are forced to make decisions that involve environmental or social criteria, their own interests, like economic benefits, may not play as important a role. Herbert Simon expressed this as a distance between managerial practice and models of expected utility (Pomerol & Adam 2008), a fact that made boundedly rational agents the most applied logic to the design of agents.

Physical objects are usually seen as mediators between agents, establishing a clear divide between non-human elements and human actors. However, in the study of complexity and socio-technical systems, the possible agency of objects themselves, such as artifacts, documents, information systems, laws, technologies, physical tools, among others, should be taken into account. Moreover, interactions between agents are temporally affected by past (real) and future (possible) collective effects of their individual decisions. These phenomena should be more explicitly incorporated into ABM simulations. To this end, ANT (which is presented in the next part of this chapter) may help designers deal with the aforementioned ambiguities and tensions stemming from the existing multiplicity of conceptual framing.

1.3 Actor-Network Theory

ANT is a conceptual framework for exploring socio-technical processes that entail a symmetry between human and non-human actors (referred to as *actants*) in networks (Correa-Moreira 2011). ANT was developed within the discipline of science and technology studies (STS); in STS, scientists and their colleagues, in addition to the materials and artifacts available to them (documents, lab materials, literature, and information technologies) are intertwined and constantly reshape each other. Recent examples include the analysis of the role played by the main information system in a National Science and Technology System (Gonzalez 2010), the role of network dynamics in the implementation of e-government and the application of information and communication technologies (ICT) in the public sector of developing countries (Stanforth 2006).

The concept of an "actor-network" (A-N) was developed by Michel Callon, Bruno Latour and John Law in the in the context of STS in the 1980s. A-N, with the two words (and concepts) linked by a hyphen, aims to *bypass* the distinction between agent and structure. That is to say, A-N implies recognition of the fact that actors build networks by combining social and technical elements. Moreover, a network's elements are, simultaneously, constituted and shaped within the network (Stanforth 2006). ANT, as well as anthropological theories such as Bennett's (1976) "human adaptive dynamics" cited in (Bharwhani 2004), does not isolate individual actions from the relations and connections that give them purpose. Like Giddens' Structuration Theory, ANT regards actions as framed by institutional and other relations, yet ANT goes further insofar as it disrupts the dichotomy between structure and agency altogether (Steen et al. 2006). Thus, agency is not only assigned to humans, but also to non-humans, which is a *de facto* invitation to conceive of a network as a heterogeneous mix of textual, conceptual, social and technical *actants* (Ritzer 2004). According to Latour, an agent is "*any thing* that does modify a state of affairs by making a difference" (Latour 2005, p. 71). Agency is not an essence inherent to humans; rather, it is a capacity realized through the association of actors (human or non-human) and is, consequently, relational, emergent and shifting (Orlikowski 2007). From an ANT perspective, nonhumans are more than passive resources at the disposal of humans: they are active, vibrant agents that also exert power (Dwiartama & Rosin 2014). Latour goes on to add that "ANT is not the empty claim that objects do things 'instead' of human actors: it simply says that no science of the social can even begin if the question of who and what participates in the action is not first of all thoroughly explored, even though it might mean letting elements in which, for lack of a better term, we would call nonhumans. [...] The project of ANT is simply to extend the list and modify the shapes and figures of those assembled as participants and to design a way to make them act as a durable whole" (Latour 2005, p. 72).

To put ANT into action, the history of the observed phenomenon (with its concomitant micro-phenomena), the main facts (milestones) from which emergent patterns of behavior have occurred (Méndez-Fajardo & González 2014) should be identified. Using the resulting evolutionary timeline, ANT presents four constitutive elements. First and foremost, the Obligatory Passage Point (OPP) between the problem to be solved and the solution. This can be an A-N, *e.g.* the *actant* that mobilizes the system through authorizing actions, or a process to be developed by all actors in order to achieve both the system and individual goals. Second, the main A-N in a local network is determined by virtue of its relation to milestones. Third, the main A-N is identified for the global network based on its ability to interfere with the system or even impact the local network if the OPP is weakened. To avoid confusion, readers should note that A-Ns in a local network can directly interact with A-Ns in a global network.

The fourth element, referred to as "moments of translation," involves describing the dynamics between local and global networks. To wit, moments of translation are how the A-Ns align their interests, how they focus to generate successful action (Callon 1986a; Gonzalez 2010). These translations constitute the mechanisms through which networks progressively arise around power relations (Stanforth 2006). Callon (1986) proposed four moments of translation: i) *problematization*, or how the OPP makes itself indispensable; ii) *interessement*, or how allies are locked into place; iii) *enrolment*, or how roles are defined and coordinated; and, iv) *mobilization*, or how the principal A-Ns borrow the force from more passive A-Ns and become their representative or spokespeople (Callon 1986a; Stanforth 2006). Moments of translation constitute "episodes" from which milestones emerge over the course of a part of the history. Following these episodes, the ways in which A-Ns increase or decrease the gap between individual interests and the OPP's goal can be established. The closing or distancing of this gap affects the aggregation level or attachment in the global network (control over the global) or the level of mobilization in the local network (control over the local).

1.4 Towards an ANT-based approach to ABM

Approaches to the design of ABM (Section 1.2.1.) allow us to understand networks of actors and their dynamics; however, such approaches do not explicitly account for the role of objects (tools, artifacts, documents, etc.) in networks. For example, the aforementioned theory of planned behavior could be used to set up consumer interests when deciding whether or not to replace a piece of equipment with a new one. This theory may even apply to the decision regarding disposal of the old equipment. Yet, the influence of the appliance itself is not included in the consumer's decision-making process. One of the main questions remaining unanswered, which is in fact addressed here, is: Perhaps that object has agency?

Likewise, theories of organizational dynamics fail to include the actual role of organizational norms or technological infrastructure (computers and software) in the achievement, or lack thereof, of organizational goals.

Agent-based simulation tools, such as *SocLab* (Sibertin-Blanc et al. 2013), hold that ANT does not place power relations at the heart of their analysis, as, they claim, is the case for Crozier's sociology of organized action (1964). However, in the sociology of translation (Callon 1986b), moments of translation do indeed represent power relations: power relations are shown by the ways in which actor-networks are defined, associated and obligated to remain faithful to their alliances (Stanforth 2006).

Different studies have integrated ABM into the analysis of social networks (Baber et al. 2013; El-Sayed et al. 2012; Hamill & Gilbert 2010) or collaborative social networks (Madey et al. 2003). Nevertheless, to date, the studies conducted have not treated nonhumans as *actants*, nor have they sufficiently investigated the moments of translations (*problematization*, *interessement*, *enrolment*, *mobilization*) per the tenets of ANT.

1.4.1 ANT Concepts related to ABM

ANT proscribes the division between agency and structure, human and non-human or micro-level and macro-level phenomena. ANT is premised on the intertwining of these facets through collective dynamic activity (Ritzer 2004). In particular, the A-N concept allows model designers to eliminate the human/non-human distinction in that an actor is itself a network made up of human and material elements. In contrast to other theories supporting the design of ABMs focused on human agency, both human and non-human A-Ns can become agents in ABM. In fact, they need not be distinguished, for the emphasis is placed on networks, not on individuals. As a result, designers can directly translate between human A-N *interessement* and agent decision criteria, although there is a difference when treating nonhumans: ANT proposes the agency of artifacts , which can be understood not as "things making decisions", but rather "things generating human decisions" when there is some sort of relationship between them—mainly when non-humans are members of moral and political associations (Sayes 2014).

In ANT, macro-level phenomena are considered "more stable" networks (see "Solid projects" in Figure 1.4). In such networks, nodes are semiotically derived, making networks local, variable and contingent (Ritzer 2004). This can be translated as emergence in ABM. In other words, the mobilization process in ANT can be translated as an emergent pattern, and this translation dynamic in ANT reveals the key elements needed for an A-N to cooperate (*enrolment*) or defect (low degree of attachment in the global network). Cooperation has been linked to the "shadow of the future" concept (Bó 2005; Cohen et al. 2001), in which a rational agent expects its present actions to affect the future behavior of other agents. ANT employs ABM as an explicit framework for the study of interactions between agents, not only in the form of message exchanges, but also as extensions of an agent to their network, thereby redefining the agent in relation to the network. In so doing, ANT provides a theoretical support for the design of ABM in socio-material settings.

1.5 Design guidelines

To find solutions to real problems, designers use modelling as part of their research methodologies. They seek to represent the real world in order to understand phenomena and contextual factors, such as related issues, actors, actor relations and causes and effects, among others. Models also serve to stimulate discussion and learning processes for stakeholders by explaining phenomena, raising enlightening questions or disciplining the policy dialogue (Epstein 2008). To understand and describe the context in which a problem manifests, action-research and exploratory case-study methods are suggested in this chapter as methodological companions to ANT, including, but not limited to, interviews and participatory observation. The following process for applying ANT to the design of an ABM is abstracted from a case study developed below; see Figure 1.2 for more details. The first step entailed the definition of the initial focal problem corresponding to the main problem to be addressed. Building from initial design aspects, the second step requires the identification and review of documents to reconstruct an initial description of the case history, as well as to link actors to each discovered fact, which is the third step.

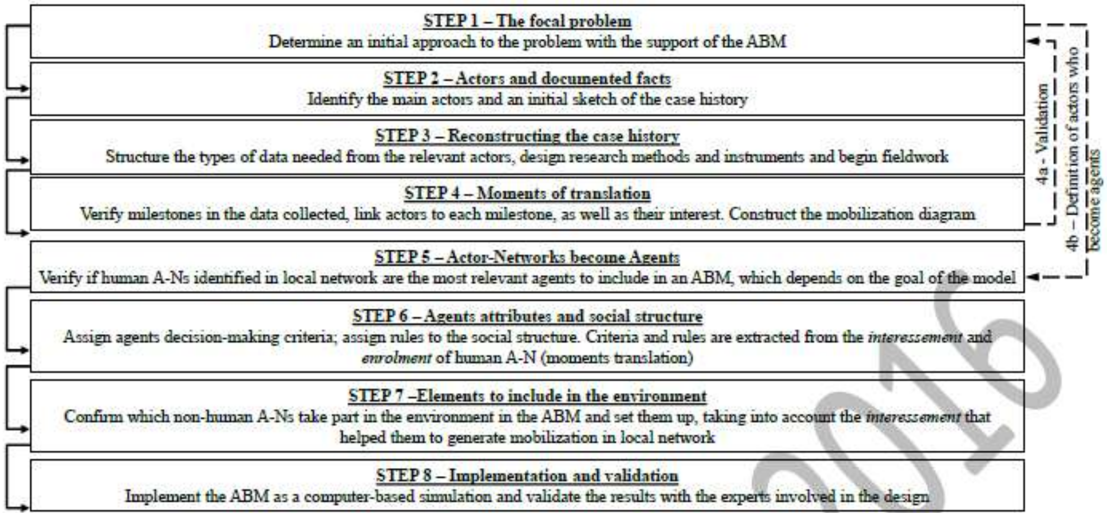

Figure 1.2. Abstraction of steps for applying ANT to the design of an ABM

On the basis of these data (steps 1 and 2), the structure and schedule of interviews must be developed before commencing fieldwork. Interviews should include, at a minimum, the following elements:

a. Information about the relevant experience of the interviewee, including timeline.
b. Facts he or she considers to have changed the situation or a specific project's trajectory within the larger case story, including dates (at least years, though hopefully more precise dates), locations, people and organizations that participated, as well as relevant documents, studies, etc.
c. Ask for opinions about the system's main elements in order to determine the importance of each, according to the interviewee. Include opinions about the system's ideal future, which may help confirm interviewee interests.

To represent the moments of translation (step 4), a graph is invaluable; see, for instance, the graph in Figure 1.3: changes in the path mean that some milestone has occurred and generated important changes in the composition of the local and global networks.

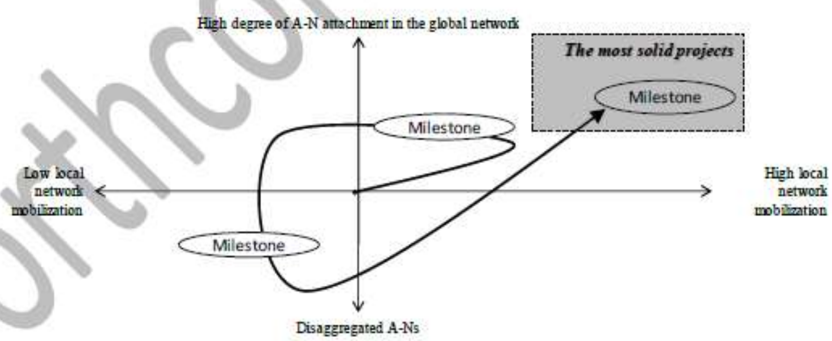

Figure 1.3. Graph of the mobilization of A-Ns in local and global networks. Adapted from (Méndez-Fajardo & González 2014; Stanforth 2006)

As the previous figure shows, the most solid projects are those in which both higher degree of A-N attachment in a global network and high local network mobilization occur. In such situations, the interests of all actors are strongly aligned, and the result is a successful project (program, strategy, action). Looking at the same graph, and before deciding which A-Ns become agents (step 5), each milestone must be documented, along with which actors constitute the local network. Then, these A-Ns are selected based on the two most solid moments, *i.e.* moments of translation in which A-N are both more aggregated and more highly mobilized—more solid moments appear in the upper-right quadrant of the mobilization diagram (Figure 1.3).

In order to define which A-Ns should be included in ABM, the focal problem should be adjusted via a validation of milestones and identified A-Ns (step 4a), a process carried out with the participation of relevant actors. As a result of this adjustment, we can establish the list of A-Ns to be included (step 4b), allowing for the definition of agent attributes (Step 6). To design decision-making aspects, we identify the criteria within the moments of translation (*interessement* and *enrolment*), especially with respect to prioritization. It behooves us to mention that some actors may falsely express their most important need to keep up an image with the rest of the actors.

In Step 7, we can see that some non-human A-Ns will form part of the environment, *e.g.* as physical compounds. The result of Steps 6 and 7 are the rules that agents should follow in the model.

To easily validate the ABM as the last part of the methodology proposed (Step 8), the model should be implemented as computer-based simulation. Doing so facilitates evaluation of the rules (through experiments) included in the design by observing the resultant emergent patterns. In this step, it becomes especially relevant to include the participation of experts, in addition to that of the actors involved in the case.

The application of ANT to particular subjects can be useful when looking to discover the potential of ANT for socio-technical studies. In the next part of this chapter, an exploratory case study on Waste of Electrical and Electronic Equipment (WEEE) management in Colombia is presented and interpreted using this theory. Nevertheless, the complete ABM, and its implementation and validation (Step 8), are not included in this chapter, for the main goal here is to debate the possibilities opened up by ANT's conceptualization of design for an ABM.

1.6 The case of WEEE management

In developing countries, institutions responsible for territorial planning are faced with rapid urbanization and the concomitant solid waste management problems (Guerrero et al. 2013). As part of the municipal solid waste, WEEE[1] has taken on added importance due to the potential risks to public health and the environment, which can be traced to the toxic components they contain, such as heavy metals (Ongondo & Williams 2011; Wäger et al. 2011; Widmer et al. 2005). To tackle the negative impact of poor WEEE management, policy makers tend to make decisions from a limited perspective, generally restricted to technical or economic outlooks, while neglecting a systems-based approach that involves additional dimensions, *e.g.* social, legal, ecological, political and even cultural dimensions (Marshall & Farahbakhsh 2013), as well as different management processes, different interests of all actors involved and the cause-effect phenomenon (Méndez-Fajardo & González 2014). In contrast, the principle of Extended Producer Responsibility (EPR) has been widely implemented in developed countries, and EPR requires a systems approach since it demands the participation, cooperation and coordination of all stakeholders (Agamuthu & Victor 2011; Mayers 2007). To design more sustainable strategies for EPR in both developed and developing countries, the effects of past decisions should be analyzed in an attempt to understand the processes that have generated successful (or at least differential) actions in the past.

WEEE management can be characterized as a typical socio-technical system insofar as it demands technical artifacts to achieve material goals and is strongly affected by human attitudes and decisions. Therefore, ANT helps us to learn from past WEEE management experiences, identifying the key elements for the design of a more sustainable WEEE management and identifying key elements influencing decision making so as to increase sustainability in future actions.

The research herein was carried out in the South American nation of Colombia as an exploratory single-case study to study current phenomena in a real-world context (Maguire et al. 2010; Yin 2003a; Yin 2003b). The Colombian study is embedded: it includes two units of analysis (Yin 2003b). These two units are decision-making roles and operational roles within Colombian WEEE management, respectively. The main purpose of the case study was to ascertain whether or not decisions regarding WEEE management in Colombia were made using systemic processes. A corollary goal was to investigate whether or not decision-makers applied a systems-based approach to their own decisions.

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[1] According to the European WEEE Directive, "'electrical and electronic equipment' or 'EEE' means equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1 000 volts for alternating current and 1 500 volts for direct current" (The European Parliament & The Council on Waste Electrical and Electronic Equipment 2012). The categories of WEEE can be distinguished as follows: i) Large household appliances; ii) Small household appliances; iii) IT and telecommunications equipment; iv) Consumer equipment; v) Lighting equipment; (vi) Electrical and electronic tools (with the exception of large-scale stationary industrial tools); vii) Toys, leisure and sports equipment; viii) Medical devices (with the exception of all implanted and infected products); ix) Monitoring and control instruments; and, x) Automatic dispensers (The European Parliament & The Council on Waste Electrical and Electronic Equipment 2012).

1.6.1 Contextualizing the case study

Per assessments, in 2013 the generation of WEEE (aggregated EU categories; see Footnote 1) in Colombia was around 120,000 tons, which corresponds to 2.5 kg/inhabitant/year. The breakdown of Colombian WEEE was as follows: large household appliances (24%), IT and telecommunications equipment (16%), consumer equipment (38%) and lighting equipment (13%). Although not explicitly included into these categories, Colombia has implemented post-consumer program for batteries (9%).

The main related processes inside and outside Colombia are shown in Figure 1.4 (below). In this figure, we see that production involves international producers and importers of electrical and electronic equipment (EEE), as well as local (domestic) assemblers (which account for less than 10% of EEE). When obsolete EEE is discarded, it becomes WEEE. Some EEE pre-treatment materials are recovered locally or disposed of in local (regional) landfills, while post-treatment elements are exported and processed in other countries. In the same graph, primary distribution refers to the sale of new equipment—either imported or locally assembled—that could be developed directly by the companies producing them, or by large and small market-chains. In addition, disassembling, also called dismantling (León 2010), is the manual process by which devices or parts (*e.g.* CD drives, memory cards, etc.) are separated for subsequent material recovery (such as ferrous metals).

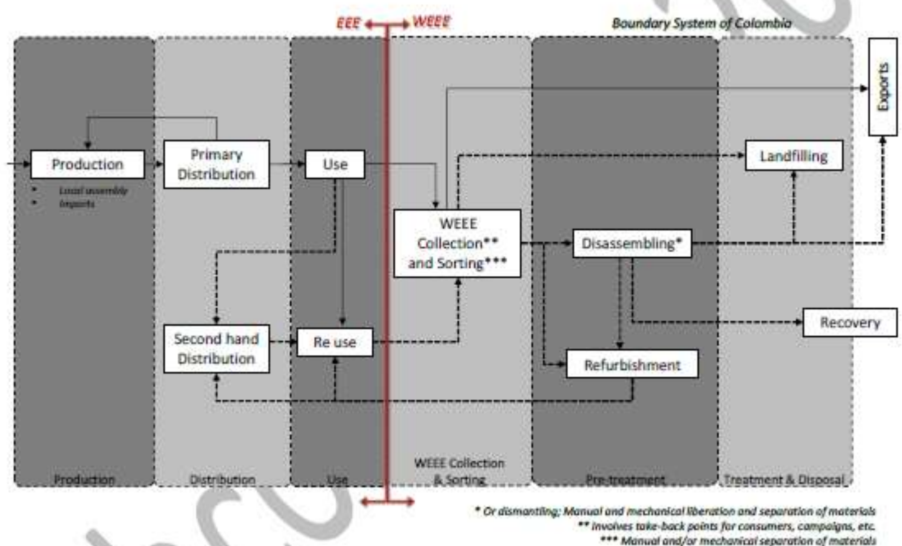


Figure 1.4. WEEE management processes in Colombia.

The processes illustrated in Figure 1.4 are restricted to the formal system, *i.e.* processes authorized by the environmental authority. In Colombia, formal systems only exist for waste from computers, batteries, lighting, and mobile phones; however, unknown amounts of small (irons, hair dryers, blenders, etc.) and large household appliances (refrigerators, washing machines, etc.) have also been pre-treated in an informal chain. Informality is present in most waste management activities of developing countries (Chi et al. 2011; Guerrero et al. 2013): equipment is dismantled by pounding the objects against the ground in public areas, private households or warehouses (León 2010; Streicher-Porte et al. 2005; Widmer et al. 2005). These activities increase public health and environmental risks.

1.6.2 ANT applied to WEEE management in Colombia

The historical evolution of WEEE management in Colombia is described in Figure 1.5. It is important to highlight the relevance of regulations and working groups or committees in this evolution.

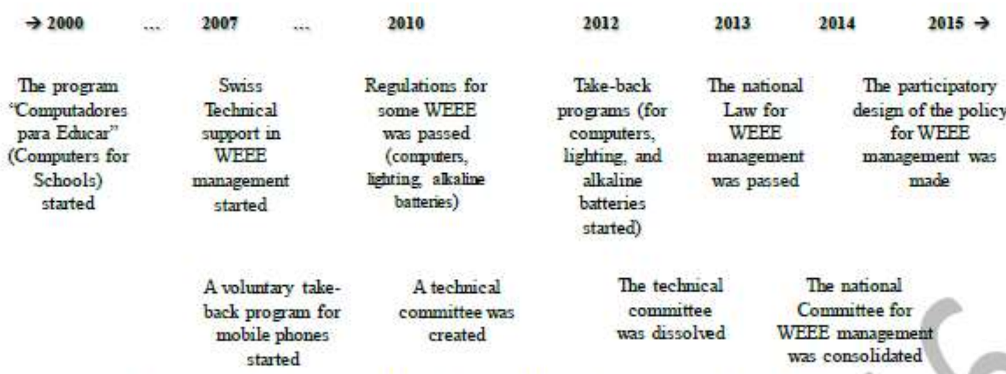


Figure 1.5. The general timeline of WEEE management in Colombia

Generic human A-Ns in WEEE management refer to producers, distributors, consumers, recyclers and the Government at the national, regional, and/or local levels (including national and international technical support, an innovative legal strategy). National governmental organizations include the Ministry of Environment and Sustainable Development (MESD), the Ministry of Health and Social Protection, the Ministry of Information and Communication Technologies and the Ministry of Commerce, Industry and Tourism. Informal recycling is not legally included, despite its relevance as an A-N in the system. In the same vein, associations that bring together producers, distributors or recyclers, such as FENALCO (National Federation of Traders) for dealers or ANDI (Industry Group of Colombia) for producers, must also be considered A-Ns.

Figure 1.7 shows local (see shaded section in the figure) and global networks. To reiterate, the term A-N in ANT (Latour 2005) encompasses not only human but also non-human actors, such as documents and laws. For the present research, local networks involved actors who participated in all of the different "episodes," while the global network only includes actors who took part of one or two episodes without current active participation. The global network also includes actors expected to play an active role in the system, *e.g.* consumers as a generic A-N or the Ministry of Education.

Actor-networks in the milestones of the WEEE management in Colombia *	
Ministry of the Environment and Sustainable Development (MESD)	Computers for Schools program and CENARE (2000 - present)
Ministry of Commerce, Industry and Tourism	Mobile phone service operators
Ministry of Education	Post-consumer programs to collect computers, lighting, and batteries (2012)
Ministry of Social Protection	Voluntary agreement regarding the collection and management of mobile phones (2010)
Regulations for the management of computers, lighting and batteries (2010)	Recyclers (formal and informal)
National Law for WEEE management (2013)	National Cleaner Production Center (CNPML)
Colombian Chamber of Informatics and Telecommunications (CCIT)	Academia
Decree on Hazardous Waste Management in Colombia (2005)	Swiss Federal Laboratory for Materials Sciences (EMPA)/ State Secretariat for Economic Affairs (SECO)
FENALCO (National Federation of Traders)	Assessments of WEEE management in Colombia (2008-2010)
ANDI (Industry Group of Colombia)	World Resources Forum (WRF)
National WEEE Committee (NWC) (2014) **	Consumers

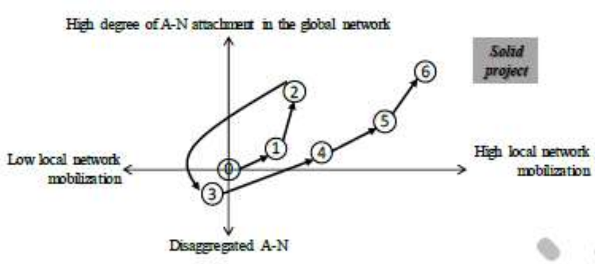
** Documents, groups, programs, laws and regulations are assigned the date of their creation*
*** Involves Government representatives, producers, distributors, recyclers, experts*

Table 1.1. Actor-networks in Colombia's WEEE management system.

Explicit relationships or links between all actors are not displayed due to the complexity of meaningful presentation in the graph. Furthermore, relationships change, have different strengths, include feedback loops and result in high interaction density, such that any presentation of all links would be subject to modification. Nevertheless, in the description of the moments of translation, the main relations between actors are explicitly stated.

1.6.2.1 Moments of translation

The structured interviews of relevant actors included questions about the most important facts in the Colombia's WEEE management history and which actors were involved at each stage. Based on interviews and a thorough document review (*e.g.* reports and assessments), the milestones (or mobilization moments) in the evolution of the WEEE management system and the A-N involved for each milestone were identified (Figure 1.8). The system's OPP was determined to be the MESD.



Milestone	General Description
0	Computers for Schools program was created
1	The Switzerland - Colombia cooperation started
2	Computer and mobile-phone working groups started
3	Regulations for computers and lighting were passed
4	The post-consumer programs *EcoComputo*, *Lumina* and *Pilas con el Ambiente* were implemented
5	The national law for WEEE management was passed
6	Increased involvement of stakeholders in the participatory design of national policy on WEEE management

Figure 1.6. Mobilization of actors in local and global networks

The starting point (Milestone *0* in Figure 1.6) is the creation of the Computers for Schools program in 2000. In the following years, two parallel courses were charted: on one hand, industry mobilization; on the other, governmental mobilization. As for the former, industry interest in donating computers was driven by four benefits: i) the social and community benefits of improving technological access for children and their future development options; ii) the positive environmental impact of preventing the toxic compounds from being disposed of in sanitary landfills; iii) the economic incentives stemming from not having to pay for the management of this waste; and, iv) the financial savings stemming from new processes adapted to comply with internal environmental management strategies.

With regard to the latter, the Government began to design regulations for hazardous waste management in the face of mounting pressure related to international agreements, such as the Basel Convention (1992) or the Kyoto Protocol (1997), as well as the pressure generated by domestic laws, such as the National Environmental and Natural Resources Management Law (1993) and the National Hazardous Waste Law passed in 2005. This 2005 law was instrumental in spurring industry action. As a result, an agreement was forged between the Swiss and Colombian governments, ratified in 2007 (Milestone *1* in Figure 1.6); this agreement called for the participation of the most relevant A-Ns. Local network mobilization increased as a function of the *interessement* or attraction of interests which was, for the OPP, the prevention of negative environmental impacts, compliance with hazardous waste laws and international sustainability accords, and, for the Swiss Federal Laboratory for Materials Sciences (EMPA) and the State Secretariat for Economic Affairs (SECO), assisting in WEEE management in developing countries. The Swiss initiative had previously been carried out in China, India and South Africa through the "Swiss e-Waste Program"; its focus turned to Colombia and Peru from 2007 onwards. During the first two years of this collaboration, not only did local network mobilization of the A-N increased, but so too did global network attachment. Results included the creation of the Computer and Mobile Phone Working Groups (Milestone *2* in Figure 1.6*)* and assessments of EEE and subsequent WEEE. These technical documents (assessments) were critical for WEEE-related decision making in Colombia (2008-2013).

In 2009, the local network visited Switzerland as part of a "study tour" of the Swiss WEEE management locations with an eye towards obtaining primary information to be used in Colombian WEEE management design strategies. Nevertheless, after this trip, the working groups fell into an internal crisis caused by divergent member interests. As a result, global network A-N aggregation and local network mobilization decreased; despite the emergence of this crisis, we witness one especially important positive outcome: the MESD passed regulations (2010) to achieve mandatory collection rates of computers and lighting (Milestone *3* in Figure 1.6).

A leadership shift, which saw producer representation move to ANDI, in combination with a change in the composition of the local network, eventually led to increased mobilization and participation. Three post-consumer programs for collecting waste from computers (*EcoComputo*), lighting (*Lumina*) and alkaline batteries (*Pilas con el Ambiente*) emerged as a result (Milestone *4* in Figure 1.6). The *interresement* to achieve this milestone was based on two targets: producer legal compliance and avoidance of penalties and economic opportunities for authorized recyclers, which represented financial savings for producers. These developments are different from the experience of the second working group, for the mobile-phone working group engendered a voluntary agreement by some mobile-phone service operators to set up take-back points for consumer equipment (*i.e.* to collect mobile-phone WEEE from subscribers or users of the telephone service). The equipment collected was then passed on to authorized recyclers.

The National WEEE Management Law was passed in 2013 (Milestone *5* in Figure 1.6), consolidating the process begun in 2010 by the A-N in the local network and spearheaded by the OPP. The passage of this law laid the foundations for the creation of the National WEEE Committee (2014). Implementation of the regulations passed from 2010 on has demonstrated the importance of public laws when it comes to increasing rates of WEEE collection. The dynamics of post-consumer programs proved to be an instructive learning process to avoid (when possible) failures in the implementation of the system.

However, the system still has not reached stability: currently, the MESD—supported by the CNPML, EMPA/SECO and the Javeriana University (Bogota, Colombia)—is designing the instruments and regulations to implement the law and establishing a control system. The National WEEE Committee has been involved in this design process, above all as pertains to policy design (Milestone *6* in Figure 1.6), in order to constantly encourage interest in and motivate the rest of the actors in the local network (A-N *enrolment*). The use of participatory methodologies has allowed us to identify the causes and effects of the current insufficient WEEE management system in Colombia, as well as identify the relations among causes, define structural causes, design strategies and the policy's action plan. Likewise, it has increased confidence and motivation in A-Ns, in turn strengthening the local network.

To recap, the most relevant milestone (the most solid project in Figure 1.6) has been the passing of laws given that these laws also includes previous episodes aimed at aligning the interests of relevant actors. Indeed, the implementation of regulations has illustrated the importance of mandatory strategies in terms of increasing WEEE collection rates and more responsible WEEE management. In addition to these regulations, technical and methodological support has been played a key role in getting the focal actor, MESD, to take crucial actions. That being said, there are other elements observed during fieldwork that should not be ignored when implementing sustainable WEEE management: i) actors in local networks should designate the same representative for the duration of the process; ii) this representative should take an active interest in the topic, rather than view it as an obligation; iii) for non-human A-Ns, detailed reports should be made of all strategies designed and implemented, including key elements (actors, actions, type of WEEE, failures, successes, possible future problems and consequences, etc); and, iv) it is crucial to have complementary strategies to ensure project sustainability on schedule and the availability of resources.

1.6.3. ANT – ABM translation based on the case study

In ANT, human and non-human A-Ns are ontologically understood as anything that modifies another A-N through a series of *actions*; they are referred to as *actants* (by Latour, 2005), whereas *actor* has been exclusively to refer to humans. In the same sense, an *agent* in ABM is anyone who makes decisions and acts accordingly. As this chapter has demonstrated, the human A-Ns in local and global networks may become agents, while non-human A-Ns may form part of the ABM environment, in spite of the fact that their set-up should feature mobilized actions in the (ANT) networks.

The case study has clearly shown that regulations (incentives or penalties), take-back mechanisms (post-consumer programs in Table 1.1), should be incorporated into the environment. Furthermore, decision-making processes in agents should be related to these two aspects. In this model, regulations, take-back mechanisms and educational programs are included in the design of *Sustainability Strategies* (see Figure 1.7.).

Relevant actors, although they should become agents, may not be explicitly accounted for in the ANT analysis, depending on the goal. For example, the goal of the exploratory case study in the WEEE management was focused on policy makers and strategies implemented over the last few years, essentially ignoring consumer behaviors related to these strategies. Given that WEEE recovery is the primary common interest of WEEE management actors, consumers play an important role, so they should be included in the model, regardless of whether they were explicitly included or not in the local networks. However, this is a question of boundary and scope, which is not directly addressed by the present proposal beyond the suggestions of ANT analysis in terms of what is meaningful for mobilizing and aligning A-Ns.

The moments of translation become the relationships and rules within the social structure and the criteria and weights for agent decision making. For instance, in light of ANT analysis results, producers decided to participate, that is, create a post-consumer mechanism, for it ensured legal compliance, which was the criterion assigned the most significant weight (*i.e.* interest). Hence, the passage and enforcement of the new law highlights the relationship between producers and the Government, represented in this case by the environmental authority (MESD). In this example, the law's crafting, its publication and the instruments to ensure compliance are part of the *interessement* used by the system's OPP.

The interests of human A-Ns (that is, their criteria) and the level of participation in global and local networks in relation to the milestones were identified and taken from the ANT analysis to be used in the design of two parts of the ABM: on one hand, the processes of the decision-making tool in agents, and, on the other, the relations and rules in the social structure (Figure 1.7). These data are based on local/global networks (Figure 1.7.) and mobilization dynamics (Figure 1.6).

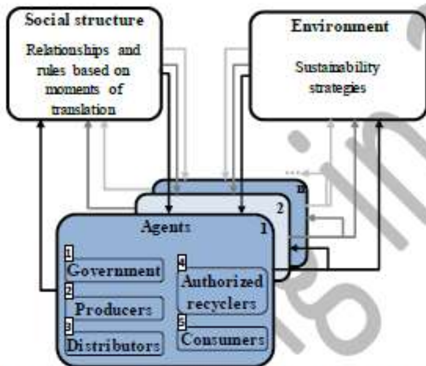


Figure 1.7. ABM elements based on the application of ANT for the case study.

1.6.4. Open issues and reflections

While not every ABM is destined to support real-world interventions, the aim of the present research has been to properly apply ANT to the design of an ABM that can be used to enact policy changes. Therefore, the interest is not to endow ABM with theoretical validity or provide a conceptual framework for ABM to make theoretical contributions. Rather, the goal here is utility, *i.e.* to be pragmatic with a focus on problem-solving. The connection between ANT and pragmatism has been already discussed: according to Rimpiläinen (2013), ANT and pragmatism undermine the distinction between subjects and objects (Rimpiläinen 2013), given that knowledge emerges from transactions (Dewey & Bentley 1949) or events and practices (Mol 2005; Mol 1999). On the basis of the recognition that knowledge emerges from practice, this chapter has sought not to build theory, but to apply ANT in ABM design, framing it as a heuristic for intervention.

Multiple studies have evinced the relevance of using decision-support systems with ABM in policy design. The present research contributes further evidence of its relevance by emphasizing the importance of including past milestones documented through action-research with the principal actors (ideally policy makers) and by involving the agencies of nonhumans. Armed with an understanding of these dynamics arrived at via ABM, designers and policy makers can form more successful alliances in order to achieve more sustainable solutions.

The ABM designed using ANT has been implemented in a computational tool that supports decision-making processes for WEEE management. In such processes, the agency of regulations, such as policies, and technical artifacts, such as take-back mechanisms, merit further discussion. Both the computational tool and participatory validation in a decision-making exercise represent the subject matter of forthcoming publications.

One open issue worth highlighting is a deeper engagement with the philosophy of works such as Latour's Actor-Network Theory (Latour 2005) in order to more clearly delineate more clearly the agency of objects from an ontological point of view. A good example would be a close reading of Barad's agential realism (Barad 2007; Barad 2003; Barad 1996), which holds that "the adjectival form of the word 'agency' modifies and specifies the form that realism takes here, in defiance of traditional forms of realism that deny any active participation on the part of the knower. Agency is a matter of intra-acting, that is, agency is an enactment, it is not something someone has" (Barad, 1996 p.183). Similarly, the socio-materiality developed by Orlikowski (2007) or Leonardi (2013), among others, could be ontologically compared with the A-N concept. For example, in the proposed methodology, which links ANT and ABM, we assigned some agencies to non-humans (think of take-back mechanism); this lines up with logic of the agential realism as a pragmatic decision. However, further studies are needed to extend this pragmatic decision, to position the "agency" concept within other ontological discussions.

A last open issue is related to this ontological approach: the importance of reviewing the goal-seeking concept in the management science contribution of Simon (Simon 1997; Simon 1955) and purposeful design (Kroes 2012). Both theories should be applied to the artifact design process (*e.g.* take-back mechanisms in WEEE management). In this regard, the ontology of the objects, a foundational concept in ANT, has been studied by some contemporary philosophers, but many elements remain to be linked environmental systems, considered as a socio-technical systems.

1.7 Conclusions

This chapter proposes the use of the actor-network theory (ANT) as an innovative theoretical approach to the design of an agent-based model (ABM) for socio-material contexts. In so doing, we employed ANT theoretical foundations, *i.e.* the representation of historical trajectories in socio-technical systems. This allowed for the identification of networks of human and non-human actors, as well as their past interaction dynamics, which can either mobilize and align or distance these actors. Furthermore, this chapter relies on ANT to provide an initial advance in the achievement of design guidelines that express the way that results of ANT-based studies can be further developed for ABMs.

An exploratory case study in the context of WEEE provides support for applying the abstracted process described here to design. ANT and agent-based modelling may be combined in cases where non-human agency is relevant and merits inclusion in the resulting ABMs. Problematic situations for which this proposal could facilitate a generalization of the method are: industrial processes in which people and machines are continuously interacting; the design and construction of physical infrastructure that may generate social and environmental impacts (*e.g.* bridges, highways, prisons or sanitary landfills), among others. Therefore, linking ANT and agent-based modelling can strengthen the ability of ABMs and other simulations in terms of informing decision-making processes and policy makers where interactions between human and non-human actors generate emergent collective behavior. In addition, by incorporating an ANT approach to the reconstruction of historical trajectories, we can further explore and/or explain previously identified collective patterns that, in socio-technical network terms, are aligned or misaligned. Extensions of the present work include the implementation of computational agent-based simulations, as well as empirical validation of the decision-making enhancement that they provide. Future work may also look to deepen the dialogue with *socio-materiality* as an evolving topic in information system design and practice.

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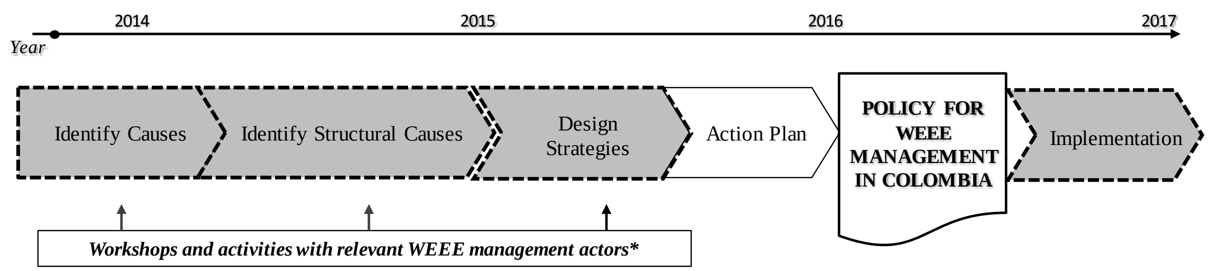
Appendix C. Participatory design of the policy for the integral WEEE Management in Colombia

The *problem tree* method proposed by CEPAL (2005) as part of the logical framework for designing and evaluating projects (CEPAL et al., 2005) has been used to design public policies in Colombia on the basis of the identification of causes and effects constellated around a focal problem. In this research, three main participatory activities were included in this design: i) the identification of the focal issue and causes and effects; ii) the identification of the structural causes; and, iii) the design of potential strategies to address structural causes and the focal issue.

The design of this policy already began in 2010 under the leadership of the *Ministerio de Ambiente y Desarrollo Sostenible* (MADS), with the involvement of some relevant actors. Nevertheless, the delay in the alignment of their interests led the MADS to publish a similar law (2013) instead of the policy. This Appendix describes the participatory policy design developed in 2014 and 2015 as part of the single-case study "WEEE Management in Colombia."

As Figure AC1 shows, this design was developed in different workshops and activities. Stronger participation of the relevant actors centered on the three first steps (see gray portions of Figure AC1) and the final document review.

Figure AC1. Methodology for policy design for integral WEEE management in Colombia



The relevant actors in this design included members of the National WEEE Management Committee (NWM-Committee), which is made up of guilds of producers (ANDI – the *Asociación de Industriales de Colombia*, and CCIT – *Cámara Colombiana de Telecomunicaciones*) and distributors (FENALCO – the *Federación Nacional de Comerciantes*), as well as the MADS, the *Ministerio de Protección Social*, the *Ministerio of TICs*, and the *Ministerio de Comercio, Industria y Turismo*. To round out the committee, delegates from Authorized WEEE Managers (formal recyclers) and two advisers, one national (the *Centro Nacional de Producción Más Limpia*, CNPML), and one international (the Swiss Government represented by the World Resources Forum – WRF, and the Swiss Federal Laboratory for Materials, Technology and Society - Empa) were included.

Methods applied in the first participatory steps are described below.

Step 1: Identify causes

The first workshop was developed on October 14, 2014 with a total of 14 attendees who represented the organizations included in the table AC1 (Figure AC2 - left). In order to use the *problem* *tree*, relevant actors defined the focal problem to be addressed: "the insufficient and inadequate WEEE management in the country." Then, actors identified causes and effects through a *think tank,* classifying them into the following dimensions: environmental, socio-cultural, economic, technical, and political (Figure AC2 - center). Additionally, the method of *visualizing the vote* was used to prioritize the identified causes (Figure AC2 - right).

Figure AC2. Visual results of the workshop to identify causes and effects related to the focal problem

Table AC1. Organizations represented at the first workshop, "Identification of the focal problem and its causes and effects (October 14, 2014)"

Organization	WEEE actor represented
MADS (3 representatives)	Government
Red Verde	Post-consumer program
CI Recyclables	Formal recyclers
Empa, Switzerland	International expert
Lasea Soluciones	Formal recyclers
WRF, Switzerland	International expert
CNPML	National expert
ANDI	Producers association
UNE (Telecom service provider)	Distributor
Eco Cómputo	Post-consumer program
Lúmina	Post-consumer program

Each attendee evaluated the concept of systems approach at the end of this first workshop. As a result, the following keywords were obtained: interactions (71.4%), parts (42.9%), analysis (35.7%), cause-effect (35.7%), influences (35.7%), holistic (28.6%), actors (14.3%) and methodology (14.3%).

Participant votes traced the main cause of the focal problem to consumer behaviors (14 votes), the lack of a systems approach in decision making (10 votes) and the lack of monitoring and control by authorities (7 votes). Likewise, the most important solution was identified as the implementation of environmental education (8 votes), followed by institutional strengthening (3 votes). To avoid confusion, readers should note that consumer behavior here includes two approaches: increasing EEE consumption while simultaneously generating more WEEE; and, a lack of consumer participation, that is, consumers failing to deliver their WEEE to formal WEEE management programs.

Table AC2 displays all identified causes and effects; the presentation of causes and effects in the table does not reflect subsequent prioritization.

Table AC2. List of causes of the "the insufficient and inadequate WEEE management in the country", according to actors involved in the first workshop

Failure of selective waste collection mechanisms
Insufficient dissemination of information from producers/distributors to consumers (regarding collection and management programs)
Insufficient monitoring-controlling of formal and informal sectors by the environmental authority
Insufficient technical capacity and related research
Lack of ongoing training of public staff
Lack of control of exports and foreign trade by the environmental authority
Lack of Information Systems to support monitoring-controlling activities
Lack of surveillance at Customs (EEE imports)
Lack of technical standards for recycling WEEE
Lack of technical standards related to EEE (import and domestic assembly)
Lack of regulations for disposal of EEE/WEEE used by public institutions
Lack of Law´s regulations
Non-recognition of consumer costs (externalities)
Poor public-private cooperation
Poor general dissemination of information (related to differentiated WEEE management) to consumers (including the obligation to deliver WEEE to the formal system)
Poor information from producers to managers regarding potentially hazardous components
Poor integration of WEEE management in federal educational programs
Poor inter-institutional coordination
Poor monitoring of Extended Producer Responsibility to implement post-consumer programs
Consumer expectation of positive economic valorization
Lack of reverse logistics

Existent opportunity to generate direct-income strength informal recycling

Upon completing the workshop, the main suggestions to increase the systems approach in the subsequent steps were to identify the links between effects (problematic situations), causes and actors, as well as to prioritize the identified causes.

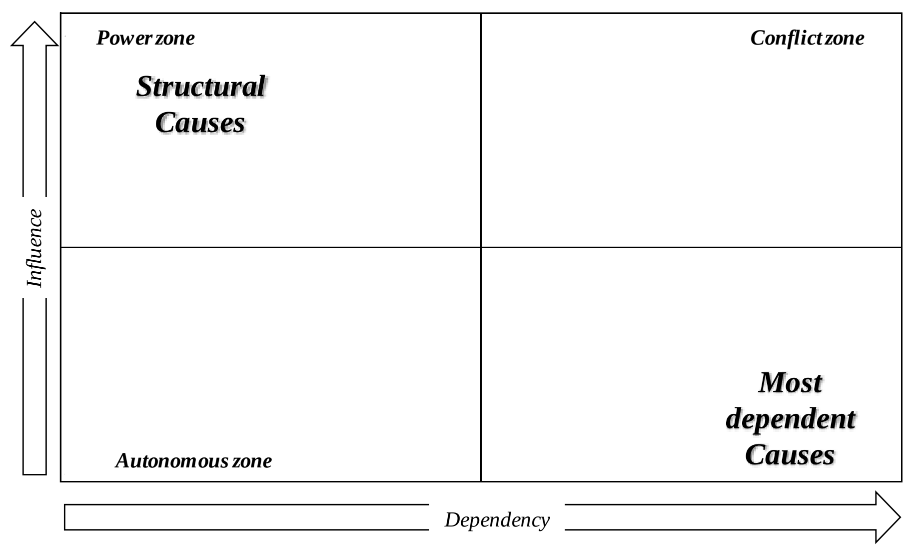
Step 2: Identify structural causes

To identify structural causes, the structural analysis method based on the matrix of influences—MICMAC (Godet, 1993)—was used (Figure AC3 - left). Relying on MICMAC allowed actors to map both direct and indirect influences among different causes (in a meeting of the NWM-Committee). Therefore, actors reached a consensus on the most dependent and influencer facts. To achieve the active participation, and avoid misunderstandings or different interpretations by participants, the matrix was translated into tables, emailed after the meeting and collected one week later.

Figure AC3. Matrix of influences. *Adapted from* (Godet, 1993)

Influence

	Causes	1	2	...	...	n	Σ	%
1	Cause 1	-	0	1	1	0	2	25
2	Cause 2	1	-	1	1	1	4	50
...	.....	0	0	-	0	0	0	0
...	.....	0	0	1	-	0	1	12.5
n	Cause *n*	0	0	1	0	-	1	12.5
Dependency Σ		1	0	4	2	1		*100*
%		13	0	50	25	13	*100*	

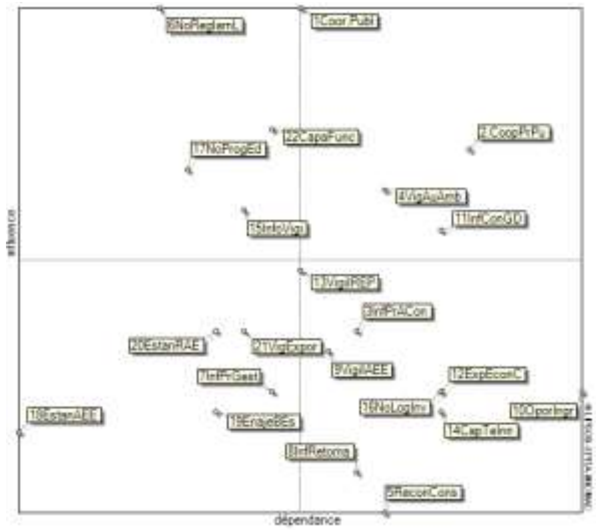


Structural causes (Figure AC3 – right) are the most dependent and most easily impressionable causes. More direct influences mean a cause is more conflictive. However, if a cause has few dependencies, it can be considered an autonomous cause (if it does not influence several other causes) or a structural one (if it does influence several other causes).

The final matrix of influences is shown in Figure AC4 (left), as well as the diagram in which the conflictive, autonomous and power (structural) causes were visualized.

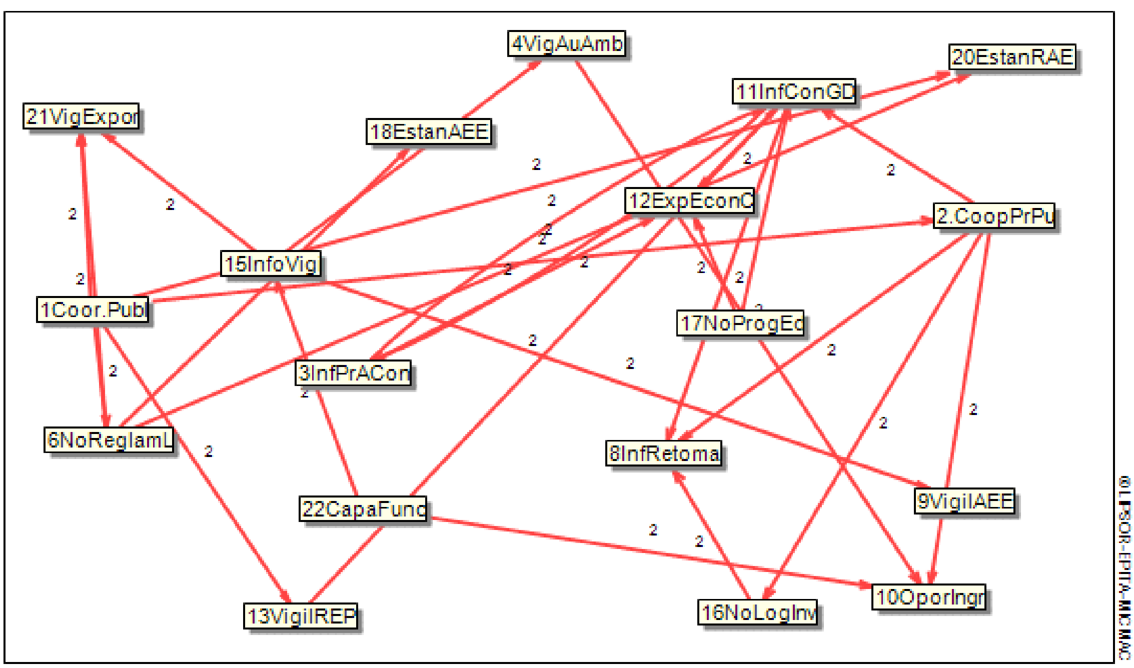
Figure AC4. The final matrix of influences and the graph used visualize cause tendencies

	1 : 1Coor.Publ	2 : 2.CoopPrPu	3 : 3InfPrACon	4 : 4VigAuAmb	5 : 5ReconCons	6 : 6NoReglamL	7 : 7InfPrGest	8 : 8InfRetoma	9 : 9VigilAEE	10 : 10OporIngr	11 : 11InfConGD	12 : 12ExpEconC	13 : 13VigilREP	14 : 14CapTeInn	15 : 15InfoVigi	16 : 16NoLogInv	17 : 17NoProgEd	18 : 18EstanAEE	19 : 19EnajeBEs	20 : 20EstanRAE	21 : 21VigExpor	22 : 22CapaFunc
1 : 1Coor.Publ	0	2	1	2	0	2	0	1	2	1	1	1	2	1	2	0	2	1	2	2	2	2
2 : 2.CoopPrPu	1	0	1	1	1	0	1	2	1	2	2	1	1	1	1	2	1	0	1	0	1	1
3 : 3InfPrACon	0	1	0	0	1	0	0	1	0	1	2	2	0	1	0	1	1	0	1	1	0	0
4 : 4VigAuAmb	1	1	1	0	1	1	1	1	1	2	1	1	1	1	1	1	0	0	1	1	1	1
5 : 5ReconCons	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0
6 : 6NoReglamL	2	2	1	1	1	0	2	1	2	1	1	1	2	1	1	1	1	2	1	2	2	1
7 : 7InfPrGest	0	0	1	0	1	0	0	0	0	1	1	1	0	1	0	0	1	0	0	1	1	1
8 : 8InfRetoma	0	1	1	0	1	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0
9 : 9VigilAEE	1	1	1	1	1	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	1	1
10 : 10OporIngr	1	1	0	1	1	0	0	1	0	0	0	2	0	1	0	1	0	0	1	0	0	0
11 : 11InfConGD	1	1	2	1	1	1	1	2	0	1	0	2	0	1	0	1	1	0	1	0	0	1
12 : 12ExpEconC	0	1	1	1	1	0	1	1	0	2	0	0	0	1	0	1	0	0	0	0	0	0
13 : 13VigilREP	1	1	1	1	1	0	1	1	1	1	2	0	0	1	1	1	0	0	0	0	1	1
14 : 14CapTeInn	0	1	0	0	1	0	1	1	0	1	1	0	0	0	1	1	0	0	0	1	0	0
15 : 15InfoVigi	1	1	0	2	0	0	1	0	2	1	1	0	2	1	0	1	1	0	1	1	2	1
16 : 16NoLogInv	0	1	1	0	1	1	0	2	0	1	1	1	0	1	0	0	0	0	0	0	0	0
17 : 17NoProgEd	1	1	1	1	2	1	1	1	1	1	2	2	1	2	0	1	0	0	1	0	0	1
18 : 18EstanAEE	0	0	0	0	0	1	1	0	1	0	0	0	1	1	1	1	0	0	0	1	0	0
19 : 19EnajeBEs	1	1	1	1	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0
20 : 20EstanRAE	1	1	1	1	0	1	1	0	1	1	1	1	0	1	0	0	0	1	0	0	0	1
21 : 21VigExpor	1	1	0	2	1	0	0	0	1	1	0	1	1	1	1	1	0	0	0	0	0	1
22 : 22CapaFunc	1	1	1	1	1	0	1	1	2	2	1	1	2	1	2	1	1	0	1	1	1	0



In the same sense, the net of direct influences is depicted in Figure AC5.

Figure AC5. The net of direct influences



The causes that emerged as structural as a result of the matrix of influence exercise are shown in Table AC3.

Table AC3. Structural (or the more dependent) causes prioritized through the MICMAC method

Cause
Poor inter-institutional coordination
Lack of legal regulations
Lack of ongoing training of public staff
Poor public-private cooperation
Poor integration of WEEE management in federal educational programs
Insufficient monitoring-controlling of formal and informal sectors by the environmental authority
Lack of Information Systems to support monitoring-controlling activities
Poor general dissemination of information (related to differentiated WEEE management) to consumers (including the obligation to deliver WEEE to the formal system)
Poor monitoring of Extended Producer Responsibility to implement post-consumer programs

Step 3: Design strategies

The third participatory activity worked off of the prioritized causes. Its goal was to design potential strategies. This workshop took place on April 15, 2015 at the Pontificia Universidad Javeriana in Bogotá, Colombia. A total of 27 people attended, representing the organizations described in Steps 1 and 2 above.

The *round robin* method (LUMA Institute, 2012) was adapted here to ensure the integration of different actors and their opinions. This method facilitates the construction of solutions in the form of written strategies, which are developed via a two-round process that critically engages attendees put into different groups. Inputs for this activity were structural causes and five strategic objectives; these strategic objectives were defined prior to the meeting in collaboration with the MADS and the CNPML and were based on the relevant law (passed in 2013). The five objectives are as follows:

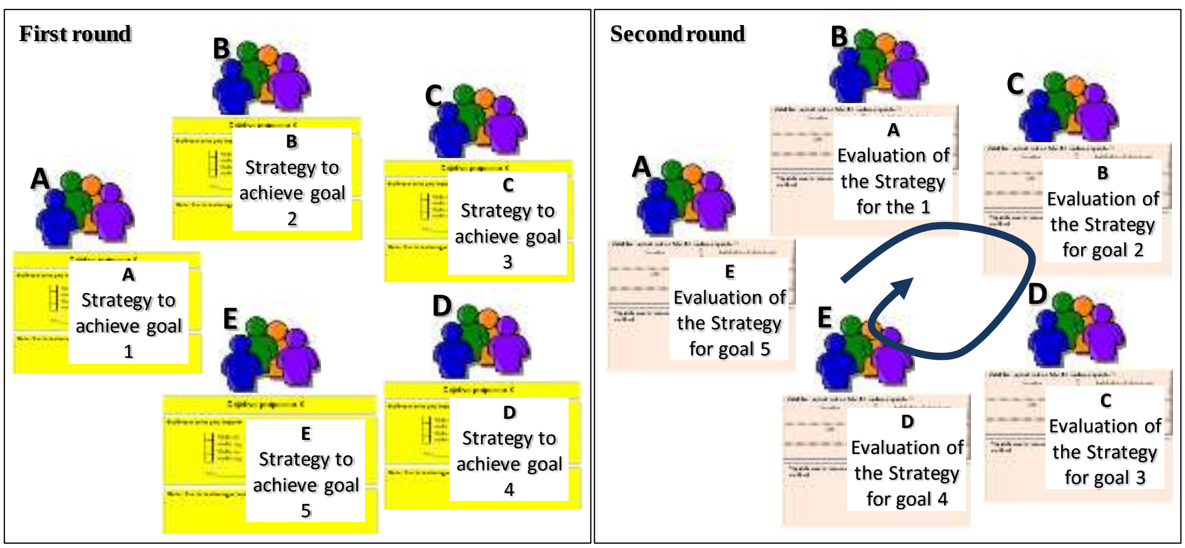
- Objective 1: Minimize public health and environmental impacts potentially caused by inefficient WEEE management.
- Objective 2: Increase cleaner production and responsible consumption through more sustainable WEEE management by primarily focusing on minimizing generation and offering socio-economic incentives for properly discarding of WEEE.
- Objective 3: Promote the engagement of actors involved in the EEE and WEEE production chain, especially with regard to the design and implementation of strategies, plans and projects related to WEEE management.

- Objective 4: Facilitate consumer participation through collection programs and infrastructure to prevent informal activities and the presence of WEEE in public areas and sanitary landfills.
- Objective 5: Improve the functional efficiency, transparency and reliability of Extended Producer Responsibility systems.

An additional input was a list of possible strategic media to achieve goals emerging from both the law and previous activities to identify and prioritize causes and effects, above all the structural causes.

Attendees at the *round robin* meeting were organized into five groups and the two rounds were broken down thusly: in the first round (Figure AC4 - left), each team proposed a maximum of four media from the list, wrote the strategy that integrates those media and described related responsibilities of public and private sectors, as well as civil society. Then, in the second round (Figure AC4 - right), each team reviewed a form filled out by a different team to review and subsequently gave their opinion about whether or not they believed the strategy proposed was viable from economic, legal, technical, and institutional points of view. If this last step improved the strategy, specific changes proposed were reported on the form. At the end of the workshop, a list of strategies was proposed for each strategic goal. These were taken into account in the final design of the policy, a process led by the MADS.

Figure AC4. Materials and dynamics employed in the *round robin* method

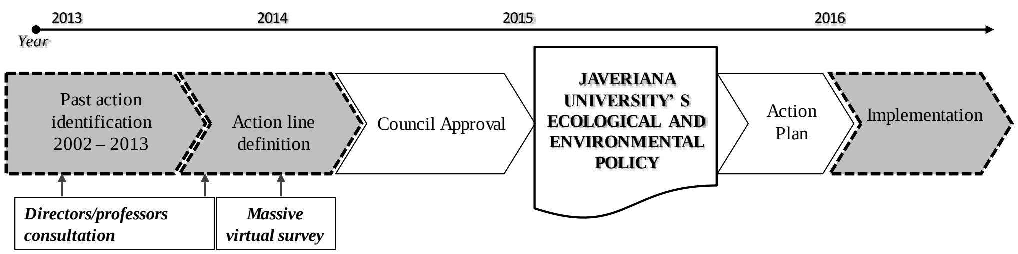


Appendix D. Participatory design of the ecological and environmental policy for the Pontificia Universidad Javeriana

A review of the case history showed two past attempts to obtain the approval of an environmental policy for the campus (2002 and 2008); the designs for these policies did not include participatory methods. This Appendix describes the participatory design developed in 2014 and 2015 as part of the single-case study "WEEE Management at the Pontificia Universidad Javeriana."

Figure AD1 shows the general design process led by the Javeriana Environmental Group. The group included representatives of the Vice-President of Social Welfare, the Campus Administration Office and the faculties of Engineering, Environmental Sciences, Architecture and Design, Sciences and Theology.

Figure AD1. Methodology used to design the Javeriana's policy



In addition to the document review, there were two main participatory activities; see Steps 1 and 2 below for more details. The approved policy has also been included (see Step 3). The design process was maintained up-to-date via different university media, mostly monthly magazines and the official Javeriana website. Figure AD2 displays two examples of publications regarding policy design and the implementation of the battery post-consumer program (*Pilas con el Ambiente*). These two facets formed part of the strategies for environmental education on the campus, which, in turn, was part of the participatory design.

Figure AD2. Publications related to policy design as part of the strategies to engage university actors.

Step 1: Consultation with directors and professors

In order to identify experiences and weaknesses related to environmental actions on the campus, structured forms were emailed to the deans and department heads (managerial staff) and professors. These forms were only concerned with actions carried out from 2000 on—for 2000 is the year in which the first relevant actions related to waste management took place.

In total, 112 actions were identified, including assessments, management plans, campaigns, conferences, research projects, undergraduate or graduate theses, physical infrastructure improvement and related committees/groups. The topics of these reported actions can be divided into seven groups: solid waste management (63), water management (24), environmental education (15), wood resources and ecosystems (4), energy management (3), and air quality (3).

The areas of the university that developed the reported initiatives were the Campus Administration Office (33%), the Faculties of Engineering (19.6%), Sciences (17.9%), Environmental and Rural Studies (9.8%) and Theology (5.4%). The remaining 14.3% of actions were led by faculties of Arts, Dentistry, Biology, Psychology, Social Sciences, among others.

Step 2: Massive virtual survey

Based on the fields identified in the previous step, the following ten areas were determined to require intervention and prioritized though a virtual survey: health/nutrition, water management, energy management, mobility and inclusion, air quality, sustainable construction, solid waste management, landscaping and open areas, responsible consumption and wood resources and ecosystems.

There were a total of 1,907 completed registries that included students (44.8%), professors (25.9%), administrative staff (25.4%), and directors/department heads (3.9%). A total of 960 (54.8%) respondents were from the faculties of Economic and Management Sciences, Engineering, Communication and Psychology.

Table AD1. Prioritization of topics requiring intervention on campus

Topic to work on	%Votes
Water Management	16.5
Health/nutrition	14.7
Mobility and inclusion	11.2
Energy management	11.1
Air quality	10.1
Solid waste management	8.8
Sustainable construction	8.7
Responsible consumption	7.2
Landscaping and open areas	6.8
Wood resources and ecosystems management	4.7

Step 3: Final document approval and publication

The committee responsible for the design of the policy translated the aforementioned data into ten strategies:

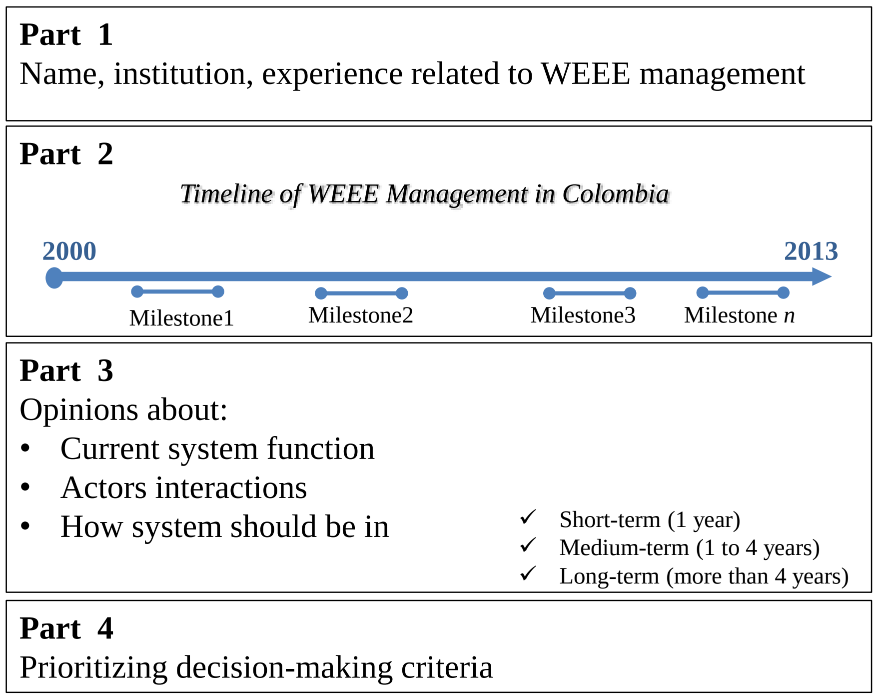
1. Articulate and incorporate the environmental and ecological dimension into processes of teaching, research, extension, university social welfare and campus administration.
2. Lead the educational community habits and sustainable behavior in order to preserve the environment.
3. Maintain a relationship of dialogue and collaboration with public and private institutions, as with the projects of the Company of Jesus, NGOs and other social actors with responsibilities or interests in ecological and environmental.
4. Increase community awareness and education to achieve more active participation in the environmental management of the University and strengthen *Citizen Culture*, which optimizes the community's commitment to environmental preservation.
5. Prevent, reduce and compensate negative impacts that may arise from University activities, in accordance with the standards of responsible consumption and efficient use of supplies, goods and services.
6. Promote a sustainable campus, with environmental standards and criteria which reflect the proper management of resources, infrastructure, and our commitment to the natural and urban environment.
7. Promote conditions of clean production, in the purchase of supplies, receipt of donations, building infrastructure and the relationship with suppliers.

The final document was approved by the Directing Council of the University and involved both sectionals of the institution which are located in Bogotá (the main sectional), and in Cali. The publication was made on November 4th of 2015.

Appendix E. Interviews instrument and results

The structured interview (Figure AE1) collected data related to WEEE management in Colombia and other developing countries; it was applied to the relevant actors identified in the literature review.

Figure AE.1. Structure of the interview of relevant actors in the single-case study of Colombia´s WEEE management



The actors interviewed actors are shown in Table AE1; the table includes interview date, time and medium.

Table AE.1. Actor interviewed

Interviewed person	Institution	Date	Time (min.)	Medium
Edwin Camelo	*Ministerio de Ambiente y Desarrollo Sostenible* – MADS	30.4.2014; 3.5.2014	240	Skype
Angel Camacho		7.5.2014	180	Face interview
Florencia Leal	Industrial Association of Colombia – ANDI	4.5.2014	120	Face interview
Edgar Erazo		6.5.2014	120	Face interview
María Cristina Camejo	*Federación Nacional de Comerciantes* - FENALCO	9.3.2015		Skype
Carlos Hernández	*Centro Nacional de Producción Más Limpia* - CNPML (National Expert)	7.2.2014; 12.2.2014	240	Face interview

Interviewed person	Institution	Date	Time (*min.*)	Medium
Darío Villa	Computers for Schools (part of the Ministry of ICT)	27.3.2014	120	Face interview
Alberto Riaño	Gaia Vitare (authorized recycler)	6.3.2014	90	Face interview
Daniel Ott	International expert	2.4.2014	180	Skype
Heinz Böni	The Swiss Federal Laboratory for Materials Sciences - Empa	12.4.2014	120	Face interview
Mathias Schluep	World Resources Forum, Switzerland (international expert)	18.4.2014	90	Face interview

Part 2: the timeline of the WEEE management in Colombia

Figure AE.2 contains the main facts recalled by the actors interviewed; interviewees identified the creation of Computers for Schools program as the first milestone.

Figure AE.2. General timeline of WEEE management in Colombia

→ **2000** … **2007** … **2010** **2012** **2013** **2014** **2015** →

The program "Computadores para Educar" (Computers for Schools) started

Swiss Technical support in WEEE management started

Regulations for some WEEE was passed (computers, lighting, alkaline batteries)

Take-back programs (for computers, lighting, and alkaline batteries started)

The national Law for WEEE management was passed

The participatory design of the policy for WEEE management was made

A voluntary take-back program for mobile phones started

A technical committee was created

The technical committee was dissolved

The national Committee for WEEE management was consolidated

Part 3: Current System Function

Interviewed experts gave their opinion about the current WEEE management in the country. In consensus, in spite of the existent post-consumption programs are considered successful, these are just collecting small devices and they are not enough to collect important amounts of WEEE. In addition, there is a very low participation of consumers as well as an important amount of informal recyclers.

Actor Interactions

To explore actors' relationships, two questions were proposed. First, if you want to propose or carry out a project related to waste management, which actors must be involved (negotiating objectives or resources, receive authorization or support, ensure cooperation) at the federal level? Second, if you want to propose or carry out a project related to waste management, which actors must be involved (negotiating objectives or resources, receive authorization or support, ensure cooperation) at the city (Bogotá) level?

Table AE.2. Actor relationships (interviewee responses)

	Actors identified by interviewed experts	**Generic actor (expert) inteviewed** *(Main goal in the identifyed relationship)* **Recyclers**	**National experts**	**Environmental Authority**	**Post-consumption programs**	**Distributors**
At national level	**Producers**	Collection Logistics, campaigns	According to the goal to be supported	Support in decisions and monitoring	Economic support	Economic support and cooperation
	Consumers	Collect their WEEE	According to the goal to be supported			
	Distributors	Campaigns	According to the goal to be supported	Support in monitoring	Collection partners	As guild: define strategies, defend interests, evaluate
	Environmental authority	Campaigns	According to the goal to be supported		Support partnerships. Monitoring and control	
	ICTs authority			Support in monitoring		
	Import/Export Authority			Combat smuggling		
	Recyclers	Competitiveness	According to the goal to be supported	Support in monitoring		
	National committee			Technical support		
	National experts	Technical support	According to the goal to be supported	Technical support	Technical support	
	International experts		Technical and economical support	Technical support	Technical support	
	Academy			Technical support		
Bogota	**Environmental Authority**	Campaigns	To implement pilot projects	Informal recycler inclusion	Support in public education	
	Public utilities office		To implement pilot projects	Informal recycler inclusion	Monitoring and control of recyclers	

The representative for producers (ANDI) stated that producers are autonomous, i.e. they can develop their own projects.

How the system should be in…?

Twelve WEEE management elements were prioritized by each expert, according to the issues to tackle in Colombia in the short- (high importance), medium- (medium importance) and long- (low importance) term. Results are shown in Tables AE.3 and AE.4 below.

Table AE.3.

MANAGEMENT ELEMENT		Interviewed Person																																
		EC			AC			FL			EE			MCC			CH			DV			AR			DO			HB			MSch		
		H	M	L	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L
Generation and take-back process	Reduction of WEEE linked to responsible consumption of EEE (less WEEE generating)		X		X				X		X				X		X			X					X			X			X		X	
	Strategies to increase the take-back of WEEE from users: awareness, education, incentives and fines	X			X			X			X			X			X			X			X			X				X		X		
	Strengthen producer incentive system to promote recycling (cleaner production, responsible design, eco-design, etc.)		X				X	X				X		X								X		X				X		X			X	
	Strengthen strategies to producers and marketers penalty for non-participation in the take-back	X			X			X				X			X					X			X			X			X			X		
	Implement take-back points and strategies related to market chains and related service providers to end users		X			X				X	X					X	X			X			X			X			X			X		
Collection and recycling	Design and implement selective routes to collect WEEE, public or private		X		X					X			X			X	X				X		X					X			X			X
	Design and implement new recycling plants		X				X	X				X			X			X		X				X				X			X	X		
	Formalize recycling business (formal / semi-formal)	X			X			X				X		X			X			X			X			X			X			X		
	Implementf economic-tax incentives for the collecting / recycling / disassembling / re-conditioner businesses to increase their technological capabilities			X			X		X					X								X		X			X			X				X
Participation and Education	Strengthen the role of guilds of producers and marketers		X				X	X			X					X	X				X				X			X	X			X		
	Strengthen the role of educational institutions in the country - education, research (high schools and universities)	X			X			X			X			X			X			X			X			X			X				X	
	Implement strategies to educate citizens in environmental awareness elated to WEEE	X			X			X			X				X		X			X			X			X			X				X	

Based on the answers above, short-term strategies were prioritized as follows:

Table AE.4. Prioritizing WEEE management elements

Priority	Elements
1	Strategies to increase the take-back of WEEE from users: awareness, education, incentives and fines
2	Strengthen the role of educational institutions in the country - education, research (high schools and universities)
3	Formalize recycling business (formal / semi-formal)
4	Implement strategies for environmental education and awareness about WEEE to citizens
5	Strengthen strategies to producers and marketers penalty for non-participation in the take-back
6	Implement take-back points and strategies related to market chains and related service providers to end users
7	Reduction of WEEE linked to responsible consumption of EEE (less WEEE generating)
8	Strengthen the role of guilds of producers and marketers
9	Design and implement new recycling plants
10	Strengthen producer incentive system to promote recycling (cleaner production, responsible design, eco-design, etc.)
11	Design and implement selective routes to collect WEEE, public or private
12	Implement economic-tax incentives for the collecting / recycling / disassembling / re-conditioner businesses to increase their technological capabilities

Part 3: Prioritizing Decision-Making Criteria

Based on the literature review, the following criteria were included in the third part of the interview (listed alphabetically): economic, environmental, legislative, logistical, social and technical.

Per the prioritization of each interviewed actor, the order of these criteria as pertains to WEEE management decision making should be (in descending order of importance): economic, environmental, technical, social, legislative and logistical.

Appendix F. Consumer Behavior: The Massive Virtual Survey at the Pontificia Universidad Javeriana in Bogotá, Colombia

This virtual survey was titled "*Opinómetro Ambiental Javeriano*," which roughly translates from Spanish to English as "*Environmental Opinion Meter at the Javeriana*." The survey was done using SurveyMonkey®, a service contracted by the Pontificia Universidad Javeriana. It was applied to students, professors, researchers, deans and department heads and administrative staff in 2014.

According to (Gardner and Stern, 2002), the results of studies looking at actions to preserve the environment, such as energy and water saving behaviors in households, can be divided into two main groups: efficiency behaviors (*e.g.* installing heating systems or low-flush toilets) and curtailment behaviors (*e.g.* lowering room temperatures or switching off appliances). The first category, efficiency behaviors, corresponds to the theory of planned behavior of Ajzen (1991); it is aligned with the consumer decisions when buying appliances, etc. The second category, curtailment behaviors, corresponds to repetitive actions, that is, habits. In order to deeply understand consumer behavior, both theories were employed in the development of the massive virtual survey (Table AF1). Aligned with the sub-model designed within the agent-based model (see Chapter 3), the WEEE included here were mobile phones and computers. The most recent post-consumer program (PCP) implemented in Colombia was *Red Verde*, which collected home appliances. For that reason, the survey included questions about refrigerator management, as well as general questions to gauge awareness of existing PCPs in Colombia.

Table AF.1. Virtual survey structure

Part 1 Role within the University, unit (faculty or institute), age, city of origin	
Part 2 **Behavior about mobile phones and accesories** • *Frequency of changing* • *Storing* • *Reasons to change the equipment* • *What do they do with the old equipment*	**Part 4** **Behavior about home appliances (fridges)** • *Age of the equipment* • *Reasons to change it* • *What do they do with the old equipment*
Part 3 **Behavior about computers and accesories** • *Frequency of changing* • *Reasons to change the equipment* • *What do they do with the old equipment*	**Part 5** **WEEE management in Colombia** • *Awareness about the WEEE management potential risks* • *Knowledge about existance post-consumption programs* • *Factors that motivate the participation*

As figure AF.1 shows, the heading of the survey included the environmental and social responsibility as motivation.

Part 1: Respondent data

The survey started by asking about the faculty or institute to which the respondent belonged (as employee or student), as well as about their age range and city of origin.

The total number of completed registries was 2,139 (84%), of which 1,615 (75.5%) were filled out by people from Bogotá. The completed registries can be broken down by "social" group as follows: professors (16.9%), undergraduate and graduate students (62.6%), administrative staff (16.2%), and alumni (4.3%). A total of 697 of the respondents from Bogotá were younger than 22. The units or dependencies to which the respondents belong are shown in the following table:

Table AF.2. Units or dependencies to the respondents belong.

Faculty	%	Faculty	%
Architecture & Design, and Arts	10.2	Theology & Philosophy, and Education	5.7
Environmental Sciences, and Sciences	9.8	Psychology, Medicine and Odontology	12
Economic and Business Sciences	17.8	Engineering	14.2
Juridical Sciences and Policies $ International Relations	5.5	Institutes	0.7
Social Sciences and Communication and Language	14.1	Rectory and Vice-Presidents	10

Part 2: Mobile Phones and Accessories Behavior

The survey included 8 questions on the practices related to the WEEE generated by the use of mobile phones.

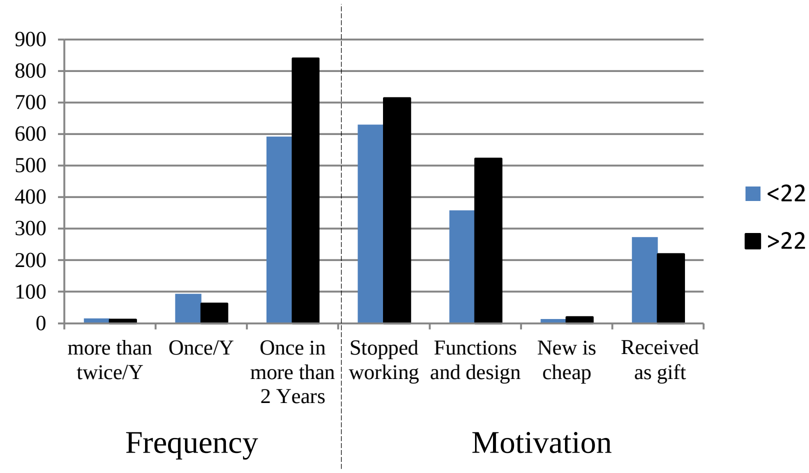
Table AF.3. Questions related to mobile phone and accessories behavior

Question	Options		
How often do you change your mobile phone?	Over twice in 1 year	Ones in a year	Once every 2 years
Do you have mobile phones stored at home?	Yes	No	
How many?	1	Between 2 and 4	More than 4
Do you have accessories like batteries or chargers stored at home or in your office?	Yes	No	
How many?	1	Between 2 and 4	More than 4
Choose 2 of the following motivations for changing your mobile phone:	No longer works	Despite it still works, it is limited in functions	A new ones is cheap
	The newer version is more powerful, lighter and more fashionable		I received one as a gift
What do you usually do with the discarded mobile phone? (Choose 2 options)	I discard it along with ordinary waste	I keep it because, although it still works, I do not know what to do with it	I keep it because, although no longer works, I think it still has financial value
	Since it still works, I keep it for future reuse it	I immediately pass it along to a relative	I donate it to social causes

	or give it to somebody		

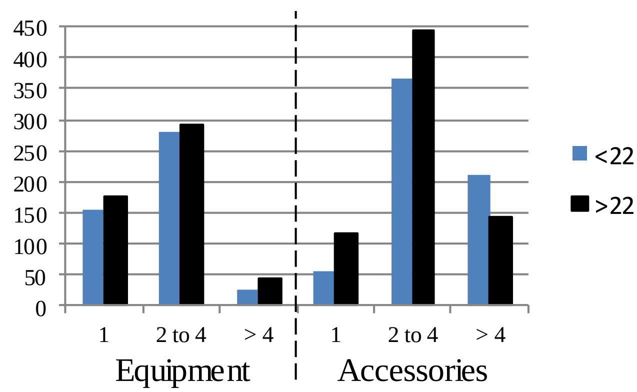
The main results are shown in the following three figures:

Figure AF.1. Changing equipment (mobile phones)



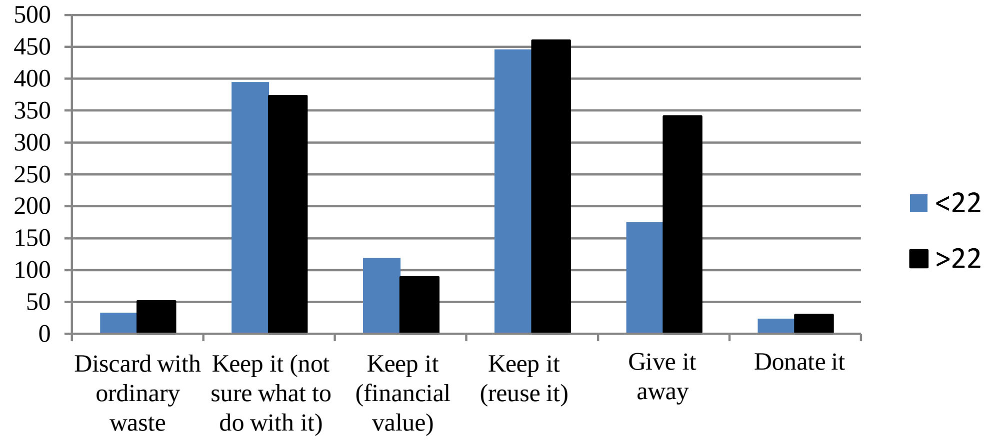
As seen in Figure AF.1, the two age groups usually use their mobile phones for more than 2 years. And the primary reason for changing is that the device no longer works. Nevertheless, the second reason was related to the speed of technological innovation rhythm and concomitant fashions, which may demonstrate the role of advertisements insofar as they tend to play on consumer emotions to increase equipment consumption.

Figure AF.2. Storage of equipment and accessories



Figures AF.2 and AF.3 capture the important consumer tendency to store equipment and accessories. The design of collection programs and collection regulations should take this tendency into account.

Figure AF.3. What they do with the WEEE from mobile phones?



However, Figure AF.3 also demonstrates the importance of mobile phone reuse in developing countries, which is seen in the actions of giving it away (especially in the older age range) and keeping it for reuse.

Part 3: Computer and accessories behavior

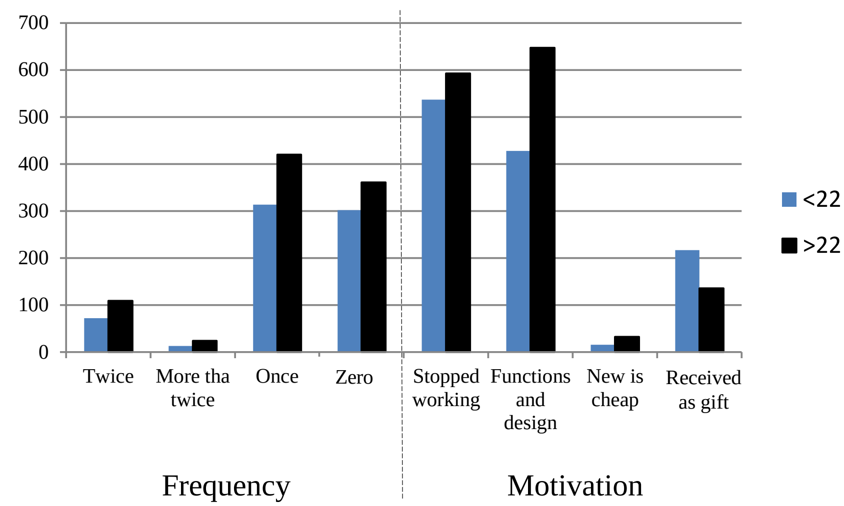
To verify behavior related to the use of mobile phones, the following questions were included regarding the use of computers (Table AF.2).

Table AF.2. Questions related to behaviors about computers

Question	Options			
How often have you changed your computer over the last 4 years?	Zero times	Ones	Twice	More than twice
Choose 2 of the following motivations for changing your computer:	No longer works	Despite still working, its functions are limited		A new one is cheap
	The newest version is more powerful, lighter and more fashionable			Received one as a gift
What do you usually do with the discarded computer? (Choose 2 options)	I discard it along with ordinary waste	Because, although it still works, I do not know what to do with it		Because, although no longer works, I think it still has financial value
	Since it still works, I keep it for reuse or give it away		I immediately pass it along to a relative	I donate it to social causes

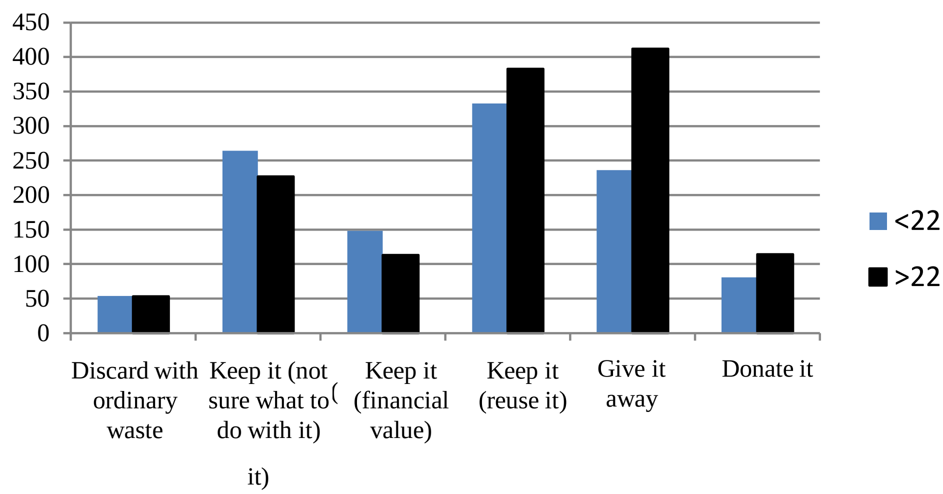
As Figure AF.4 displays, change computers is a less frequent habit than changing mobile phones. However, the main motivations proved the same the equipment stopped working or technological and design innovations.

Figure AF.4. Changing equipment (computers)



Comparing what people do with the oldest equipment in Figures AF.3 (mobile phones) and AF.5 (computers), in both cases, disposal along with ordinary waste is the most harmful habit, whereas storage and giving the equipment away others was similar both WEEE. However, donations were higher for computers than mobile phones.

Figure AF.5. What do consumers do with computer WEEE?



Part 4: Home appliance (refrigerator) behavior

Given that behavior stemming from use of large equipment, such as house appliances, may be different from behavior stemming from use of smaller EEE, the survey included questions about habits related to refrigerator management (Table AF.3). In addition, the latest PCP implemented in

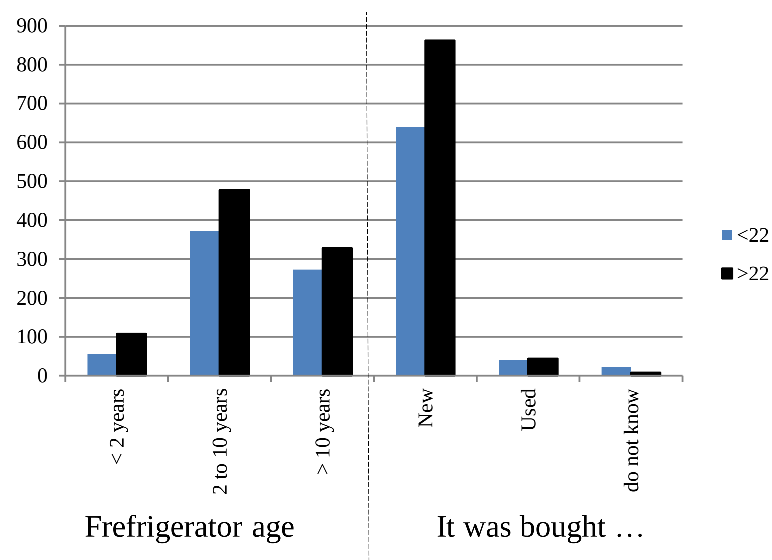
Colombia (2014) is *Red Verde* (Spanish for *Green Network*), which collected and managed this kind of EEE. The pilot phase was developed with refrigerators; therefore, the data collected here may be of use in terms of supporting *Red Verde*'s objective.

Table AF.3. Questions related to behaviors about fridges

Question	Options		
How old is the refrigerator in your home?	Less than 2 years	Between 2 and 10 years	More than 10 years
When you got the refrigerator, it was:	New	Used	Do not know
For what reasons have you changed or would you change your fridge?	It no longer works	Despite still working, it does not enough space or is inefficient	Received (or could receive) another one cheaper or for free
What do you usually do with the discarded refrigerator (Choose 2 options	I discard it along with ordinary waste	Because, although still working, I do not know what to do with it	Because, although no longer working, I think it still has financial value
If you wanted to change your refrigerator, what would you do with the discarded one? (Choose 2 options)	Since it still works, I would give it away	I would sell it (even if it no longer works)	I would deliver it to a collection system, even without receiving any payment
	I would deliver it to receive a credit towards a new refrigerator		

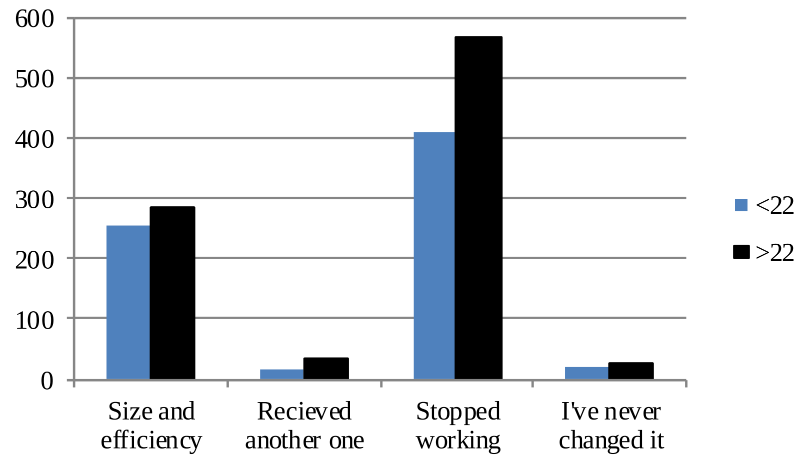
First of all, the results related to changing dynamics (Figure AF.6) show that reuse (in shorter periods) is much lower relative to the reuse of mobile phones or computers, which can be attributed to the fact that almost all refrigerators are purchased as new, and their end-of-life is 2-4 years, longer than the average end-of life for ICTs.

Figure AF.6. Changing equipment



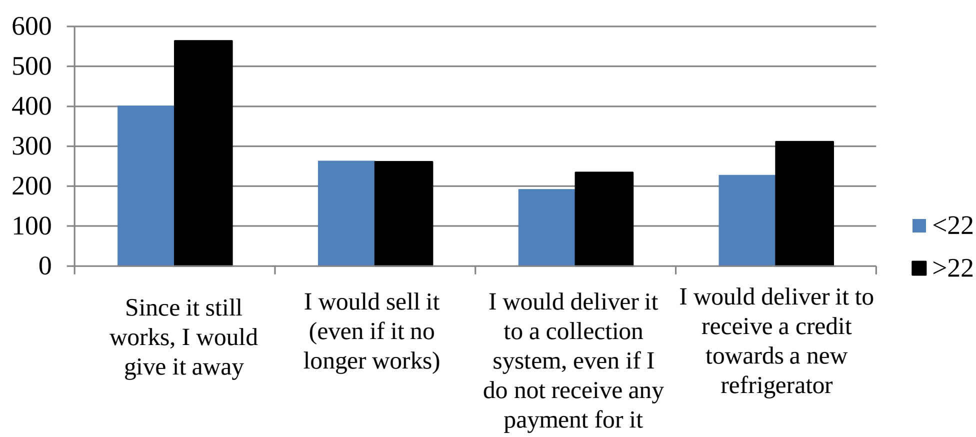
Second of all, leaving aside the reason "stopped working" in Figure AF.7, both size and efficiency were the most common motivations to change refrigerators. It is a clear demonstration of efficiency behavior in consumers, since old fridges consume much more energy than new ones, which is reflected in public utility costs.

Figure AF.7. Motivations to change the fridge



Despite the fact that Figure AF.6 shows the consumer tendency to prefer to buy new refrigerators, Figure AF.7 provides evidence of an important tendency for consumers to hold on to old equipment, give it away or sell it. However, approximately 30% (in both age groups) would deliver it to formal collection programs, even without receiving a payment as incentive.

Figure AF.7. What would you do (or have you done) with your discarded refrigerator?



Part 5: WEEE Management in Colombia and Post-Consumer Programs

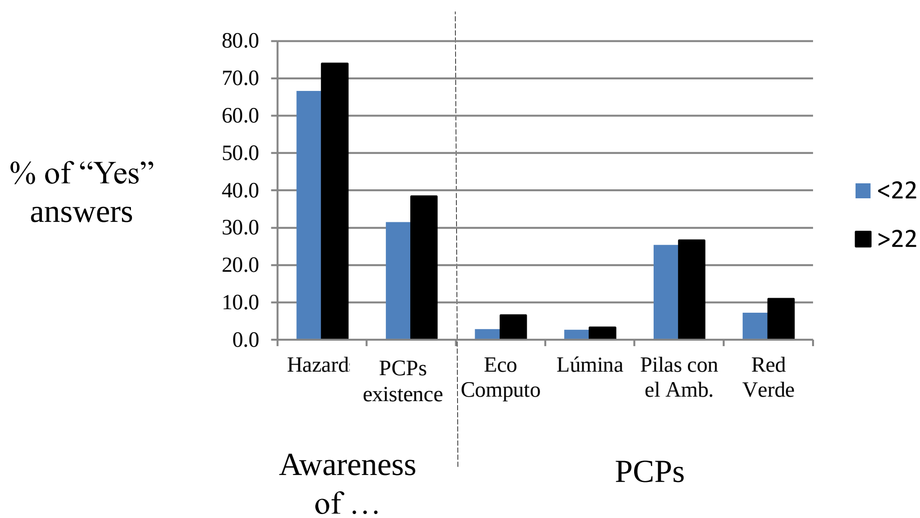
In order to gauge awareness of the potential danger caused by uncontrolled management of WEEE and awareness of the existence of post-consumer programs (PCP), as well as motivation to participate, the following questions were included in the last part of the survey (Tale AF.4).

Table AF.4. Questions related to awareness of PCPs implemented in Colombia

Question	Options	
Are you aware of the potential hazards and impacts generated by uncontrolled WEEE management?	Yes	No
Are you aware of the existence of the post-consumer programs in Colombia?	Yes	No
If yes to the previous question: Which post-consumer programs specifically?	*EcoComputo*	*Pilas con el Ambiente*
	Lumina	*Red Verde*
Which incentives would motivate you the most? (Choose 2)	Proximity	In retail stores
	Receive money	Support social-environmental project (SEP)
	Receive Information	Set an example for others

A As Figure AF.8 shows, 70.8% of the respondents were aware of the hazards presented by WEEE. However, only 35.6% of them had heard of PCPs.

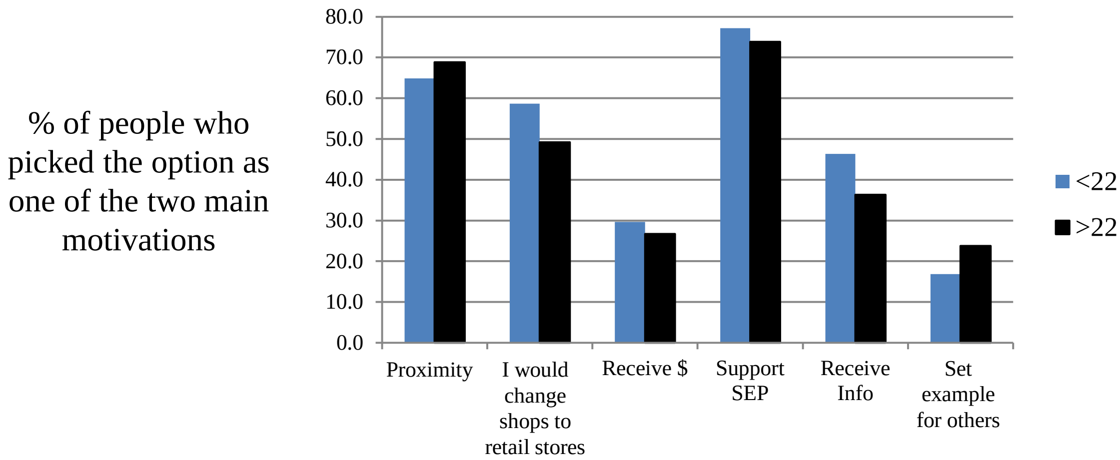
Figure AF.8. Awareness of risks and PCPs



Of the PCPs implemented in Colombia, the most well received at the Pontificia Universidad Javeriana has been *Pilas con el Ambiente*, which was implemented on campus in 2013. The success of this campaign demonstrates the importance of the support of educational institutions with regard to local, regional and national waste management initiatives.

See Figure AF.9 for motivations to participate in the PCPs.

Figure AF.9. Motivations to participate in PCPs.



Finally, extracting only answers that correspond to those who prefer to have PCPs in retail stores, the consumer's main interest was to support socio-environmental projects, even more than receiving money.

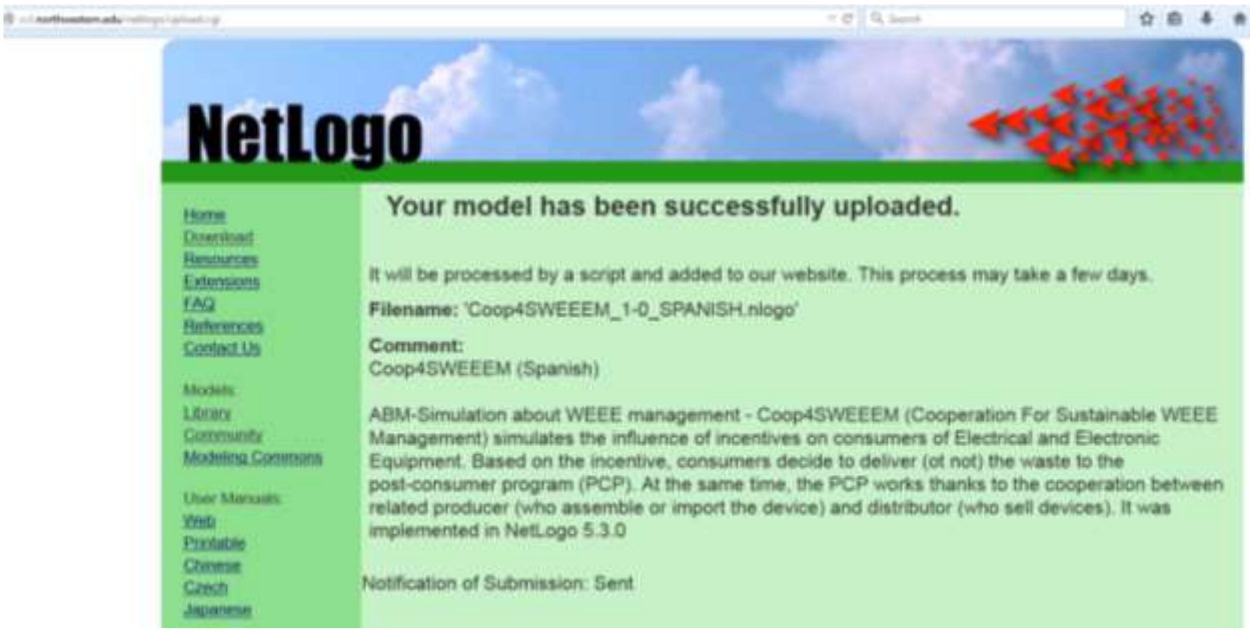
Table AF.5. Consumer main interests

Main Interest	%*
Receive money (economic incentive)	21,7
Support socio-environmental projects	70,8
Finding the box is sufficient (proximity)	3,7
Receive information about the PCP**	3,7

** Of the 53.3% who is motivated by PCP in shops*

*** About what to do with WEEE and the impacts prevented*

Appendix G. Coop4SWEEEM code: Soon available at http://ccl.northwestern.edu/netlogo/models/community/



Summary

Environmental problems in urban areas are mainly associated with air and water pollution, which, in turn, are often triggered by unsustainable Solid Waste Management (SWM). The management of Waste Electrical and Electronic Equipment (WEEE) is a prominent issue in urban waste systems due to the related toxic substances, such as mercury and PCB (Polychlorinated Biphenyls). This importance is only reinforced by the economic opportunities offered by valuable components contained in WEEE. Put simply, WEEE is a crucial part of the discussion revolving around urban sustainability, especially in developing countries. The principal causes of ineffective and inefficient WEEE management are poor or absent infrastructure, in addition to deficient coordination and cooperation among actors. Taken together, these issues result in meager WEEE collection rates via the official return network. The lack of a systems approach in policy making is one of the main hurdles to effective waste management, as evidenced by a number of prominent authors studying this socio-technical system in an extensive literature review, an exploratory multiple-case study and the author of this doctoral thesis' own experience. A non-systems-based approach is often responsible for, or fails to address, a lack of coordination among stakeholders and the failure to design and implement sustainable education strategies.

In this doctoral thesis, systemicity in decision-making for policy design used to increase sustainability in WEEE management, specifically targeting developing countries by designing and implementing of a Decision-Enhancement Studio (DES). The two main research questions that form the basis of this thesis are: (RQ1) *How can we design Decision-Enhancement Studios to support policy makers in the creation of sustainable WEEE Management programs in developing countries?* (RQ2) *What are the essential elements needed to enhance systemicity in decision-making for WEEE management?* The methodological approach to answer these questions was Design Science Research, which links relevance and design with rigor as part of the progressive problem-solving process.

Rigor cycle. The majority of worldwide regulations for WEEE management are based on the principle of Extended Producer Responsibility (EPR), geared towards promoting the improvement, in environmental terms, of production and manufacturing systems (Agamuthu and Victor, 2011; Herdiana, D.S. et al., 2014; Lindhqvist, 2000). According to Lindhqvist (2000), EPR aims to influence production processes in one of two directions (*upstream* or *downstream*): shifting responsibility to *downstream* procedures that involve different actors in collection, recycling and treatment processes and providing *upstream* incentives to producers to incorporate environmental considerations in the design of their products. An attempt to design more integral solutions for waste management is manifested in the concept of Integrated Solid Waste Management (ISWM). ISWM focuses on integrating processes (generation, segregation, transfer, collection, treatment, recovery and disposal of waste). It has been widely applied in municipal waste management planning and public policy (Tchobanoglous, 1994; Tchobanoglous et al., 1993). Based on the concept of ISWM, Decision-Support Systems have integrated simulation-based models to study waste generation dynamics (Antanasijevic et al., 2013; Benitez et al., 2008; Maddox et al., 2011),

determine landfill allocation (Alves et al., 2009; Antanasijevic et al., 2013; Kollikkathara et al., 2010) and ascertain optimal SWM planning (Yeomans, 2004), among other things.

Relevance cycle. To study the current state of WEEE management in the context of developing countries, an exploratory multiple-case study composed of two single-cases was developed. The two single-cases were WEEE management in the South American nation of Colombia and WEEE management at the Pontificia Universidad Javeriana in Bogotá, Colombia. Actor-Network Theory (ANT) was applied to analyze the data collected. Findings from the two cases indicated that, although the main decision-makers incorporated different dimensions and (occasionally) different actors, programs and strategies regarding WEEE management failed to include multi-causal analysis, multiple management stages and knowledge gained from past experiences in an explicitly methodological way. In addition, informal recycling, WEEE discarded in public areas and sanitary landfills, low rates of WEEE collection, low consumer participation, high levels of smuggling and low EEE quality in markets collectively demonstrate the absence of a systems-based approach in decision-making and system design.

Design cycle. Requirements obtained from the multiple-case study include information technology (IT) infrastructure-related aspects, as well as aspects related to physical infrastructure. Others are associated with human activities, such as education, participation, cooperation and decision-making. Public policies are advantageous when bringing together these requirements to form the basis for strategy and program development. The DES designed herein included three main elements: people (decision-makers and facilitator), processes that guided the *studio* as the main facilitative environment for decisions and a set of technological tools and protocols (Keen and Sol, 2008).

The general goal of the DES was to provide answers to the research questions formulated in this doctoral thesis, whereas the goals of the technological tools were more specific and tailored to the structural causes of insufficient and inefficient WEEE management in Colombia. Thus, the DES's goal was formulated as follows: "Decide on aspects that affect sustainability in WEEE management in Colombia." The goal of the technological tools, identified by the relevant actors, was to answer the following question: "How can consumer behavior be influenced?" This question corresponds to an urgent decision. As part of the technological tools, an agent-based model - ABM (*Coop4SWEEEM*) was designed using the ODD (Overview, Design concepts and Details) protocol and implemented as a computer-based simulation in NetLogo. In addition, a multi-criteria decision table was developed using the weighted sum method (implemented in Excel).

Applying the tenets of Design Science Research, iterative validation processes were developed. In the relevance cycle, requirements were identified and tested with the main actors involved in WEEE management case studies. The conceptual model of the ABM was validated in different moments: initially, validation was performed prior to the DES, which included the evaluation described in Chapter 3. Then, validation was performed during the DES; the ABM and simulation, in addition to other tools, were validated during the development of the DES. The validation used the technology acceptance model (TAM) instrument, as well as notes and tapes of key moments of the process. Finally, the DES validation was performed after its implementation: all the questionnaires, validation instruments and main group discussions were gathered and analyzed in order to identify the concepts and arguments of the actors involved. Validation results provided additional elements to achieve a more sustainable WEEE management.

RQ1. This question is related to how to design DES in order to support policy-makers in the creation of sustainable WEEE Management programs in developing countries. In answering this question, this doctoral research identified various elements. First of all, the idea of *designing the design problem* helps designers arrive at deeper understanding of the problematic situation. To facilitate the understanding of the problematic situation, ANT is recommended (as part of the rigor cycle) to recognize the knowledge gleaned from related experiences, whether successful or not. Second of all, and given that a DES engages people (decision-makers and the facilitator), processes (protocols and guidelines) and technology (technological tools, or T-T), it is crucial to get relevant actors to participate in all the design process. In addition, the structure of the DES allows designers to tackle two levels of goals: i) the general DES goal; and ii) the specific assigned goals of the technological tools used in the DES. By virtue of this two-level goal, the DES accounts for constraints deemed capable of hindering the design of the solution.

Once the understanding and design of the problematic situation has been achieved, the design of the technological tools becomes a relevant facet of the DES design, notably computer-based simulations. In brief, the goal of the solution arrived at via the proposed design was to highlight the system's effects on the aggregation of individual interests and on the decisions of different actors by showing emergences. In so doing, the solution stimulates learning processes in decision-makers, which frames an agent-based model (ABM) as the best option. This research further proposes the use of ANT to the design of an ABM; the two naturally prove a productive combination in light of their conceptual similarities, such as parallels between Actor-Networks (A-N) and agents or A-N moments of translations and agent decision making.

RQ2. The second research question focused on the essential elements that enhance systemicity in decision-making for WEEE management. In this regard, a systems approach is required not only for the design of solutions, but also in the identification and structuring of the problematic situation. Systemic decision-making requires the comprehension of the entire (WEEE management) system and its behavior over time. For this reason, policy makers should include the following elements in the decision-making process: i) Different dimensions of the problem, ii) Different stakeholders' targets, iii) Processes within WEEE management; and, iv) Circular cause-effect relationships resulting from current decisions focused on the short- and long-terms.

In light of the trans-disciplinary nature of this doctoral research, contributions were described in short-, medium- and long-terms, and divided into tangible or intangible ones. Tangible outputs (or short-term contributions) were identified as workshops, reports and interview results, which were aimed at increasing the interest of actors involved. Likewise, presentations at relevant conferences, publications, consumer characterization, policies designed and DES also form part of this category. For their part, intangible outputs were, to name two examples, methodological experience, such as the participatory definition of the focal problem to work on, or social experience, such as the continuous and active participation of policy-makers. In the medium and long-terms, contributions were related to the implementation of the results, as well as the transformation of concepts and knowledge in the actors involved, which will surely influence processes beyond the scope of this doctoral thesis.

Curriculum Vitae

Sandra Méndez Fajardo (Bogotá, 1976) obtained her degree in Civil Engineering in the year 2000 from Pontificia Universidad Javeriana (PUJ) in Bogotá, Colombia. Since 2001 she has been working as Professor in the Department of Civil Engineering at the PUJ, in the fields of Solid Waste Management, Impacts Assessment and Sustainable Development. In 2007 she obtained her MSc in Civil Engineering focused on environmental issues, from the Universidad de los Andes, Bogota. Also since 2001, she has integrated the research group "Ciencia e Ingeniería del Agua y el Ambiente" at the PUJ, in which has developed projects focused on environmental problems with poor and indigenous communities in Colombia. In addition, she has taken part of different policy committees at the *Ministerio de Ambiente y Desarrollo Sostenible* (2005 – 2015).

In 2010, she led the conceptualization, design, and implementation of the Social Program PROSOFI which is still developing projects with poor communities in locality of Usme, in the south of Bogota. She led the project "Community appropriation for the conservation of streams in Usme" which obtained the award Goldenseal Environmental Responsibility , in 2012. During her doctoral research she worked as academic guest at Empa, St Gallen, Switzerland (for 6 months in 2014; and for 5 months in 2015), and at the Ludwig-Maximilian University in Munich, Germany (for 2 months in 2015, with the support of a grant obtained from DAAD).