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Analysis of national policies for Circular Economy transitions: Modelling and simulating the Brazilian industry agreement for electrical and electronic equipment

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Abstract: Public policies, incentives and infrastructure are top-down instruments that can align stakeholders' roles and expectations for Circular Economy (CE) transitions. It is crucial to analyse the possible effects of such instruments before implementation. In this research, we investigate the Brazilian industrial agreement for electrical and electronic equipment (BIAEEE) that determines the responsibilities and targets for collection and treatment of waste electrical and electronic equipment (WEEE). A simulation model is adapted for the use of smartphones in Brazil, and interventions focused on the collection of end of life products are examined against the BIAEEE targets for that product. Twelve policy scenarios investigate three aspects of EEE collection: coverage increase, distribution of collection points and rewards. Although all scenarios show improvement in the EEE collection, only one met the targets. This research shows modelling and simulation can inform decision-making in public policies to enable CE transitions.

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Keywords: sustainability transitions; policy scenarios; systems thinking experimentation; forecasting; public policy

List of abbreviations

BIAEEE	Brazilian industrial agreement for electrical and electronic equipment
BNPSW	Brazilian national policy on solid waste
CE	Circular Economy
EEE	Electrical and electronic equipment
SD	System Dynamics
SFD	Stock and flow diagram
WEEE	Waste electrical and electronic equipment

1 Introduction

The current consumption and production system is only 9% circular, meaning that 91% of materials used come from linearly extracted resources (Wit et al., 2019). In contrast, the Circular Economy (CE) aims at maximising the value of resources in use via the application of the stock optimisation principle (Kalmykova, Sadagopan, & Rosado, 2018). CE systems rely on renewable sources of energy and materials and systematically decelerating the flows of resources (Bocken et al., 2016). The transition of entire industries to the CE paradigm is a necessary step forward.

The electrical and electronic equipment (EEE) industry requires a CE transition (Ellen Macarthur Foundation, 2018). Currently, only 17.4% of the total 53.6 Mt of Waste electrical and electronic equipment (WEEE) generated worldwide is collected and properly treated (Forti et al., 2020). In developing and emerging economies, such as Brazil, the situation is even more challenging. Brazil is the most significant producer of WEEE in Latin America, reaching 2.1Mt per year (Forti et al., 2020), whereas only 2% of WEEE generated is reportedly collected (Araújo et al., 2012; de Souza et al., 2016). EEE remanufacturing and recycling initiatives in the country show market potential but have been facing difficulties to scale (EMF & CE100 Brasil, 2017). The lack of harmony between state and federal laws, the high rate of the informality of companies involved in collection and treatment, and the disarrangement between rates and incentives (The World Bank, 2012) are still among the reasons for the dormant potential in WEEE initiatives in Brazil.

The use of international certifications such as Restriction of Hazardous Substances (RoHS) and the Electronic Product Environmental Assessment Tool (EPEAT) are widespread practices in the Brazilian national market (EMF & CE100 Brasil, 2017), specific public policies for managing WEEE are in their infancy and slowly evolving. The Brazilian national policy on solid waste is in place since 2010 (Brasil, 2010), determining shared responsibility among supply chain players, and setting targets and incentives for solid waste management. In the BSWP, industry agreements are the instrument to formalise the shared responsibilities among organisations, the government and civil society with resources and waste for each industry. In 2019, the Brazilian industrial agreement for electrical and electronic equipment (BIAEEE) was finally signed, requiring manufacturers, distributors, and retailers to structure and implement a reverse logistics system for EEE products of domestic use, such as computer desktops, laptops, fridges, and mobile phones (MMA et al., 2019). The BIAEEE document defines responsibilities and targets for post-use EEE collection and treatment.

The signing of the BIAEEE is a top-down initiative for a potential CE transition in the Brazilian EEE market. Clear public policies and incentives are essential for top-down CE transitions (Lieder & Rashid, 2016; Winans, Kendall, & Deng, 2017) as the inadequacy of regulations is a critical barrier for the adoption of CE strategies in supply chains (Kazancoglu & Kazancoglu, 2020). Public policy interventions should consider the total consumption and production life cycle (Zhu et al, 2019) and help to align CE initiatives locally, regionally and internationally (Milios, 2018). These instruments align the actors' roles and expectations and help to form enough demand for emerging technologies (Suurs & Hekkert, 2012; Walrave & Raven, 2016). Cainelli and colleagues (2020) demonstrated that CE related innovation in the European EEE industry was strongly dependent on environmental policies. Besides, consistency between WEEE policies objectives and implementation measures helps to prevent unanticipated consequences that can hinder more sustainable systems in the long term (Lauridsen & Jørgensen, 2010).

In practice, however, decision-makers struggle to define the appropriate targets and incentives to allow the best possible impact through policies. In that direction, modelling and simulation enable experimenting with the effects of policies implementation, the potential evolution paths of the system and obtain practical recommendations to particular cases (Holtz et al., 2015). A modelling approach for policy development enables policy-makers, business practitioners and citizens, to explore the potential outcomes of policies and explore alternatives (Janssen & Helbig, 2018). Estimates of EEE and WEEE flows are crucial for supporting decision-making within policy-makers and organisations across the supply chain (Araújo et al., 2012). These estimates can decrease economic uncertainties related to WEEE recycling (Bouzon et al., 2016; de Oliveira Neto, Correia, & Schroeder, 2017) and help to establish shared responsibility to reverse logistics (Ghisolfi et al., 2017).

The research question we seek to answer in this paper is: “How modelling and simulation can inform decision-making in the implementation of national policies for EEE collection that allow Circular Economy transitions?”. System Dynamics (SD) modelling and simulation is useful in examining public policy issues (Ghaffarzadegan, Lyneis, & Richardson, 2010). Lately, it was used to investigate the impacts of public policies on the formalisation of waste collectors cooperatives (Ghisolfi et al., 2017), and examine the benefits of policies for improving gold recovery from smartphones in India (Chaudhary & Vrat, 2020). Also, prior research demonstrated the potential of using SD to examine nation-wide CE transitions in the EEE industry by developing and applying the Circular EEE SD model (Guzzo, Rodrigues, & Mascarenhas, 2020). The BIAEEE signature is an opportunity for the use of modelling and simulation to investigate top-down CE transitions.

The aim of this research is three-fold:

(1.) Examine the implementation of CE interventions through a simulation model for the use of smartphones in Brazil.

(2.) Evaluate how interventions focused on the collection of products at the end of life can enable meeting the BIAEEE targets for a given EEE type.

(3.) Discuss the potential of modelling and simulation to assist public policy investigation in the context of CE transitions.

Smartphones constitute the case for investigation in this research as they: (a.) are developed in fast-paced product cycles leading to functional and psychological obsolescence of older devices (Cucchiella et al., 2015; Proske et al., 2016; Wit et al., 2019); (b.) hold high production footprint and short lifetime (Belkhir & Elmeligi, 2018), and (c.) are prone to be stored at customers' homes after use because of their weight and size (Cucchiella et al., 2015; Speake & Yangke, 2015). On average, smartphones are composed of 62 different types of metals, including many rare-earth metals (Rohrig, 2015). The obtention of several of these metals is under risk because of their availability (European Chemical Society, 2019). However, there are several niche CE initiatives in the smartphones market addressing different life cycle phases, demonstrating a potential for sustainable transformation in this market (Zufall et al., 2020). Investigating smartphones under a national policy can provide input to facilitate such a transformation.

2 Materials and Methods

System Dynamics (SD) was applied as it enables representing, simulating and understanding the behaviour of feedback-rich systems containing delays and non-linearities between causes and effects (Sterman, 2001). Stock and flow diagrams (SFDs) represent how these variables accumulate and deplete over time. Stocks are physical quantities and soft variables, such as mass, people, time, and engagement. Representing the system structure in terms of SFD notation enables simulation. Computer software make use of differential equations determining relationships among variables, and calculate the levels of stocks, rates of flows and auxiliaries quantities over time (Lane, 2000). Model users experiment with the model, interpret the simulation results, and learn from the process (Sterman, 2001).

The iterative process for SD modelling and simulation prescribed by Sterman (2000) guided the research comprising its five steps: **(i)** Problem articulation, **(ii)** Formulation of Dynamic Hypothesis, **(iii)** Formulation of a Simulation Model, **(iv)** Testing and **(v)** Policy[1] Design and Evaluation. The investigation scope comprised the interventions provided for in the BIAEEE as to setting a reverse logistics system for collecting post-use EEE in Brazil, considering smartphones specifically. Literature review enabled adapting the Circular EEE SD Model (Guzzo et al., 2020) to the purpose of the investigation. The literature review included academic research, applied research reports, documents from governments and the third sector, and news. Studies focusing on Brazil were prioritised, then studies focusing on other newly industrialised countries, and finally studies focusing on industrial countries. Table 1 shows the references used for modelling, simulating, and discussing the BIAEEE.

Table 1 – Nature and scope of research used for modelling, simulating, and discussing the BIAEEE

Nature and scope of research	Reference
Academic research focused on Brazil	(Abbondanza & Souza, 2019; Araújo et al., 2012; de Oliveira Neto et al., 2017; de Souza et al., 2016; Echegaray, 2016; Echegaray & Hansstein, 2017; Ghisolfi et al., 2017; Ghosh et al., 2016; Rodrigues, Boscov, & Günther, 2020)
Academic research focusing on other developing countries	(Bai, Wang, & Zeng, 2018; Qu et al., 2019; Rathore, Kota, & Chakrabarti, 2011; Tan et al., 2018; Wang et al., 2012)
Academic research not focusing on developing countries only (including conceptual research)	(Cucchiella et al., 2015; Kumar, Holuszko, & Espinosa, 2017; Makov et al., 2019; Ongondo, Williams, & Cherrett, 2011; Shevchenko, Laitala, & Danko, 2019; Speake & Yangke, 2015; Wang et al., 2013; Wilson et al., 2017; Zoeteman, Krikke, & Venselaar, 2010)
Government, Research institutes, and third sector documents	(ABDI, 2012; Balde et al., 2017; Brasil, 2010; Buchert et al., 2012; Euromonitor International, 2019; Forti, Baldé, & Kuehr, 2018; IDC, 2019; IDEC, 2013; MMA et al., 2019; Parajuly et al., 2019; Poushter, 2016; Prakash et al., 2015; Taylor & Silver, 2019; United Nations, 2019)

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[1] Policies are defined in the System Dynamics area as “efforts to solve pressing problems” (Sterman, 2000). In this research, we use ‘Intervention’ to refer to the specific efforts under examination to avoid confusion with ‘Public policy’.

The investigated literature also provided reliable sources for time series and critical variables which enabled calibrating the model against available data. The calibration process led to a Baseline scenario that represents the nation-wide stocks and flows of smartphones and related WEEE in Brazil considering the current structures. During adaptation and calibration, the model was consistently tested seeking to build trust in behaviour emerging from using it. The mass balance test is one of the tests performed – see Appendix Figure 6.

Model use followed a quantitative system modelling approach, seeking potential scenario projections driven by changes in the model structure (Turnheim et al., 2015) to enable evaluating the viability of policy targets and plans. Forecasting, and structural analysis abilities of SD based on the assumptions about reasonable scenarios (Lyneis, 2000) were applied to examine the policy targets and plans and inform decision-makers about proposals applicability.

The model structure, calibration and use are following described.

3 System description

3.1 The model structure

Five sub-models allow to investigate the BIAEEE: (1) Technology adoption; (2) EEE and WEEE flow; (3) EEE obsolescence; (4) Material supply, and (5) Collection and treatment interventions. Figure 1 details the sub-models and relationships between them.

In the **(1) Technology adoption** sub-model, a diffusion of innovation structure determines product demand considering the population size. Product demand is composed of three purchasing drivers (Sterman, 2000): adoption purchases, additional purchases, and replacing purchases. Adoption purchases constitute the first acquisition of a given EEE by an adopter. Additional purchases happen in cases which the adopter decides owning more than one product at a time. Replacing purchases happens when the owner ends its relationship with a previous product while remaining an adopter of the technology. Time series of population and penetration of the EEE technology are exogenous variables in the model.

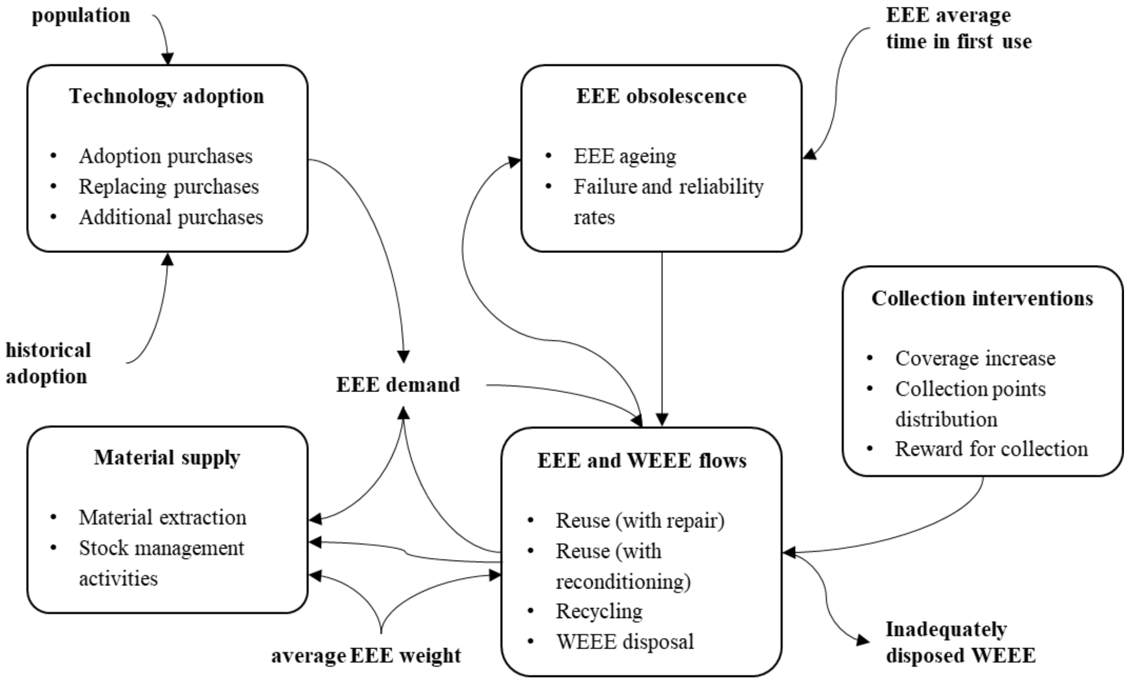

Figure 1 – Composition of the model used in the BIAEEE investigation

The **(2) EEE and WEEE flows** (detailed in Figure 2), considers the full lifecycle of EEE, from cradle-to-cradle. The “*First use EEE”* and “*Reuse EEE”* satisfy the demand generated by users. If needed, *“first use commissioning”* is activated to meet additional demand. The process of EEE ageing, determined by a co-flow structure that measures the average age of stocks in the **(3) EEE obsolescence** sub-model, drives products’ obsolescence considering the average lifetime of products. Some products get the status of “*Hibernated EEE*” before becoming available. When decommissioned, products acquire the status of “*Available used EEE*”. That status is determinant to additional use cycles, additional life cycles or reaching the end of the material life. Products enter the reuse market considering consumers’ willingness to buy products with a given expected remaining lifetime after potential repair. EEE will reach the formal collection system according to the existence of collection infrastructure and the willingness of customers to adequately dispose of "*Available used EEE"* into *"EEE collected for treatment*". An infrastructure for *"sorting"* and *"WEEE recycling"* enables the material to return in the value chain. If not collected, WEEE will follow less adequate treatment through the mixed waste path (Forti et al., 2018), represented by the *"Inadequately disposed WEEE"*.

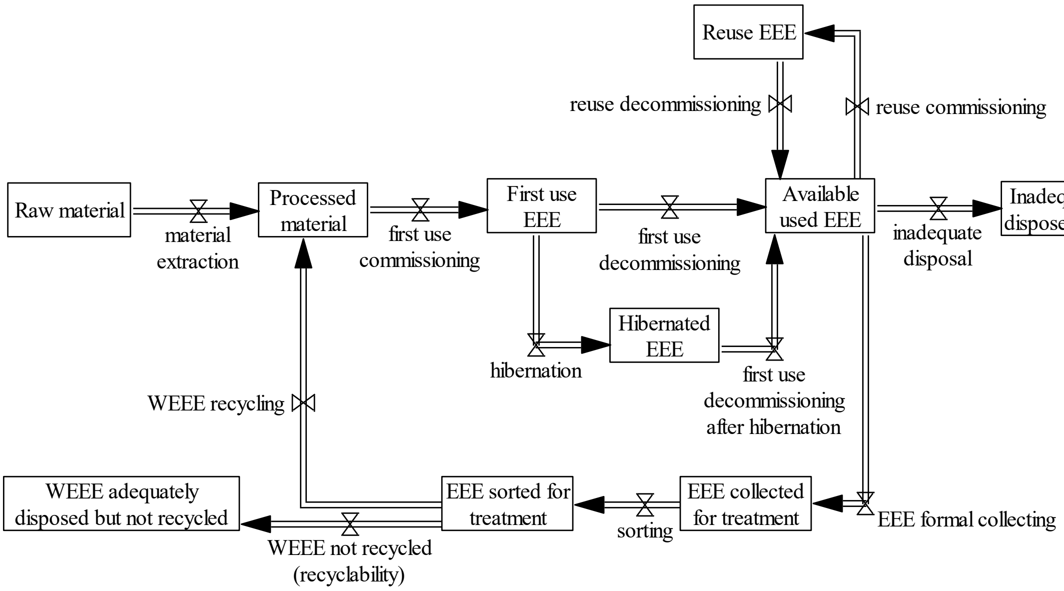

Figure 2 – A simplified representation of the stocks and flows of the EEE and WEEE flows sub-model

The **(4) Material supply** sub-model determines the need for additional processed material for product commissioning. The *"average EEE weight"* sets all material-product transformations. The implementation of interventions for collection consonant with the BIAEEE discussions occurs in the **(5) Collection interventions** sub-model.

3.2 Model calibration and use

3.2.1 Setting the baseline scenario

Table 2 presents the variables, values and sources setting the baseline scenario. The baseline scenario is driven by historical and projection data for the Brazilian population (United Nations, 2019) and historical data of smartphones penetration in the country following the Pew Research Center (Poushter, 2016; Taylor & Silver, 2019). For the sake of simplicity, the adoption of smartphones stabilises from 2018 onwards. The average time in first use is of 2.6 years, following the survey by the Brazilian Institute of Consumer Protection (Echegaray, 2016; IDEC, 2013).

Smartphones may hibernate in users' homes after reaching the first use cycle end because some adopters want a replacement smartphone and when there is no possibility for adequate disposal of the EEE (Rathore et al., 2011; Wilson et al., 2017). According to IDEC (2013), 41% of people store their mobile phones after the first use cycle for an average time of 3 years. After possible hibernation, smartphones become available and eventually reach the reuse market. Smartphones broken beyond economical repair or outdated from a technological perspective do not reach reuse markets. According to Rodrigues et al. (2020), in São Paulo, 12% of smartphones are broken beyond economical repair, which was adopted.

The market depreciation curve for Samsung smartphones identified by Makov et al. (2019) determines the fraction of available used smartphones commissioned into second use following the average age of available used EEE after eventual rejuvenation through repair – see Appendix Figure 9 . The depreciation curve determines the average share of value preserved considering launch and resale of smartphones (Makov et al., 2019) and thus, the fraction of smartphones that hold value for a reuse transaction. The original depreciation curve was normalised to the Brazilian case. The reuse market coverage was considered as

100%, meaning country-wide coverage as web-based applications and local markets are widespread.

Table 2 – Input data and sources used for the baseline scenario

Variable	Value	Unit	Source
Population	f(t)	People	United Nations (2019) – see Appendix Figure 7.a
potential adoption fraction	f(t)	Dimensionless	Pew Research Center (2016; 2019) – see Appendix Figure 7.b
historic annual EEE put on market	f(t)	Unit/year	IDC (2019) – see Appendix Figure 8. Used for calibration purposes.
average time in first use	2.6	Year	IDEC (2013) and Echegaray (2016)
average hibernation time	3	Year	IDEC (2013)
fraction of decommissioned that hibernate	0.41	Dimensionless	IDEC (2013) and Echegaray (2016)
fraction of decommissioned because broken beyond economical repair	0.12	Dimensionless	Rodrigues et al. (2020)
fraction fit for second use	Lookup	Dimensionless	Makov et al. (2019) – see Appendix Figure 9
reuse market coverage	1	Dimensionless	Assumption
coverage of third party repairing unities	0.8	Dimensionless	Based on ABDI (2012)
average rejuvenation through repair	0.2	Dimensionless	Assumption
fraction of used EEE repaired in the end of the use cycle for reuse	0.2	Dimensionless	Based on IDEC (2013)
expected age for second use decommissioning	1.4 * average time in first use = 3.64	Year	Assumption
initial fraction of WEEE formally collected	0.02	Dimensionless	de Souza et al. (2016)
recyclability WEEE formal market	0.95	Dimensionless	Based on de Oliveira Neto et al. (2017) and Buchert et al. (2012)
EEE average weight per unit	0.0001	ton/unit	Forti et al. (2018)
time to sort	0.125	Year	Assumption
recycling time	0.125	Year	Assumption

More than 25,000 technical assistance workshops are reported country-wide in Brazil, holding a capillarity similar to retail (ABDI, 2012). We assumed third party repairing cover 80% of the adopters. The working conditions, access to product information and to spare parts only enable a few services: broken screen replacing, parts exchange, phone resetting, and other minor tweaks. We assumed an average rejuvenation of 20%. In Brazil, only 20% of the smartphones owners try to repair the products after a use cycle (IDEC, 2013). The average time in reuse was assumed as 40% longer than the average time in first use, as products in reuse achieve longer general lifetimes among São Paulo citizens (Rodrigues et al., 2020). The expected age of reuse EEE is, thus, of 3.64 years when decommissioning.

Available used EEE may indefinitely enter the reuse market. The products that do not reach the reuse market may follow two paths: formal collection or inadequate disposal. We considered 2% of EEE formally collected for the baseline scenario (de Souza et al., 2016), where the most valuable components of smartphones are exported for recycling (de Oliveira Neto et al., 2017). The international recycling market achieves high levels of recyclability (Buchert et al., 2012). We assumed 95% recyclability in the formal recycling market. The average weight of 0.1 kg per smartphone defines every material-product transformation (Forti et al., 2018). Sorting and recycling processes were assumed as taking 0.125 years. The products that do not reach formal collection reach inadequate disposal.

3.2.2 Developing scenarios for EEE collection interventions

In addition to collection points deployment, consumer engagement is critical to enable high collection rates of post-use EEE (Tan et al., 2018). Benefits obtained from correct disposal, the existence of a formal collection channel able to manage data privacy, and the collection process convenience are critical attributes of a collection system (Bai et al., 2018; Qu et al., 2019; Tan et al., 2018). Three factors determine the scenarios for collection of EEE in the model: the coverage increase per year, the distribution of collection points and the possibility of reward for customers. Twelve scenarios were created based on variations in the three factors for EEE collection. Table 3 shows the values used for the factors in the 12 scenarios. In all cases, the recycling capacity meet the collection rate as the installed recycling capacity in Brazil is higher than the collection (ABDI, 2012). The recyclability rate follows the baseline scenario.

Table 3 – Scenarios for interventions combining the three factors for EEE collection

Scenario	Options	Coverage increase (CI) (mi inhabitants/year)	Distribution (D) (inhabitants/collection point)	Reward (R) (dimensionless)
1	CI1 D1 R0	12.5	25,000	0
2	CI1 D1 R1	12.5	25,000	1
3	CI1 D2 R0	12.5	10,000	0
4	CI1 D2 R1	12.5	10,000	1
5	CI1 D3 R0	12.5	1,000	0
6	CI1 D3 R1	12.5	1,000	1
7	CI2 D1 R0	25	25,000	0
8	CI2 D1 R1	25	25,000	1
9	CI2 D2 R0	25	10,000	0
10 (A)	CI2 D2 R1	25	10,000	1
11 (B)	CI2 D3 R0	25	1,000	0
12 (C)	CI2 D3 R1	25	1,000	1

For the coverage increase per year, the BIAEEE's implementation plan provides a list of municipalities to be covered with collection points from 2021 to 2025 by state (MMA et al., 2019, Annex VII). Following the most populous municipalities in each state, the collection system should cover 58% of the Brazilian population, or 127 million people, by 2025, meaning an average increase of 25 million people coverage per year. Such average increase denoted a fast coverage increase. 12.5 million people/year denoted a slow coverage increase for comparison.

As for the distribution of collection points, the BIAEEE implementation plan determines that each collection point should serve a population of 25,000 (MMA et al., 2019), which was adopted as a centralised collection option. A decentralised collection option and a community collection option were set up to serve a population of 10,000 people, and 1,000 people per collection point, respectively. Higher convenience – which determines customers' adoption – is achieved as less detour from customers' daily tasks is needed. Figure 10 in the appendix details the ratio among distribution of collection points and convenience used in the simulations.

The BIAEEE foresees using incentives subject to the interest of system operators (MMA et al., 2019). The reward effects differ if applied to more or less convenient EEE collection systems (Bai et al., 2018). Two options examine the effects of a reward: with and without reward. Figure 11 in the appendix details the reward effect for the different levels of convenience reached by the EEE reverse logistics system, where less convenient options lead to higher reward effect.

3.2.3 Developing a test bench to examine the BIAEEE targets

Ultimately, the results of scenarios implementation were examined against the BIAEEE targets. A percentage in weight of EEE commissioned must be collected and “disposed of in an environmentally sound manner” (MMA et al., 2019, sec. 16). By 2025, the system must be capable of adequately collecting and treating 17% of the materials from products put on the market in 2018, which is the base year set in the industry agreement. The target must be reached for each type of EEE separately. Table 4, in the appendix, shows the yearly targets of the BIAEEE.

A test bench was set to examine the “ratio of material treated in the last n years”, and the “ratio of material lost in the last n years”. In the test bench, three structures measuring the “Total material inserted in the system in the last n years”, the “Total material formally treated in the last n years” and the “Total inadequately disposed WEEE in the last n years” determine the ratios. We have adopted 2.6 years, i.e. the average time in first use of smartphones, as n. Adopting an interval for the analysis seems more reasonable than considering only products placed on the market in 2018, which is prescribed by the agreement. The reasons are three-fold: (i.) EEEs hold different lifetime patterns, (ii.) it is rather impractical to examine only products from a specific year for actual verifications of the system, (iii.) considering the all-time material could lead to too much inertia to demonstrate any change in the collection system. The structure of the test bench created and the variables equations used are available in Figure 12 and Table 5 in the Appendix.

4 Simulation results

4.1 The material and EEE stocks and flows of smartphones in Brazil

The critical material and EEE stocks and flows for the baseline scenario were obtained from model use. Figure 3.a presents the behaviour of the stocks of EEE in units. Large numbers of idle products, either hibernating in users' homes or available for the reuse and recycling markets are expected. More than 55 million smartphones will hold the status of *"Available used EEE",* and more than 25 million smartphones will hold the status of *"Hibernating EEE" t*o sustain almost 147 million smartphones in use around 2030. This scenario of a high number of idle products while few in second use happens because the fraction of people that engage in the reuse market is still low, there is limited restoration capability from the repairing infrastructure, and the average time in second use becomes a fraction of the first use. *"Hibernating EEE"* and *"Available used EEE"* are an opportunity for the reuse and reconditioning markets. The maximum value for *"Reuse EEE" is* 1.25 million smartphones, which decreases through time as the fleet gets old. The amount of *"EEE collected for treatment"* is stable at around 1.1 million smartphones, following the continuous process of collecting and sorting.

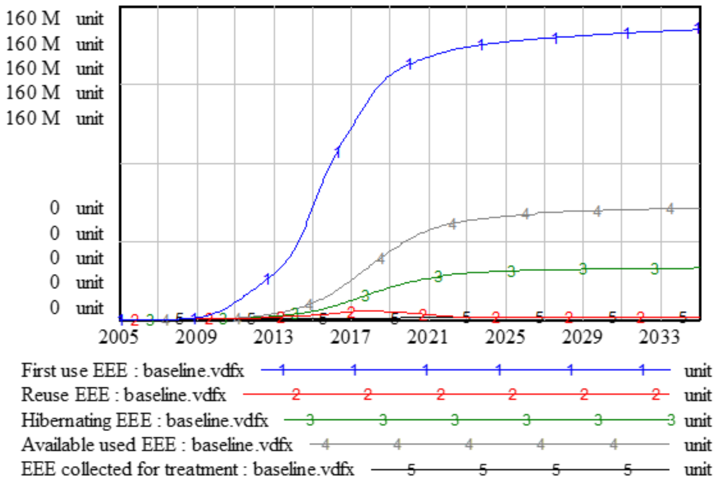

Figure 3.a – EEE stocks in the baseline scenario in unit

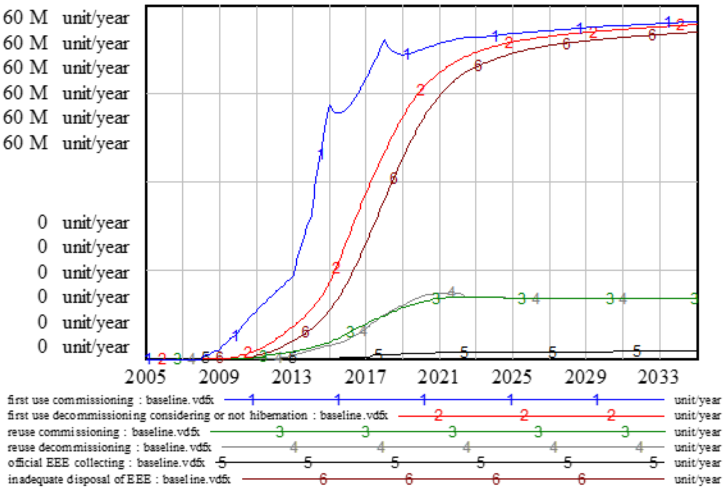

Figure 3.b – EEE flows in the baseline scenario in unit/year

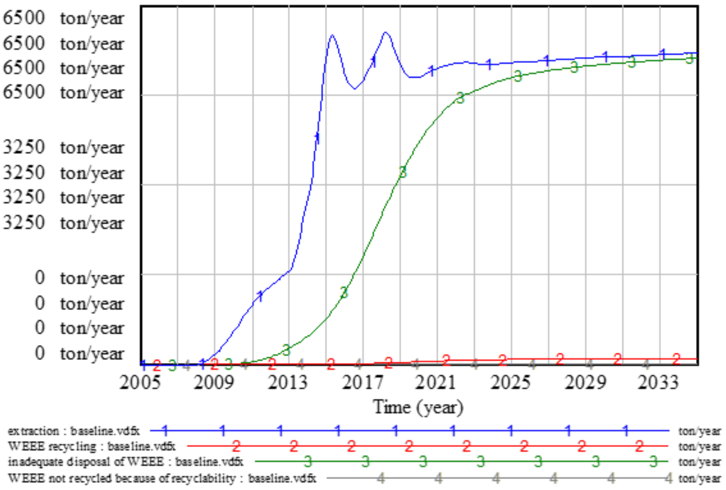

Figure 3.c – Material flows in the baseline scenario in ton/year

Figure 3 – The material and EEE stocks and flows of smartphones in Brazil

Figure 3.b shows the flows of EEE products, commissioning and decommissioning in first use and reuse markets, as well as collection and eventual disposal of such products in unit/year. *"Inadequate disposal of EEE"* presents a delayed behaviour to *"First use decommissioning*" (considering or not hibernation)[2], which presents a delayed behaviour to *"first use commissioning"*. Reuse and recycling influences such delayed behaviour and explain the difference of magnitudes among both curves. Reuse with repair influence the delay between product decommissioning and eventual disposal. In the baseline scenario, both reuse commissioning and decommissioning achieve dynamic equilibrium after 2025, reaching a similar order of magnitude. At this moment, the effect of reuse in decelerating the flow of resources decreases. Recycling, in turn, reduces the level of inadequate disposal of EEE, explaining the difference of magnitudes among *"First use decommissioning*" (considering or not hibernation) and *"Inadequate disposal of EEE"*. Following the baseline scenario, 40 million smartphones are disposed of inappropriately annually in 2020 and more than 55 million in 2035 if sustaining the 2% collection rate.

Figure 3.c shows the material flows, from extraction to eventual collection and recycling, and the inadequate disposal of WEEE in ton/year. The two peaks in *"material extraction"* follow and amplify the peaks in *"first use EEE commissioning"* because of the stock management structure. Here again, a delayed behaviour is observable between the flow of material entering the system and reaching its final destination. The delay is longer because it comprises the extraction time, the useful life of EEE, and intermediate stocks of WEEE for

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[2] We represent decommissioning considering or not hibernation as it better represents the similarity among curves 2 and 6. Products which hibernate will contribute as older products to *"Available Used EEE"*, which hinders the possibility of additional life cycles.

eventual treatment. Most of the material put in the system will flow into *"inadequate disposal of WEEE"* because of the lack of structure for collection and treatment. If the intention is treating 100% of WEEE in 2035, the infrastructure for collection and treatment needs to be able to deal with 5,542 tons of smartphones equivalent per year. 2% of smartphones collection means around 81 tons of smartphones equivalent per year in 2020. It is a 68 times increase in the capacity for collection and treatment of smartphones in 15 years.

This baseline scenario enables examining the implementation of CE interventions.

4.2 The effects of EEE collection interventions

Figure 4 shows critical flows that demonstrate the effects of the twelve scenarios. Official EEE collection (Figure 4.b) enables decreased material extraction (Figure 4.a) and decreased inadequate disposal of EEE (Figure 4.c). Scenario 1 led to the least significant values for official EEE collection, while Scenario 12 (C) leads to the most significant values for official EEE collection. In scenario 1, holding slow coverage increase and low distribution density of collection points with no reward, approximately 8.71 mi unit/year or 871 ton/year of smartphones is collected for official recycling in 2035. In scenario 12, (C), holding fast coverage increase and high distribution density of collection points with rewards, approximately 50.73 mi unit/year or 5073 ton/year of smartphones is collected for official recycling in 2035. Scenario 7, which is the most likely scenario if we consider the BIAEEE document, reaches the second-worst mark in the long run – 11.27 mi unit/year or 1127 ton/year of smartphones collected. In general, a centralised collection system – scenarios 1, 2, 7, and 8 – led to the worst results. On the other hand, scenarios that offered a reward led to the best results – scenarios 12 (C), 10 (A), 6, and 8. Scenario 11 (B) was an exception, as it presents good results without offering a reward.

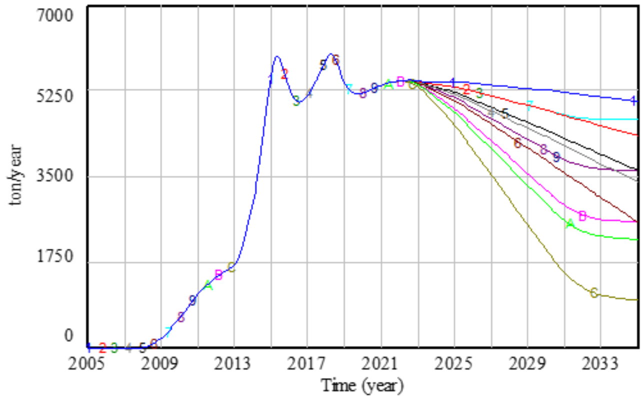

Figure 4.a – Material extraction (in ton/year)

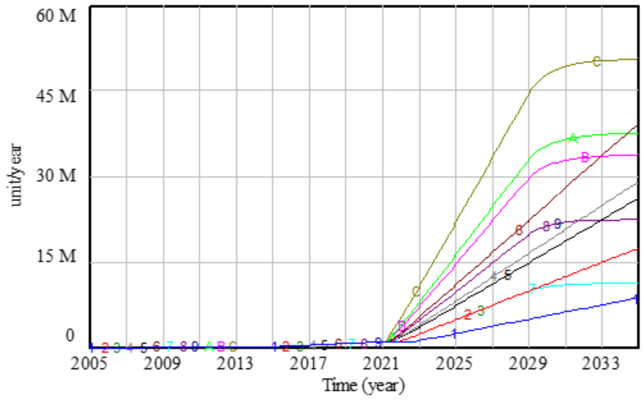

Figure 4.b – Official EEE collecting (in ton/year)

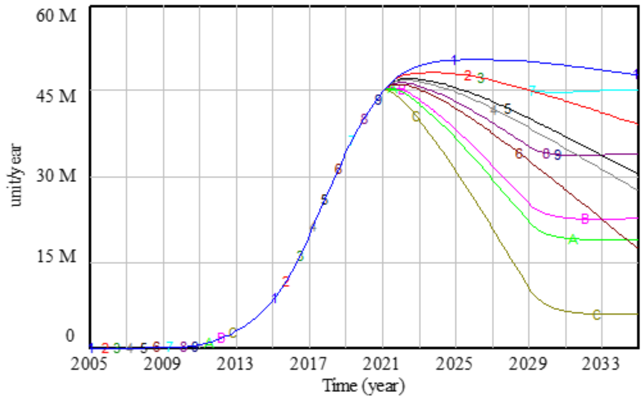

Figure 4.c – inadequate disposal of EEE (in unit/year)

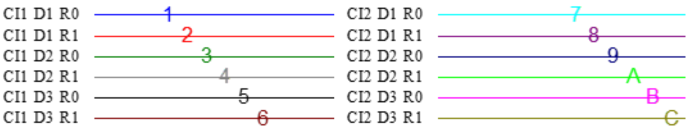

Figure 4 – Critical flows demonstrating the effects of CE implementation in the baseline scenario and in scenarios 1, 2 and 3

With a centralised collection system (one collection point per 25,000 people), it is expected that each collection point will receive up to 2,413 smartphones per year by 2025 in scenarios 2 and 8. Although a community collection system (one collection point per 1,000 people) leads to relevant collection of EEE, it is necessary to consider the implementation and maintenance of 1 million collection points by 2025 to enable that system in scenarios 11 (B) and 12 (C), holding the lowest values for average collection per collection point – reaching 14.48 smartphones per collection point per year in 2025 in scenario 11 (B). Scenarios 8 and 10 (A) reach high values for EEE collection relying on fewer collection points to function – 4,000 and 10,000 collection points respectively. Both scenarios, however, rely on a reward system that can also influence the total cost of the system due to reward-associated costs. In this sense, scenario 9 appears as an option that can lead to decent results with a lower collection cost, since the number of collection points is intermediate, and there is no associated cost of rewards. However, in this scenario, the collection capacity reaches a limit at an intermediate level of EEE collection as early as 2030. Table 6 in the appendix shows the total number of collection points and average collection rate achieved by them in 2025 for the twelve scenarios, enabling further analyses of costs and benefits of the potential interventions.

4.3 Reaching the BIAEEE targets

Figure 5 shows that only scenario 12 (C) reached the BIAEEE targets on time (see Figure 5.a), represented by the second curve number 1 (blue), by collecting 21.72 million smartphones/year in 2025. The 17% threshold curve, represented by the second curve number 2 (red), demonstrate the moment that each scenario reaches the target set to 2025 in the BIAEEE. While scenario one does not reach that threshold until 2035, scenario seven only does so in 2032, when the reverse logistics system collects 11.09 million smartphones/year.

The complementary behaviour among the ratio of material treated to the fraction of EEE lost from the system considering the last 2.6 years demonstrates that the *"ratio of material treated"* is an adequate indicator to guide decisions for the use of resources as it considers eventual loss of resources by the system.

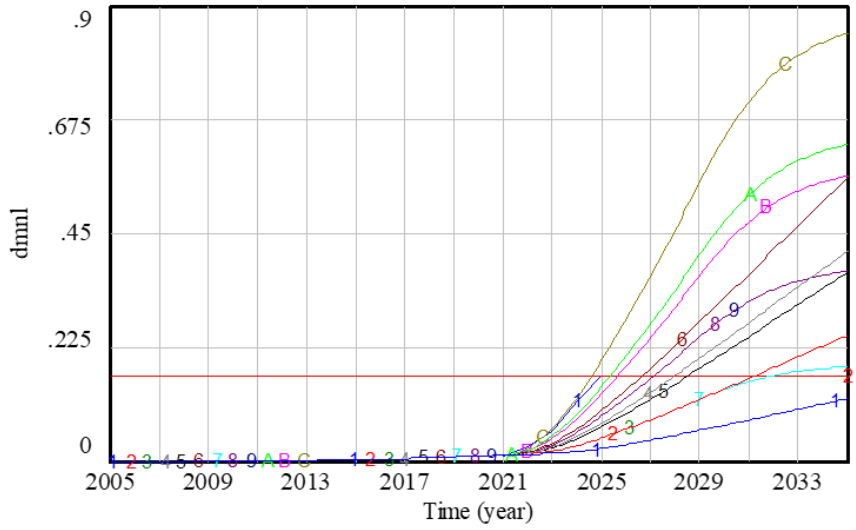

Figure 5.a – Ratio of material treated considering the last 2.6 years (dimensionless)

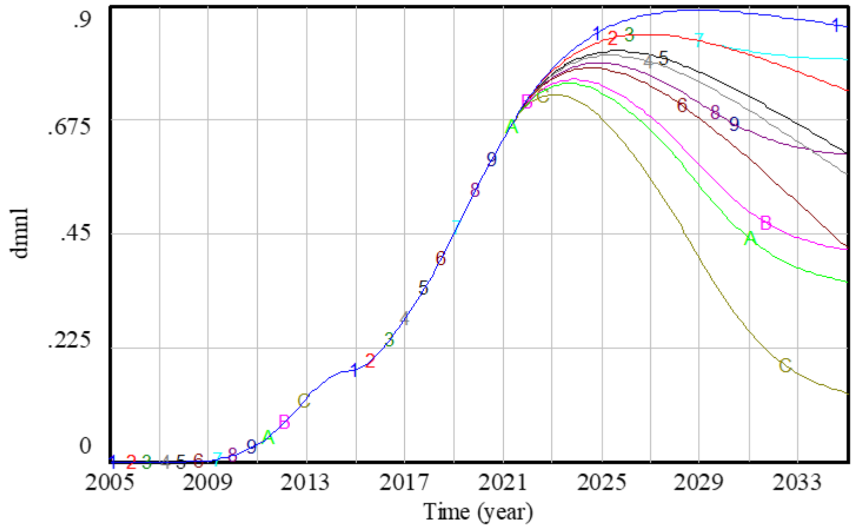

Figure 5.b – Ratio of material lost considering last 2.6 years (dimensionless)

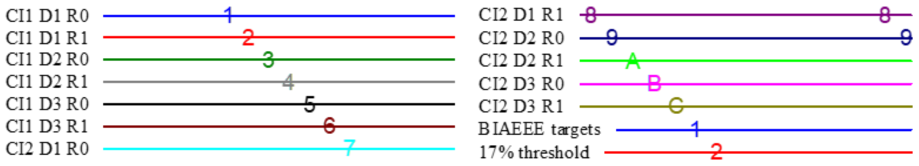

Figure 5 – Ratio of material treated and lost considering the last 2.6 years for the baseline, the three policy implementation scenarios, and an exploratory analysis

5 Discussion

The goal of this research was to: (1) examine the implementation of CE interventions through a simulation model for the use of smartphones in Brazil, (2) evaluate how interventions focused on the collection of products at the end of life can enable meeting the BIAEEE targets for a given EEE type, and (3) discuss the potential of modelling and simulation to assist public policy investigation in the context of CE transitions. Towards fulfilling those goals, we adapted the Circular EEE SD model to examine collection interventions in the Brazilian smartphones market using an extensive literature review.

The model adaptation process demonstrates the model structure, and the main assumptions sustaining it to clarify the choices made. Demonstrating the calibration for the baseline scenario reduces uncertainties regarding the results presented since it is a complex system, and we often refer to complexity to justify not understanding certain behaviours. The use of SD modelling and simulation provided a detailed view of the country's challenge to improve its results in the collection of smartphones. It is possible to experiment with CE interventions to recognise potential scenarios for enhanced collection of EEE that may be sufficient to satisfy the BIAEEE targets.

For the research question, "How modelling and simulation can inform decision-making in the implementation of national policies for EEE collection that allow Circular Economy transitions?", discussions about the insights obtained from the implementation of the interventions using the simulation model will follow three axes. First, we make recommendations for the implementation of the BIAEEE. Second, we describe the continuous use of modelling and simulation as a path to governing the reverse logistics system. Third, the contributions for theory and practice are outlined along with further research avenues.

5.1 Recommendations for the implementation of the BIAEEE

The trade-offs in the choices that influence the capillarity of the system and customer engagement are essential aspects to enable a reverse logistics system that meets the BIAEEE targets. For low-density distribution of collection points, a network of electronics retailers and mobile carrier stores can sustain the reverse logistics system. It is a possibility for a collection system with high coverage in a short time. On the other hand, greater distance and less convenience should lead to limited consumer adherence. Furthermore, the growing online purchases of mobile devices in the country (from 15.1% in 2014 to 27.4% in 2019 (Euromonitor International, 2019)) reinforces the limit of far collection, as people go less and less to commercial centres. Also, retailers will need to manage the collection of more than 100 smartphones per month on average, which is an additional operational requirement and an opportunity to maintain relationship to customers. Bai et al. (2018) reports potential positive effects in sales from EEE collection activities.

The effects of opting for collection points closer to the customers are substantial as the ease in disposing of the products would cause more customers to discard correctly. Previous results indicate a high rate of use of the selective collection system to dispose of WEEE in a Brazilian city with high coverage (Abbondanza & Souza, 2019). More decentralised options require the participation of other stakeholders such as cooperatives, supermarkets to enable them. In the most decentralised options, collection associates will manage around 15 smartphones per year, which provides a still limited potential source of income.

The scenarios with rewards showed promising results. Stakeholders involved in the design and implementation of BIAEEE should consider rewards systems for meeting the targets. Financial, environmental and social incentives (Shevchenko et al., 2019) can be used to influence the donor of used EEE. Alternative reward systems may optimise the relationship between EEE collecting and systemic costs.

In none of the investigated cases, the adoption level to the system reaches 100% because there are many other barriers and factors to be considered towards a potential full-collection system. Managing the privacy of consumers data and adequate communication of the system functioning are critical requirements in EEE collection (Tan et al., 2018). There is also an intention-behaviour gap in the number of people interested in adequately disposing of products from the current number of people that adequately dispose of them (Echegaray & Hansstein, 2017; Tan et al., 2018). Besides, reports show a considerable proportion of consumers keep old mobile phones as a memento in China (Qu et al., 2019). Thus, the 80% adoption limit for the case of community collection with reward seems to be a reasonable limit for a first investigation. Such limit reinforces soft requirements of selective collection systems as trust development with the users and the dissemination of the collection services.

A final recommendation concerns the scope of the instruments contained in the BIAEEE. The industrial agreement can promote the alignment and action of the various stakeholders to enable better results of collection and treatment in the Brazilian EEE industry. However, the results presented in this article demonstrate that only recycling presents limited results for decelerating resource flows. In a proactive path for Future WEEE scenarios, Parajuly et al. (2019) recommend products designed for longer lifetime, service-oriented business models, reward-based schemes, among other initiatives. The BIAEEE signed in 2019 should be considered a first wave of policy implementation to allow a Circular EEE industry in Brazil. Following waves of the BIAEEE could provide instruments – targets, market incentives – that promote other forms of decelerating the flow of resources and thus, the impacts of the EEE industry.

5.2 The use of modelling and simulation to governing the BIAEEE implementation

Along with enabling examination and recommendations, the use of modelling and simulation can assist in the ongoing process of governing the reverse logistics system for EEE products in a few ways. Using the model can further help to detail the requirements for the reverse logistics system. Detailing the processes of collection, sorting, consolidation and transportation in stock and flow structures can bring insights regarding the required infrastructure capacity, their distributions in municipalities and regions, the operating costs, and identification of operations management challenges. Simulation results may disclose investment opportunities in recycling specific types of components in the country. Locally pre-processing and dismantling while recycling in international end-processing facilities can be used as a transient situation until local end-processing is viable (Wang et al., 2012).

Obtaining reliable data enables continuous decision-making between policy-makers and business practitioners to enforce public policy implementation. The variables used to structure the model are essential, as they determine the behaviour of stocks and flows in the system. These variables must be tracked and managed. Understanding the condition of collected EEE and their fate in the treatment paths can help to calibrate the simulation model and bring greater clarity to the system's behaviours. A better understanding of the age, the reason for discarding, hibernation aspects, and paths of EEE into WEEE will allow better visibility regarding the BIAEEE targets. The implementation of systematic data collection is a significant opportunity to resolve the problem of scarce reliable data on the WEEE market in Brazil (cf. Balde et al., 2017– Annex 2; de Oliveira Neto et al., 2017; Ghosh et al., 2016).

Forti et al. (2018) argue that data from post-use EEE collection are essential sources to trace WEEE. Survey and census data about post-use EEE for a region can be scaled up to the national level (Kumar et al., 2017). Analyses of waste streams sorting in collection points, consolidation centres or recycling plants are appropriate instruments to collect lifetime data (Prakash et al., 2015). Each collection and treatment point is a potential source for a survey system for continuously assessing the status of the collection and treatment system. Company shares of mobile phones sales in the country (Euromonitor International, 2019) may determine the share of each company to reach BIAEEE the targets. Meeting the share of BIAEEE targets is verifiable using the unique serial number contained in the central module of the products.

An initiative-based learning approach (Turnheim et al., 2015) could be used in parallel to modelling and simulation, as real-world experiments can help to further understanding system behaviour and enhance the odds of meeting the BIAEEE targets. For example, it is essential to examine users reactions to potential reverse logistics structures. Incentives could be tested on smaller scales (e.g. cities) to examine whether the results meet the actual expectations for system behaviour.

Further use of this simulation model for decision making should consider model limitations. For example, smartphone adoption stagnates after 2018 by 60% of the country's population. Thus, the amount of EEE and WEEE is possibly underestimated. Besides, this research considers a homogeneous type of adopter, using values from researches that took place in more developed regions of the country. The Brazilian reality is most probably similar to what is reported to India in terms of smartphone usage (see Rathore et al., 2011, fig. 2), with a large discrepancy between regions and among social classes within regions. One possibility is to discretise the model considering the types of adopters, and the different regions of the country: regional adoption rates, lifetimes, and collection interventions would be required. This path could lead to further insights into the behaviour of implementing EC interventions in developing countries.

5.3 Contributions and further research avenues

The process of adapting the model, the results and discussions contribute to theory and practice. To **theory**, this work provides a case of modelling and simulation to examine future stocks of EEE and WEEE in different scenarios of implementation of CE interventions. The adapted model is one level below global or regional WEEE estimates (see Cucchiella et al., 2015; Ongondo et al., 2011; Zoeteman et al., 2010) and close to the nation-wide model for forecasting specific EEE flows (see Forti et al., 2018; Wang et al., 2013). The model present two critical features: (1) the ability to cope with the three types of purchases – adoption, additional and replacing, allowing more adequate prospects when examining future EEE and WEEE stocks comparing extrapolation of time series and of surveys (see Abbondanza & Souza, 2019), and (2) the ability to examine the potential effects of CE strategies.

For transitions, this work demonstrates how the implementation of national policies can contribute to a more circular industry through a modelling and simulation approach. Hansen et al. (2015) argue that the focus of transitions research has been bottom-up and on small (local) scales. Our research clarifies the role of top-down initiatives to allow discussing CE transitions in the region-wide use of resources. The modelling and simulation scenarios described in this work demonstrate the use of a modelling cycle for developing policies (cf. Janssen & Helbig, 2018, fig. 1), which allows examining the potential evolution paths of the system to achieving given policy targets using future scenario projections. The scenarios provide further quantitative evidence towards examining the implications of public policies in CE transition scenarios.

The central contribution to **practice** is the possibility to use modelling and simulation to inform decision-making in the implementation of CE interventions through public policies. Policies to manage post-use EEE are under continuous adoption across the globe, and countries and regions should be prepared to implement them. It is possible to examine under what conditions CE interventions are sufficient to achieve policy targets and discuss manners to reach that desirable state. The available model combined with the adaptation process detailed in this document allows other researchers and practitioners to examine other EEE products and instruments that enable public policies.

Follow up research may explore several paths. First, expanding the scope of products considered in the simulation would enhance the analysis of the collection and recycling infrastructure needed. Second, further endogenizing the perspective of customers to determine the faith of post-use products can bring insights into the possible choices of individuals. Third, the systemic costs emerging from implementation, maintenance and rewards can be further investigated. Finally, involving more specialists and decision-makers in developing and using the model, by following a group modelling process (Vennix, 1999) can enhance model validity and increase the odds of policy implementation and change. The continuous use of modelling and simulation may allow more significant learning as to the potential outcomes of public policy implementation in top-down CE transitions.

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8 Appendix

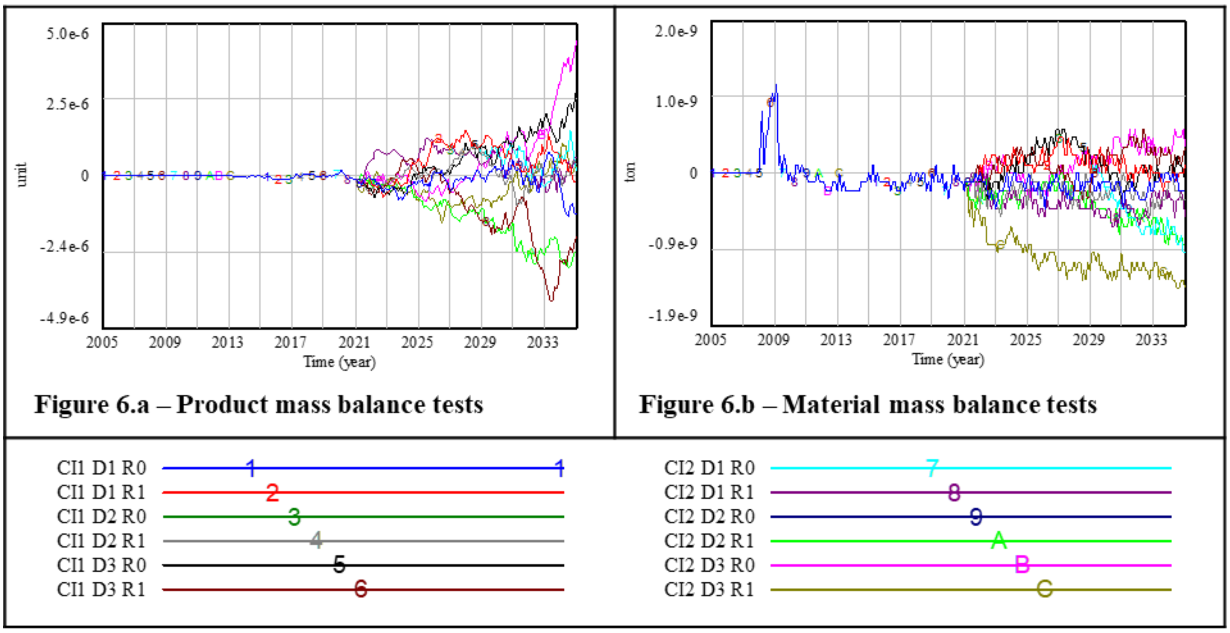

Figure 6.a – Product mass balance tests

Figure 6.b – Material mass balance tests

Figure 6 – Product and material mass balance tests in all scenarios, showing that no product or material was "lost from the system" due to model structure and equations.

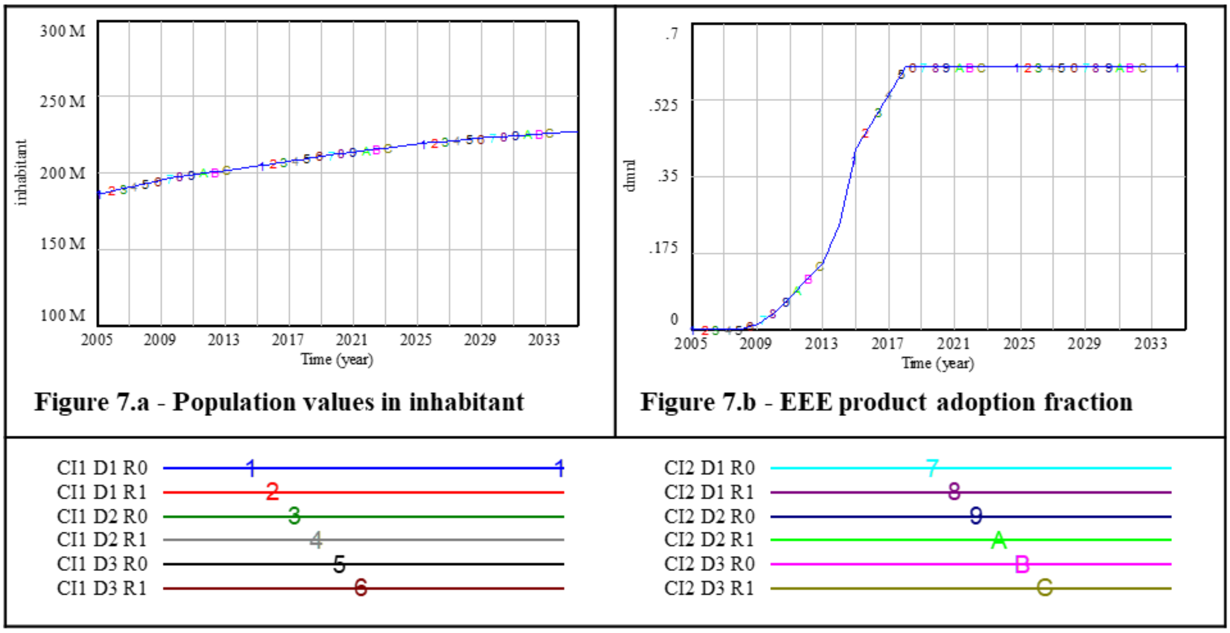

Figure 7.a - Population values in inhabitant

Figure 7.b - EEE product adoption fraction

Figure 7 – Population and technology adoption time series used as input data in the model

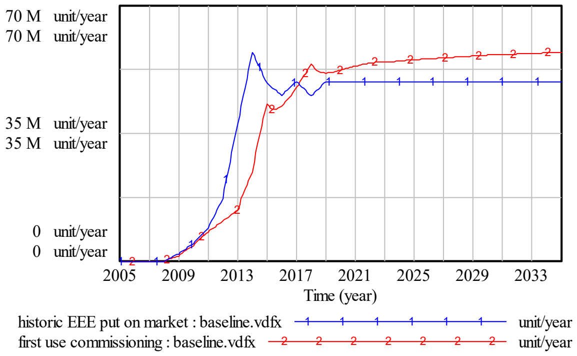

Figure 8 – Calibration results of first use commissioning and historical data from IDC (2019).

The similar behaviour and order of magnitude from the two curves demonstrate the calibration from calculated to real data.

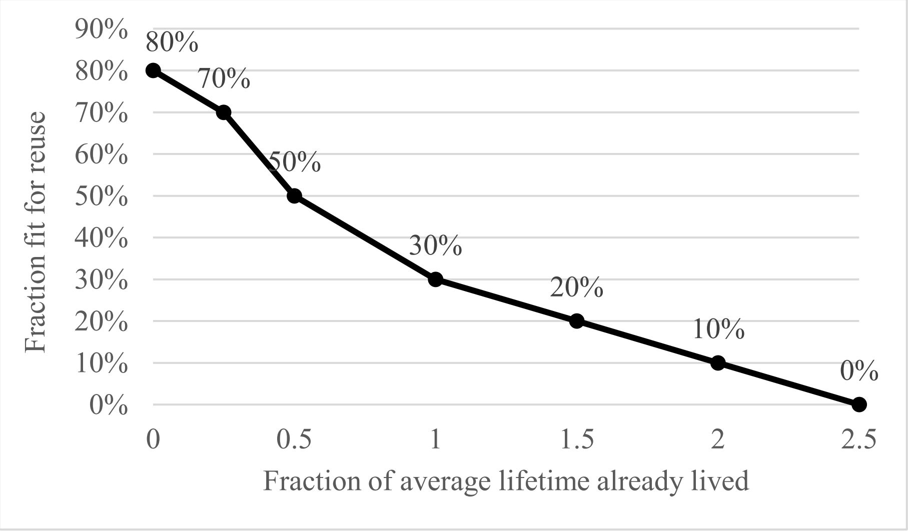

Figure 9 – Values adopted for reuse commissioning. Adapted from Makov et al. (2019)

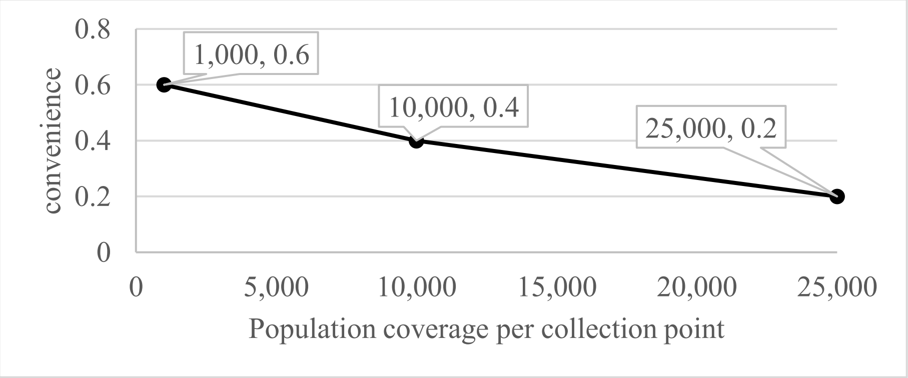

Figure 10 – Convenience of EEE reverse logistics system considering the population coverage per collection points with no rewards

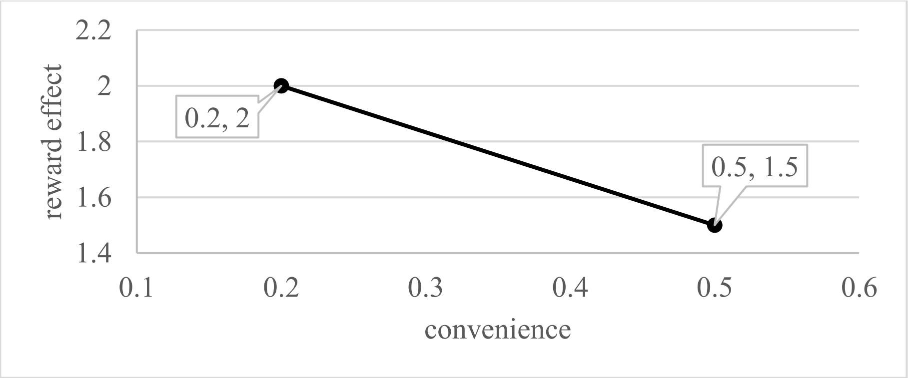

Figure 11 – Reward effect considering the EEE reverse logistics system convenience

Table 4 – Percentage of EEE to be formally collected and treated by each year

Year	Percentage of EEE
2021	1%
2022	3%
2023	6%
2024	12%
2025	17%

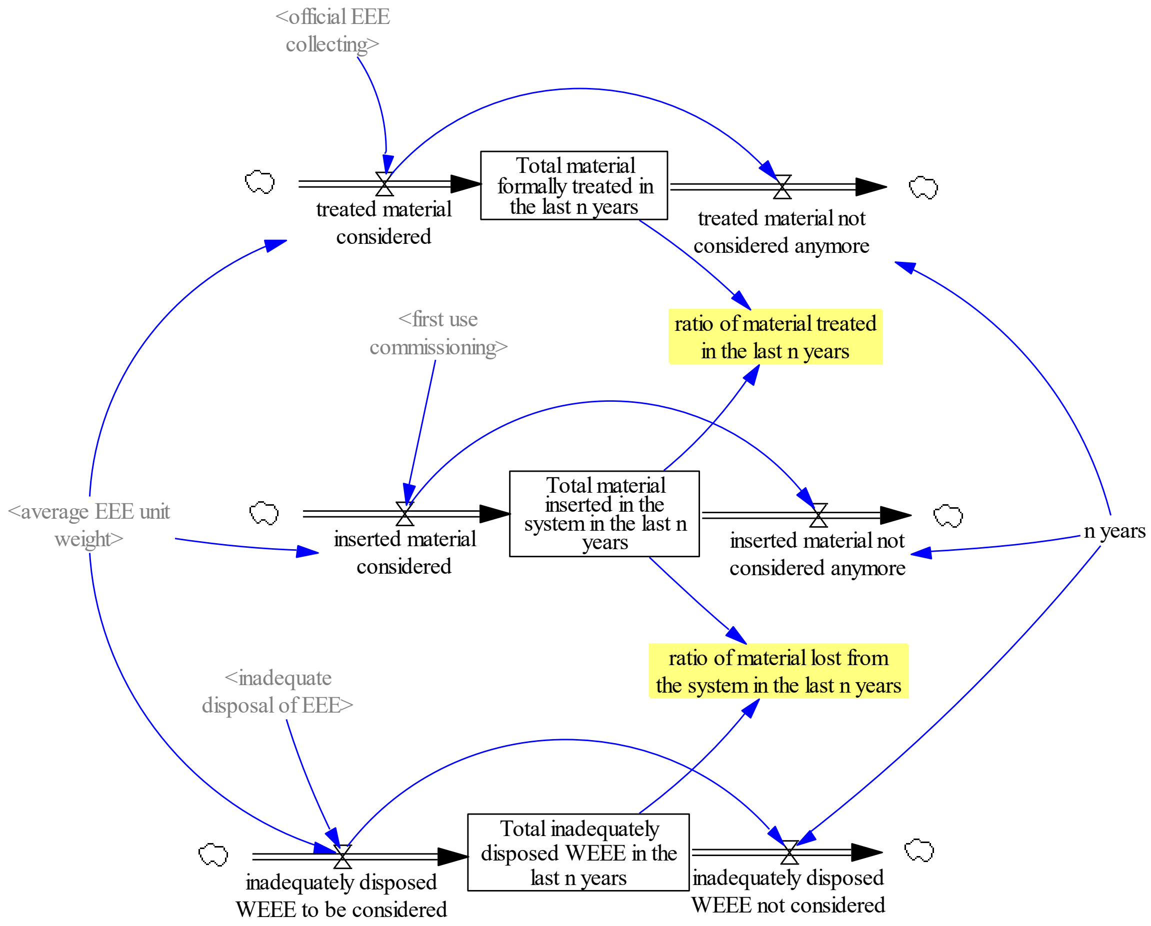

Figure 12 – Test bench created to examine the BIAEEE targets

Table 5 – Equations for the variables used in the test bench created to examine the BIAEEE targets

Variable	Equation	Unit
ratio of material treated in the last n years	ZIDZ (Total material formally treated in the last n years, Total material inserted in the system in the last n years)	dmnl
ratio of material lost from the system in the last n years	ZIDZ (Total inadequately disposed WEEE in the last n years, Total material inserted in the system in the last n years)	dmn
Total material inserted in the system in the last n years	INTEG (inserted material to be considered - inserted material not considered)	ton
inserted material considered	average EEE unit weight * first use commissioning	ton/year
inserted material not considered anymore	DELAY1(inserted material to be considered, n years)	ton/year
Total material formally treated in the last n years	INTEG (treated material to be considered - treated material not considered)	ton
treated material considered	average EEE unit weight * (official EEE collecting - official EEE reconditioning)	ton/year
treated material not considered anymore	DELAY1 (treated material considered, n years)	ton/year
Total inadequately disposed WEEE in the last n years	INTEG (inadequately disposed WEEE to be considered - inadequately disposed WEEE not considered)	ton
inadequately disposed WEEE to be considered	inadequate disposal of EEE * average EEE unit weight	ton/year
inadequately disposed WEEE not considered	DELAY1 (inadequately disposed WEEE to be considered, n years)	ton/year

Table 6 – Average collection per collection point in 2025 following scenarios

Scenario	Options	Number of collection points (collection points)	Average collection rate (units / collection points / year)
1	CI1 D1 R0	2,000	1,207
2	CI1 D1 R1	2,000	2,413
3	CI1 D2 R0	5,000	965.3
4	CI1 D2 R1	5,000	1,609
5	CI1 D3 R0	500,000	14.48
6	CI1 D3 R1	500,000	21.72
7	CI2 D1 R0	4,000	1,207
8	CI2 D1 R1	4,000	2,413
9	CI2 D2 R0	10,000	965.3
10 (A)	CI2 D2 R1	10,000	1,609
11 (B)	CI2 D3 R0	1,000,000	14.48
12 (C)	CI2 D3 R1	1,000,000	21.72