

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

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

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

26 **List of abbreviations**

27 BIAEEE                      Brazilian industrial agreement for electrical and electronic equipment

28 BNPSW                     Brazilian national policy on solid waste

29 CE                            Circular Economy

30 EEE                            Electrical and electronic equipment

31 SD                            System Dynamics

32 SFD                            Stock and flow diagram

33 WEEE                        Waste electrical and electronic equipment

## 34 **1 Introduction**

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

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

54 The use of international certifications such as Restriction of Hazardous Substances  
55 (RoHS) and the Electronic Product Environmental Assessment Tool (EPEAT) are widespread  
56 practices in the Brazilian national market (EMF & CE100 Brasil, 2017), specific public  
57 policies for managing WEEE are in their infancy and slowly evolving. The Brazilian national

58 policy on solid waste is in place since 2010 (Brasil, 2010), determining shared responsibility  
59 among supply chain players, and setting targets and incentives for solid waste management.  
60 In the BSWP, industry agreements are the instrument to formalise the shared responsibilities  
61 among organisations, the government and civil society with resources and waste for each  
62 industry. In 2019, the Brazilian industrial agreement for electrical and electronic equipment  
63 (BIAEEE) was finally signed, requiring manufacturers, distributors, and retailers to structure  
64 and implement a reverse logistics system for EEE products of domestic use, such as computer  
65 desktops, laptops, fridges, and mobile phones (MMA et al., 2019). The BIAEEE document  
66 defines responsibilities and targets for post-use EEE collection and treatment.

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

80 In practice, however, decision-makers struggle to define the appropriate targets and  
81 incentives to allow the best possible impact through policies. In that direction, modelling and  
82 simulation enable experimenting with the effects of policies implementation, the potential

83 evolution paths of the system and obtain practical recommendations to particular cases (Holtz  
84 et al., 2015). A modelling approach for policy development enables policy-makers, business  
85 practitioners and citizens, to explore the potential outcomes of policies and explore  
86 alternatives (Janssen & Helbig, 2018). Estimates of EEE and WEEE flows are crucial for  
87 supporting decision-making within policy-makers and organisations across the supply chain  
88 (Araújo et al., 2012). These estimates can decrease economic uncertainties related to WEEE  
89 recycling (Bouzon et al., 2016; de Oliveira Neto, Correia, & Schroeder, 2017) and help to  
90 establish shared responsibility to reverse logistics (Ghisolfi et al., 2017).

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

102 The aim of this research is three-fold:

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

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

107 (3.) Discuss the potential of modelling and simulation to assist public policy

108 investigation in the context of CE transitions.

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

## 121 **2 Materials and Methods**

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

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

142 **Table 1** – Nature and scope of research used for modelling, simulating, and discussing the  
 143 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)

<sup>1</sup> 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’.

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

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

156 The model structure, calibration and use are following described.

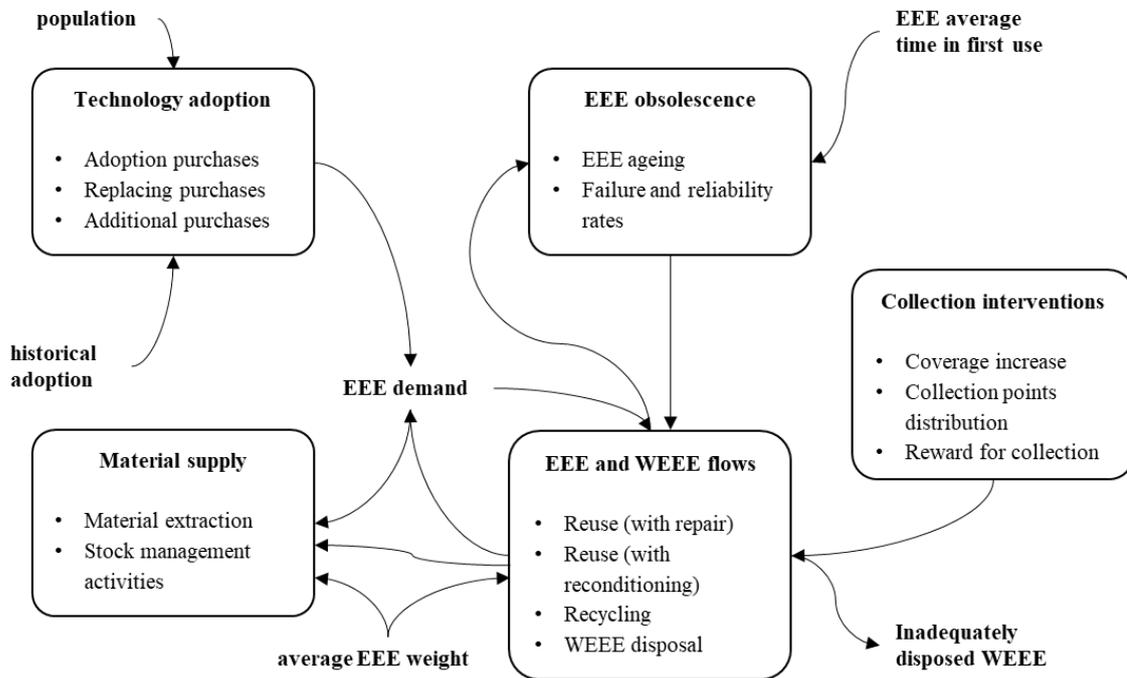
### 157 **3 System description**

#### 158 **3.1 The model structure**

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

162 In the **(1) Technology adoption** sub-model, a diffusion of innovation structure  
163 determines product demand considering the population size. Product demand is composed of  
164 three purchasing drivers (Stermann, 2000): adoption purchases, additional purchases, and  
165 replacing purchases. Adoption purchases constitute the first acquisition of a given EEE by an  
166 adopter. Additional purchases happen in cases which the adopter decides owning more than

167 one product at a time. Replacing purchases happens when the owner ends its relationship  
 168 with a previous product while remaining an adopter of the technology. Time series of  
 169 population and penetration of the EEE technology are exogenous variables in the model.

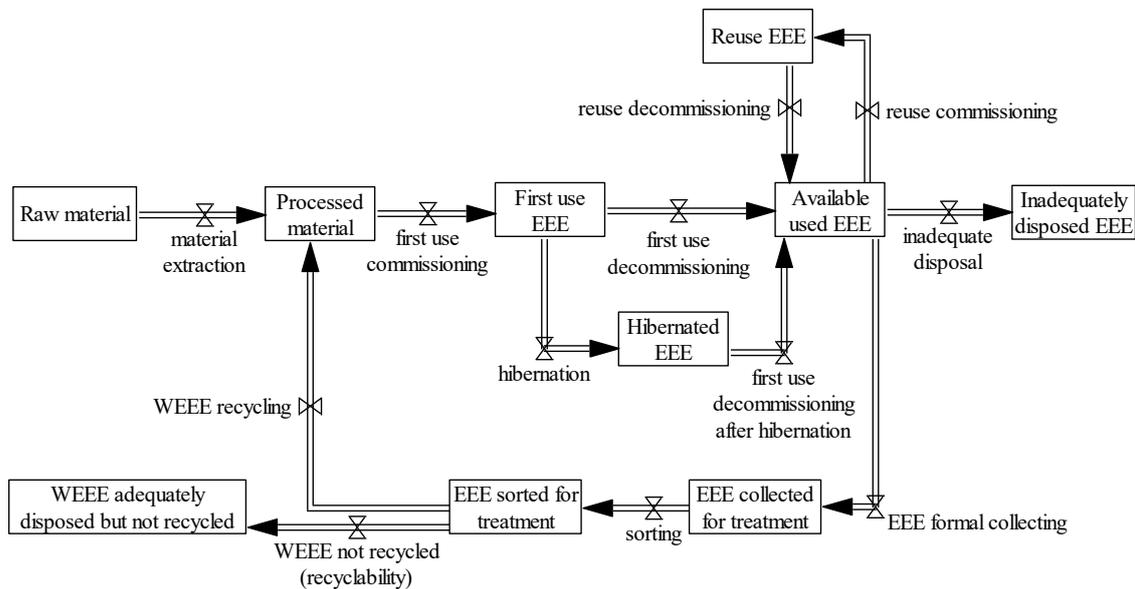


170

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

172 The **(2) EEE and WEEE flows** (detailed in Figure 2), considers the full lifecycle of  
 173 EEE, from cradle-to-cradle. The “*First use EEE*” and “*Reuse EEE*” satisfy the demand  
 174 generated by users. If needed, “*first use commissioning*” is activated to meet additional  
 175 demand. The process of EEE ageing, determined by a co-flow structure that measures the  
 176 average age of stocks in the **(3) EEE obsolescence** sub-model, drives products’ obsolescence  
 177 considering the average lifetime of products. Some products get the status of “*Hibernated*  
 178 *EEE*” before becoming available. When decommissioned, products acquire the status of  
 179 “*Available used EEE*”. That status is determinant to additional use cycles, additional life  
 180 cycles or reaching the end of the material life. Products enter the reuse market considering  
 181 consumers’ willingness to buy products with a given expected remaining lifetime after  
 182 potential repair. EEE will reach the formal collection system according to the existence of

183 collection infrastructure and the willingness of customers to adequately dispose of “*Available*  
 184 *used EEE*” into “*EEE collected for treatment*”. An infrastructure for “*sorting*” and “*WEEE*  
 185 *recycling*” enables the material to return in the value chain. If not collected, WEEE will  
 186 follow less adequate treatment through the mixed waste path (Forti et al., 2018), represented  
 187 by the “*Inadequately disposed WEEE*”.



188

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

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

## 195 3.2 *Model calibration and use*

### 196 3.2.1 Setting the baseline scenario

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

204 Smartphones may hibernate in users' homes after reaching the first use cycle end because  
205 some adopters want a replacement smartphone and when there is no possibility for adequate  
206 disposal of the EEE (Rathore et al., 2011; Wilson et al., 2017). According to IDEC (2013),  
207 41% of people store their mobile phones after the first use cycle for an average time of 3  
208 years. After possible hibernation, smartphones become available and eventually reach the  
209 reuse market. Smartphones broken beyond economical repair or outdated from a  
210 technological perspective do not reach reuse markets. According to Rodrigues et al. (2020),  
211 in São Paulo, 12% of smartphones are broken beyond economical repair, which was adopted.

212 The market depreciation curve for Samsung smartphones identified by Makov et al.  
213 (2019) determines the fraction of available used smartphones commissioned into second use  
214 following the average age of available used EEE after eventual rejuvenation through repair –  
215 see Appendix Figure 9 . The depreciation curve determines the average share of value  
216 preserved considering launch and resale of smartphones (Makov et al., 2019) and thus, the  
217 fraction of smartphones that hold value for a reuse transaction. The original depreciation  
218 curve was normalised to the Brazilian case. The reuse market coverage was considered as

219 100%, meaning country-wide coverage as web-based applications and local markets are  
 220 widespread.

221 **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

222 More than 25,000 technical assistance workshops are reported country-wide in Brazil,  
 223 holding a capillarity similar to retail (ABDI, 2012). We assumed third party repairing cover  
 224 80% of the adopters. The working conditions, access to product information and to spare  
 225 parts only enable a few services: broken screen replacing, parts exchange, phone resetting,  
 226 and other minor tweaks. We assumed an average rejuvenation of 20%. In Brazil, only 20% of  
 227 the smartphones owners try to repair the products after a use cycle (IDEC, 2013). The

228 average time in reuse was assumed as 40% longer than the average time in first use, as  
229 products in reuse achieve longer general lifetimes among São Paulo citizens (Rodrigues et al.,  
230 2020). The expected age of reuse EEE is, thus, of 3.64 years when decommissioning.

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

### 240 3.2.2 Developing scenarios for EEE collection interventions

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

252 **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

253 For the coverage increase per year, the BIAEEE’s implementation plan provides a list of  
 254 municipalities to be covered with collection points from 2021 to 2025 by state (MMA et al.,  
 255 2019, Annex VII). Following the most populous municipalities in each state, the collection  
 256 system should cover 58% of the Brazilian population, or 127 million people, by 2025,  
 257 meaning an average increase of 25 million people coverage per year. Such average increase  
 258 denoted a fast coverage increase. 12.5 million people/year denoted a slow coverage increase  
 259 for comparison.

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

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

### 274 3.2.3 Developing a test bench to examine the BIAEEE targets

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

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

292 system. The structure of the test bench created and the variables equations used are available  
293 in Figure 12 and Table 5 in the Appendix.

## 294 **4 Simulation results**

### 295 **4.1 *The material and EEE stocks and flows of smartphones in Brazil***

296 The critical material and EEE stocks and flows for the baseline scenario were obtained  
297 from model use. Figure 3.a presents the behaviour of the stocks of EEE in units. Large  
298 numbers of idle products, either hibernating in users' homes or available for the reuse and  
299 recycling markets are expected. More than 55 million smartphones will hold the status of  
300 "*Available used EEE*", and more than 25 million smartphones will hold the status of  
301 "*Hibernating EEE*" to sustain almost 147 million smartphones in use around 2030. This  
302 scenario of a high number of idle products while few in second use happens because the  
303 fraction of people that engage in the reuse market is still low, there is limited restoration  
304 capability from the repairing infrastructure, and the average time in second use becomes a  
305 fraction of the first use. "*Hibernating EEE*" and "*Available used EEE*" are an opportunity  
306 for the reuse and reconditioning markets. The maximum value for "*Reuse EEE*" is 1.25  
307 million smartphones, which decreases through time as the fleet gets old. The amount of "*EEE*  
308 *collected for treatment*" is stable at around 1.1 million smartphones, following the continuous  
309 process of collecting and sorting.

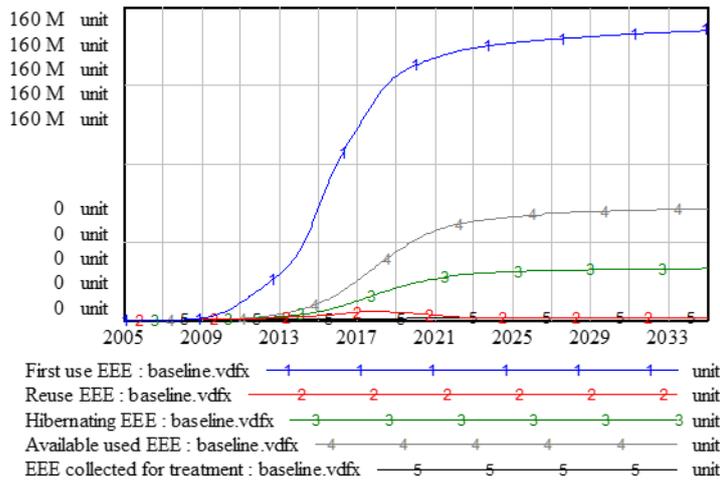


Figure 3.a – EEE stocks in the baseline scenario in unit

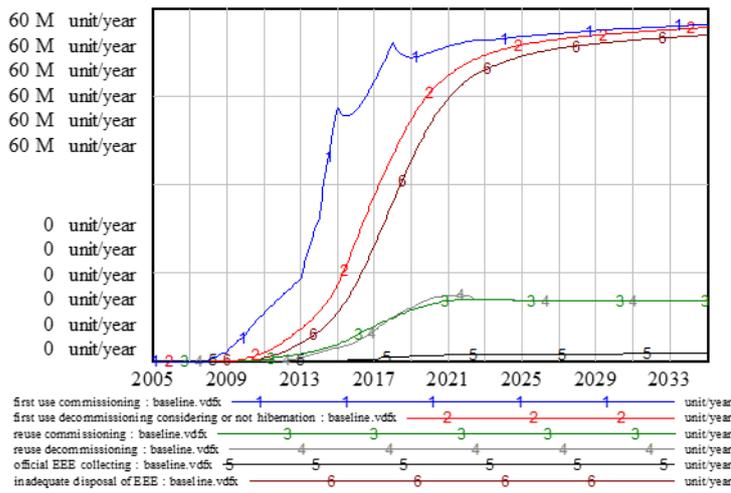


Figure 3.b – EEE flows in the baseline scenario in unit/year

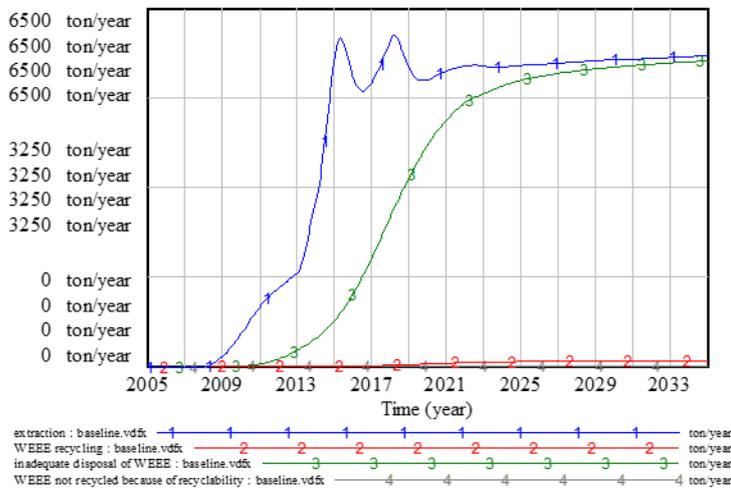


Figure 3.c – Material flows in the baseline scenario in ton/year

310

311

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

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

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

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<sup>2</sup> 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.

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

338 This baseline scenario enables examining the implementation of CE interventions.

#### 339 **4.2 The effects of EEE collection interventions**

340 Figure 4 shows critical flows that demonstrate the effects of the twelve scenarios.  
341 Official EEE collection (Figure 4.b) enables decreased material extraction (Figure 4.a) and  
342 decreased inadequate disposal of EEE (Figure 4.c). Scenario 1 led to the least significant  
343 values for official EEE collection, while Scenario 12 (C) leads to the most significant values  
344 for official EEE collection. In scenario 1, holding slow coverage increase and low  
345 distribution density of collection points with no reward, approximately 8.71 mi unit/year or  
346 871 ton/year of smartphones is collected for official recycling in 2035. In scenario 12, (C),  
347 holding fast coverage increase and high distribution density of collection points with rewards,  
348 approximately 50.73 mi unit/year or 5073 ton/year of smartphones is collected for official  
349 recycling in 2035. Scenario 7, which is the most likely scenario if we consider the BIAEEE  
350 document, reaches the second-worst mark in the long run – 11.27 mi unit/year or 1127  
351 ton/year of smartphones collected. In general, a centralised collection system – scenarios 1, 2,  
352 7, and 8 – led to the worst results. On the other hand, scenarios that offered a reward led to  
353 the best results – scenarios 12 (C), 10 (A), 6, and 8. Scenario 11 (B) was an exception, as it  
354 presents good results without offering a reward.

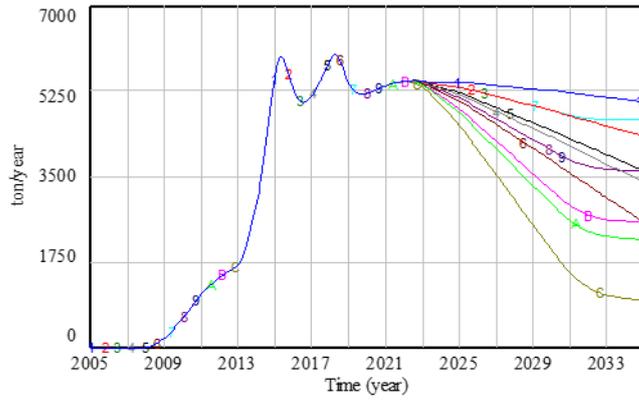


Figure 4.a – Material extraction (in ton/year)

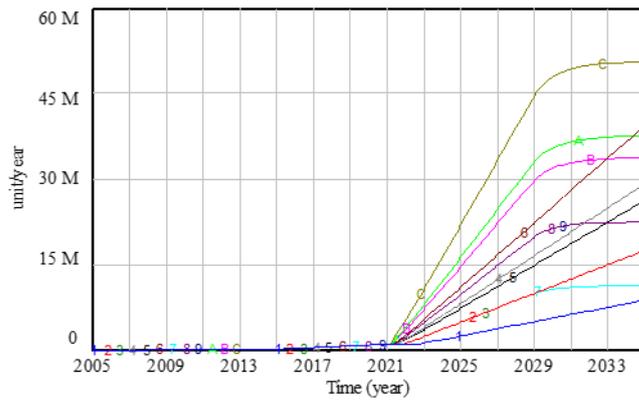


Figure 4.b – Official EEE collecting (in ton/year)

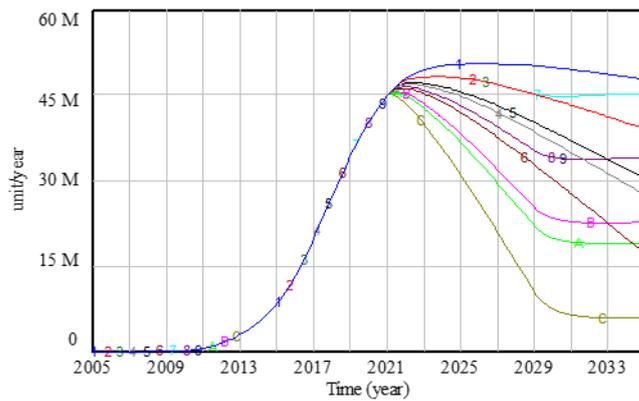
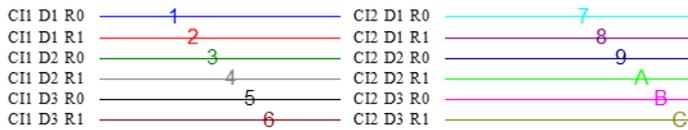


Figure 4.c – inadequate disposal of EEE (in unit/year)



355

356 **Figure 4** – Critical flows demonstrating the effects of CE implementation in the baseline

357 scenario and in scenarios 1, 2 and 3

358 With a centralised collection system (one collection point per 25,000 people), it is  
359 expected that each collection point will receive up to 2,413 smartphones per year by 2025 in  
360 scenarios 2 and 8. Although a community collection system (one collection point per 1,000  
361 people) leads to relevant collection of EEE, it is necessary to consider the implementation  
362 and maintenance of 1 million collection points by 2025 to enable that system in scenarios 11  
363 (B) and 12 (C), holding the lowest values for average collection per collection point –  
364 reaching 14.48 smartphones per collection point per year in 2025 in scenario 11 (B).  
365 Scenarios 8 and 10 (A) reach high values for EEE collection relying on fewer collection  
366 points to function – 4,000 and 10,000 collection points respectively. Both scenarios, however,  
367 rely on a reward system that can also influence the total cost of the system due to reward-  
368 associated costs. In this sense, scenario 9 appears as an option that can lead to decent results  
369 with a lower collection cost, since the number of collection points is intermediate, and there  
370 is no associated cost of rewards. However, in this scenario, the collection capacity reaches a  
371 limit at an intermediate level of EEE collection as early as 2030. Table 6 in the appendix  
372 shows the total number of collection points and average collection rate achieved by them in  
373 2025 for the twelve scenarios, enabling further analyses of costs and benefits of the potential  
374 interventions.

### 375 **4.3 Reaching the BIAEEE targets**

376 Figure 5 shows that only scenario 12 (C) reached the BIAEEE targets on time (see  
377 Figure 5.a), represented by the second curve number 1 (blue), by collecting 21.72 million  
378 smartphones/year in 2025. The 17% threshold curve, represented by the second curve number  
379 2 (red), demonstrate the moment that each scenario reaches the target set to 2025 in the  
380 BIAEEE. While scenario one does not reach that threshold until 2035, scenario seven only  
381 does so in 2032, when the reverse logistics system collects 11.09 million smartphones/year.

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

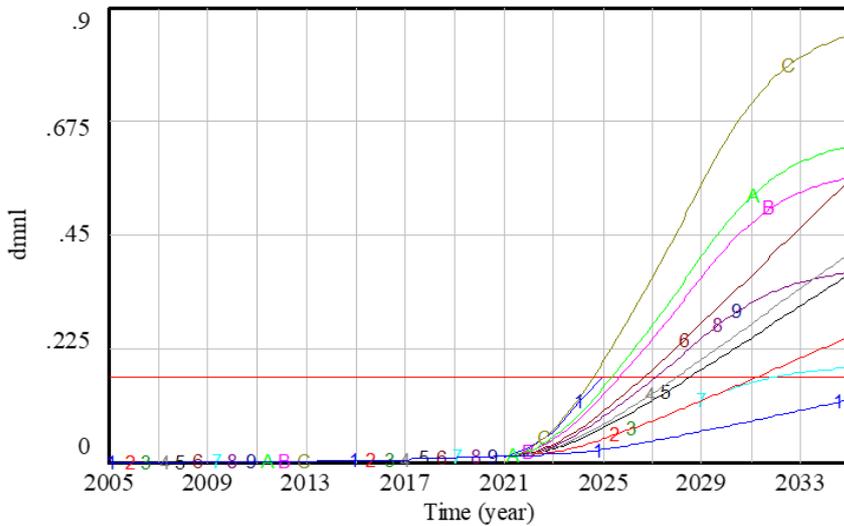


Figure 5.a – Ratio of material treated considering the last 2.6 years (dimensionless)

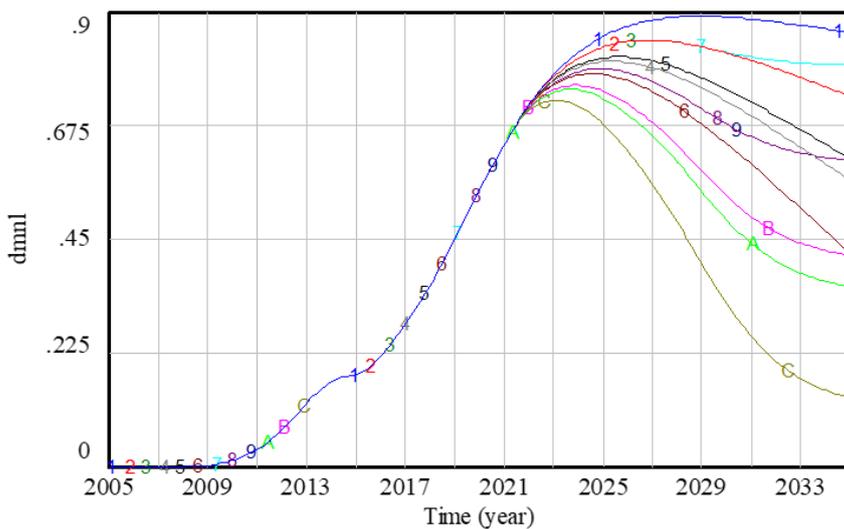
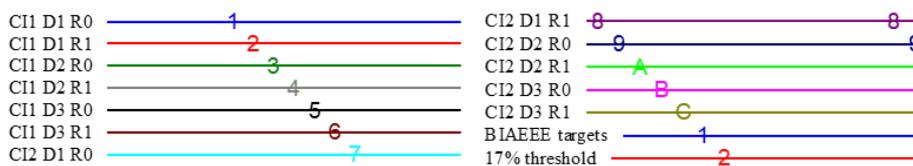


Figure 5.b – Ratio of material lost considering last 2.6 years (dimensionless)



386

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

## 389 5 Discussion

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

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

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

## 413 **5.1 Recommendations for the implementation of the BIAEEE**

414 The trade-offs in the choices that influence the capillarity of the system and customer  
415 engagement are essential aspects to enable a reverse logistics system that meets the BIAEEE  
416 targets. For low-density distribution of collection points, a network of electronics retailers  
417 and mobile carrier stores can sustain the reverse logistics system. It is a possibility for a  
418 collection system with high coverage in a short time. On the other hand, greater distance and  
419 less convenience should lead to limited consumer adherence. Furthermore, the growing  
420 online purchases of mobile devices in the country (from 15.1% in 2014 to 27.4% in 2019  
421 (Euromonitor International, 2019)) reinforces the limit of far collection, as people go less and  
422 less to commercial centres. Also, retailers will need to manage the collection of more than  
423 100 smartphones per month on average, which is an additional operational requirement and  
424 an opportunity to maintain relationship to customers. Bai et al. (2018) reports potential  
425 positive effects in sales from EEE collection activities.

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

433 The scenarios with rewards showed promising results. Stakeholders involved in the  
434 design and implementation of BIAEEE should consider rewards systems for meeting the  
435 targets. Financial, environmental and social incentives (Shevchenko et al., 2019) can be used

436 to influence the donor of used EEE. Alternative reward systems may optimise the relationship  
437 between EEE collecting and systemic costs.

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

449 A final recommendation concerns the scope of the instruments contained in the BIAEEE.  
450 The industrial agreement can promote the alignment and action of the various stakeholders to  
451 enable better results of collection and treatment in the Brazilian EEE industry. However, the  
452 results presented in this article demonstrate that only recycling presents limited results for  
453 decelerating resource flows. In a proactive path for Future WEEE scenarios, Parajuly et al.  
454 (2019) recommend products designed for longer lifetime, service-oriented business models,  
455 reward-based schemes, among other initiatives. The BIAEEE signed in 2019 should be  
456 considered a first wave of policy implementation to allow a Circular EEE industry in Brazil.  
457 Following waves of the BIAEEE could provide instruments – targets, market incentives –  
458 that promote other forms of decelerating the flow of resources and thus, the impacts of the  
459 EEE industry.

## 460 5.2 *The use of modelling and simulation to governing the BIAEEE implementation*

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

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

481 Forti et al. (2018) argue that data from post-use EEE collection are essential sources to  
482 trace WEEE. Survey and census data about post-use EEE for a region can be scaled up to the  
483 national level (Kumar et al., 2017). Analyses of waste streams sorting in collection points,

484 consolidation centres or recycling plants are appropriate instruments to collect lifetime data  
485 (Prakash et al., 2015). Each collection and treatment point is a potential source for a survey  
486 system for continuously assessing the status of the collection and treatment system. Company  
487 shares of mobile phones sales in the country (Euromonitor International, 2019) may  
488 determine the share of each company to reach BIAEEE the targets. Meeting the share of  
489 BIAEEE targets is verifiable using the unique serial number contained in the central module  
490 of the products.

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

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

### 508 5.3 *Contributions and further research avenues*

509 The process of adapting the model, the results and discussions contribute to theory and  
510 practice. To **theory**, this work provides a case of modelling and simulation to examine future  
511 stocks of EEE and WEEE in different scenarios of implementation of CE interventions. The  
512 adapted model is one level below global or regional WEEE estimates (see Cucchiella et al.,  
513 2015; Ongondo et al., 2011; Zoeteman et al., 2010) and close to the nation-wide model for  
514 forecasting specific EEE flows (see Forti et al., 2018; Wang et al., 2013). The model present  
515 two critical features: (1) the ability to cope with the three types of purchases – adoption,  
516 additional and replacing, allowing more adequate prospects when examining future EEE and  
517 WEEE stocks comparing extrapolation of time series and of surveys (see Abbondanza &  
518 Souza, 2019), and (2) the ability to examine the potential effects of CE strategies.

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

529 The central contribution to **practice** is the possibility to use modelling and simulation to  
530 inform decision-making in the implementation of CE interventions through public policies.  
531 Policies to manage post-use EEE are under continuous adoption across the globe, and

532 countries and regions should be prepared to implement them. It is possible to examine under  
533 what conditions CE interventions are sufficient to achieve policy targets and discuss manners  
534 to reach that desirable state. The available model combined with the adaptation process  
535 detailed in this document allows other researchers and practitioners to examine other EEE  
536 products and instruments that enable public policies.

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

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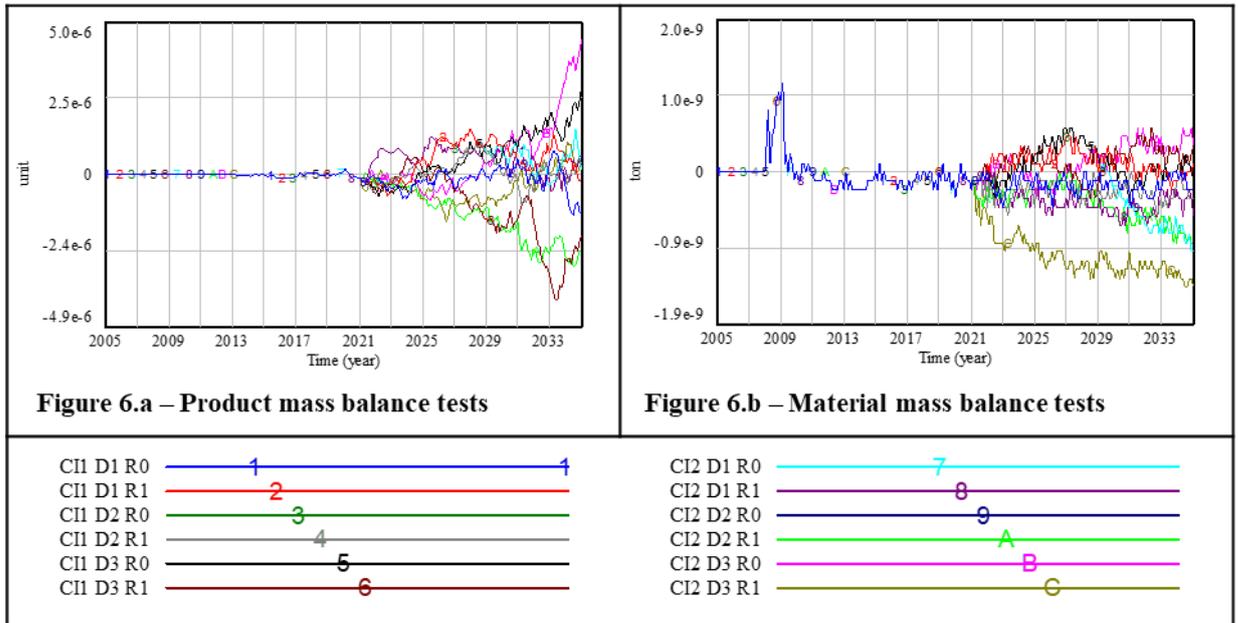
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760 **8 Appendix**



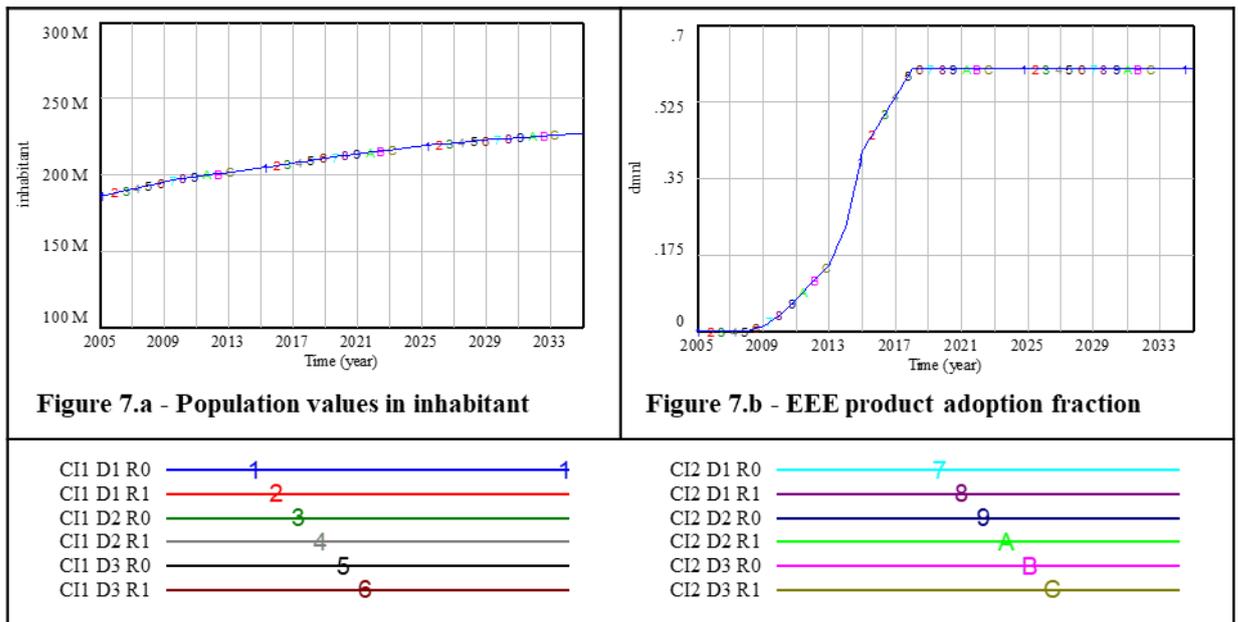
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**Figure 6 – Product and material mass balance tests in all scenarios, showing that no product or**

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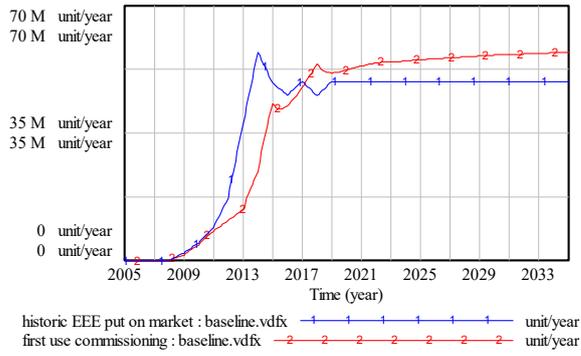
material was “lost from the system” due to model structure and equations.



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765

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

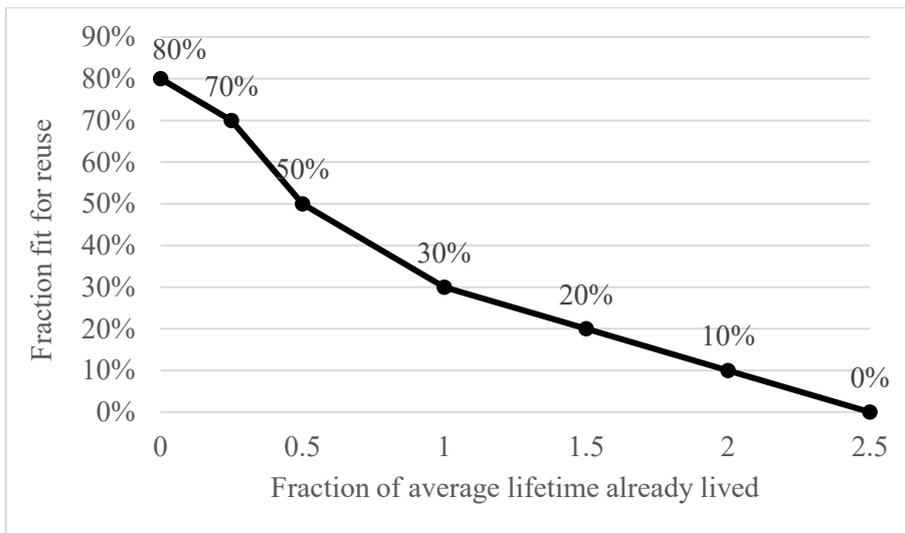


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767 **Figure 8** – Calibration results of first use commissioning and historical data from IDC (2019).

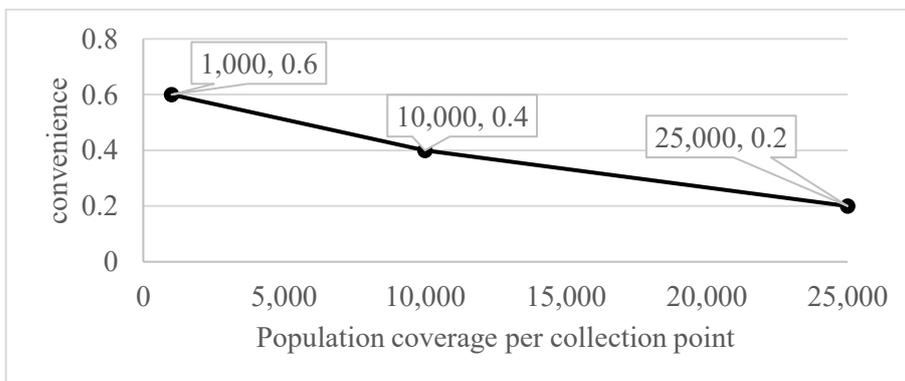
768 The similar behaviour and order of magnitude from the two curves demonstrate the calibration from

769 calculated to real data.



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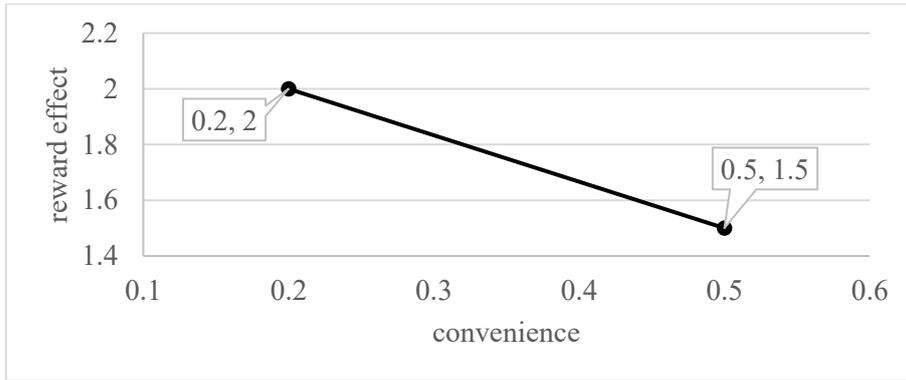
771 **Figure 9** – Values adopted for reuse commissioning. Adapted from Makov et al. (2019)



772

773 **Figure 10** – Convenience of EEE reverse logistics system considering the population coverage

774 per collection points with no rewards



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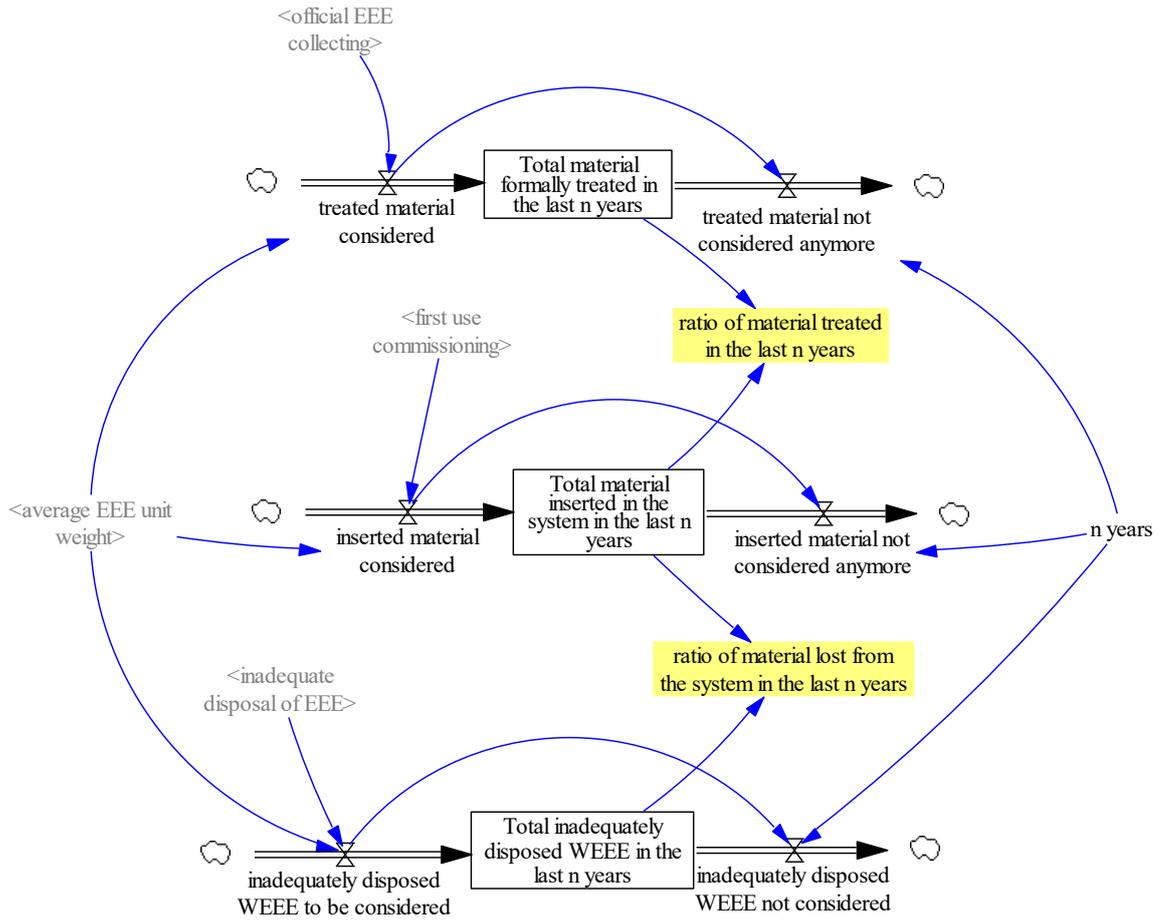
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**Figure 11** – Reward effect considering the EEE reverse logistics system convenience

777

**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%



778

779

**Figure 12** – Test bench created to examine the BIAEEE targets

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

781 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

 782 **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

783