DANIEL GUZZO

# A system view on Circular Economy transitions: examining the deceleration of resource flows

PhD Thesis

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# Uma visão de sistemas para transições de Economia Circular: examinando a desaceleração do fluxo de recursos

Versão definitiva

Tese apresentada à Escola de Engenharia de São Carlos da Universidade de São Paulo para a obtenção do título de Doutor em Ciência

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Definitive version

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Research Area: Processes and Operations Management

Promoter: Janaina Mascarenhas

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# RESUMO

Guzzo, D. (2020). *Uma visão de sistemas para transições de Economia Circular: examinando a desaceleração do fluxo de recursos* [Tese de doutorado, Escola de Engenharia de São Carlos da Universidade de São Paulo]

Uma Economia Circular (EC) somente poderá ser alcançada pela transição de sistemas de consumo e produção para modos aprimorados de uso de recursos. A desaceleração dos fluxos de recursos e a apreciação das relações de feedback entre os sistemas econômicos e terrestres são necessários em tais transições. O pensamento sistêmico está no centro das transições de EC. No entanto, crescente complexidade emerge dos sistemas de EC e as ferramentas disponíveis atendem de forma insuficiente às necessidades de experimentação dos tomadores de decisão nas transições de EC. Esta tese visa resolver a seguinte questão de pesquisa: *"Como uma abordagem de sistemas pode ajudar a compreender e facilitar as transições de EC?*". Neste sentido, dois objetivos complementares foram definidos: um objetivo teórico de interpretar as transições de EC através de uma perspectiva de sistemas e um objetivo prático de gerar ferramentas para facilitar a tomada de decisão em transições de EC. A execução de seis pacotes de trabalho permite responder à questão geral de pesquisa e aos objetivos complementares. Conceitos-chave dos campos de pesquisa de EC, ecologia industrial, transições de sustentabilidade e Dinâmica de Sistemas (DS) sustentam os fundamentos da tese. Modelagem e simulação utilizando DS conecta os esforços descritivos e prescritivos nesta tese por meio de três estudos de modelagem e simulação para examinar casos de diferentes escopos: a adoção de uma plataforma de compartilhamento por uma empresa, a implementação de estratégias de EC em todo um país (Holanda) para um tipo de equipamento eletro-eletrônico (EEE), e implantação de intervenções de coleta de *smartphones* pós-uso para atendimento às metas do acordo industrial brasileiro de EEE. Cada estudo resulta em um artigo que compõe a tese. Os três estudos permitem a proposição de um modelo conceitual para sistemas de CE, de uma ferramenta de acesso aberto para examinar os sistemas de CE (o modelo DS para EEE Circular), de diretrizes para para examinar as transições de EC usando DS e a discussão de potenciais insights para profissionais de negócios e formuladores de políticas públicas ao aplicar uma abordagem de sistemas para examinar sistemas com diferentes escopos. Os resultados aqui apresentado permitem decisões e discussões cruciais para viabilizar a desaceleração urgente dos fluxos de recursos nos sistemas de consumo e produção. Esta tese contribui para a teoria e para a prática, esclarecendo o significado e o papel de uma abordagem de sistemas para permitir transições de EC.

**Palavras-Chave:** Economia Circular; pensamento sistêmica, transições em sustentabilidade; inovação em negócios; políticas públicas

# ABSTRACT

Guzzo, D. (2020). *A systems view on Circular Economy transitions: examining the deceleration of resource flows* [Doctoral thesis, School of Engineering of São Carlos at the University of São Paulo]

An envisioned Circular Economy (CE) can only be achieved by the transition of consumption and production systems to enhanced modes of resource use. The deceleration of resource flows and appreciation of feedback relationships among the economic and Earth systems are essential to such transitions. Systems thinking is, thus, at the core of CE transitions. However, increasing complexity emerges in CE systems and available tools insufficiently address the experimenting needs of decision-makers in bottom-up and top-down CE transitions. This thesis aims at resolving the following general research question "*How can a systems approach help decision-makers to understand and facilitate CE transitions?*". In this regard, two complementary goals were defined: a theoretical goal of interpreting CE transitions through a systems perspective, and a practical goal of generating tools to facilitate decision-making in CE transitions. The fulfilment of six work packages permits responding to the general research question and complementary goals. Key concepts from the CE, industrial ecology, sustainability transitions, and System Dynamics fields sustain the foundations of the thesis. Modelling and simulation using System Dynamics (SD) bind the descriptive and prescriptive efforts in this thesis through three modelling and simulation studies to examine cases of different scopes: the adoption of a sharing platform by one company, the implementation of nationwide CE strategies implementation for a type of electrical and electronic equipment (EEE) in the Netherlands, and the implementation of collection interventions for post-use smartphones to meet the targets of the Brazilian industrial agreement for EEE (BIAEEE). Each study results in an article that composes the thesis. The three studies enable the proposition of a conceptual model for CE systems, of an open-access tool to examine CE systems (the Circular EEE SD model), of guidelines for examining CE transitions using SD, and discussion of potential insights for business practitioners and policy-makers when applying a systems approach in examining systems with different scopes. The results allow for crucial decisions, and discussions to enabling the urgent deceleration of resource flows in consumption and production systems. This thesis contributes to theory and practice by clarifying the meaning and role of a systems approach to enable CE transitions.

**Keywords:** Circular Economy; systems thinking; sustainability transitions; business innovation; public policy

# LIST OF PAPERS IN THIS PhD THESIS

## Paper 1

Guzzo, D., Jamsin, E., Balkenende, R., & Costa, J. M. H. (in-press). The use of System Dynamics to verify long-term behaviour and impacts of circular business models : a sharing platform in healthcare. In N. Nissen & M. Jaerger-Erbens (Eds.), *PLATE Product Lifetimes And The Environment 2019*. TU Berlin University Press.

## Paper 2

Guzzo, D., Rodrigues, V. P., & Mascarenhas, J. (in-press). A systems representation of the Circular Economy: Transition scenarios in the Electrical and Electronic Equipment (EEE) industry. *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2020.120414

## Paper 3

Guzzo, D., Rodrigues, V. P., Pigosso, D.C.A & Mascarenhas, J. (2020). Analysis of national policies for Circular Economy transitions: Modelling and simulating the Brazilian industry agreement for electrical and electronic equipment. Manuscript submitted for publication.

# LIST OF SUPLEMENTARY PAPERS (NOT INCLUDED IN THIS PhD THESIS)

## Paper 4

Guzzo, D., Trevisan, A. H., Echeveste, M., & Costa, J. M. H. (2019). Circular Innovation Framework: Verifying Conceptual to Practical Decisions in Sustainability-Oriented Product-Service System Cases. *Sustainability*, *11*(12), 3248. https://doi.org/10.3390/su11123248

## Paper 5

Guzzo, D., Carvalho, M. M., Balkenende, R., & Mascarenhas, J. (2020). Circular business models in the medical device industry: paths towards sustainable healthcare. *Resources, Conservation and Recycling*, *160*(April), 104904. https://doi.org/10.1016/j.resconrec.2020.104904

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# LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| BIAEEE | Brazilian industrial agreement for electrical and electronic equipment |
| BOL | Beginning of life |
| CE | Circular Economy |
| CLD | Causal loop diagram |
| DRM | Design Research Methodology |
| EEE | Electrical and electronic equipment |
| EOL | End of life |
| MOL | Middle of life |
| SD | System Dynamics |
| SFD | Stock and flow diagram |
| WEEE | Waste of electrical and electronic equipment |

# SUMMARY

# 1 INTRODUCTION

The Circular Economy (CE) concept emerges in the face of extraordinary challenges in decoupling economic growth from the use of resources and generation of emissions. CE systems should be carefully designed to address the mass-value-carbon tension through the systematic use of strategies to decelerate the flow of resources while maintaining or increasing access to goods and services. Transitioning to these enhanced systems involves doses of systemic thinking to enable making decisions that are consistent with the increasing complexity in CE systems and the need to improve the effectiveness of resource use. Knowledge from the System Dynamics, industrial ecology, sustainability transitions, and other fields, are investigated and applied in practice to develop tools that can help business practitioners and policymakers in this path of decelerating resource flows.

This research thesis was designed as article-based and follows with additional background information that connects, sustains and discusses the articles. The Introduction section starts by detailing the theoretical foundation that leads to the definition of two research gaps. A general research question enables inquiring paths for resolving the identified gaps. Two complementary research goals, a theoretical and a practical one, directs the research efforts to contributing to academia and to practice. The research methodology details six work packages holding specific sets of objectives, questions, methods, and outcomes with scoping, descriptive and prescriptive aims. The six work packages lead to the research plan, three articles, and additional results contained in this thesis. The main research field delimiting inquiry and support in this thesis are defined, clarifying the scope of the investigation. Justifications of the worthwhileness of this research to academia and practice are discussed. Finally, the structure of the thesis prepares the reader for the next sections.

## 1.1 Theoretical foundation and research gaps

Transformations in the environment present clear relations to human activities, which are widely more intense since the 1950s (Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015). Researchers argue that we are in a new geological era - the Anthropocene - in which humankind is the primary source of impact on the Earth systems (Rockström, Steffen, Noone, Persson, & Chapin III, 2009). Overcoming the value-carbon-mass nexus, where economic progress is tightly connected to material extraction and greenhouse gas emissions, is a critical challenge to achieve a desired sustainable state (Wit et al., 2019). If the Earth systems cannot handle the impacts performed by human activity, the impacts on society, organisations and individuals will certainly be devastating.

“The linear structure of the industrial economy” (Stahel, 1997) is perhaps the leading cause of the dependence among value creation and the negative impacts on Earth. The linear economy model of consumption and production, based on a “take-make-dispose” paradigm, dedicates little attention for ecological and social impacts of economic activity, commonly treated as externalities of the industrial system (Lacy & Rutqvist, 2015; Sauvé, Bernard, &

Sloan, 2016). This mindset sustaining the linear structure of consumption and production systems is an example of open-loop thinking, which fails to consider mutual relations of cause and effect between the economic and Earth systems. Open-loop thinking is insensitive to potential non-linearities in causal relationships and leads to unrealistic simplifications of how systems work (Lane, 1994; Sterman, 2000).

The CE is envisioned as a consumption and production paradigm opposite to the linear economy (Kalmykova, Sadagopan, & Rosado, 2018; Murray et al., 2015), a promising industrial model to achieve a future scenario of abundance (Blomsma & Brennan, 2017), which is capable of breaking the mass-value-carbon nexus (Wit et al., 2019), and serve as a path towards sustainable development capable of benefiting current and future generations (Kirchherr, Reike, & Hekkert, 2017). Meadows (1999) defines paradigm as shared social agreements of reality, which defines goals, feedbacks and structure of the system. They hold high leverage as paradigm shifts can completely transform systems.

Ideally, in a circular economy system, additional resource input and leakage of waste and emissions to maintain a specific consumption and production system are minimised or reduced to zero (Ellen MacArthur Foundation, 2012; Geissdoerfer, Savaget, Bocken, & Hultink, 2017). For the harmonisation of consumption and production systems, a separation is made between the technical and biological cycles (Ellen MacArthur Foundation, 2012) since the processes of both cycles hold different frequencies and, when poorly designed, the technical system causes detrimental effects to biological systems (Braungart, Mcdonough, & Bollinger, 2006). It also involves “designing out waste” and understanding “waste as food” in both biological and technical cycles (Ellen MacArthur Foundation, 2012).

CE systems rely on the systematic application of circular strategies, which narrow, close and slow the flows of resources to enable an overall deceleration of these flows along with positive economic impacts (Bocken, de Pauw, Bakker, & van der Grinten, 2016; Geissdoerfer et al., 2017). Sharing, servitisation, maintenance provision, designing for optimal lifespan, industrial symbiosis, and use of renewable resources are among such strategies (Guzzo, Trevisan, Echeveste, & Costa, 2019). The systematic use of strategies aims to maximise the value of resources in use at all stages of the value chain, starting with the attitudes of users (participants in technical cycles) and consumers (participants in biological cycles) of these systems. Kalmykova et al. (2018) names the search for maximising the value of resources in use as the stock optimisation principle.

CE systems occur at different levels: micro-, meso-, and macro- (Ghisellini, Cialani, & Ulgiati, 2015; Kirchherr et al., 2017; Su, Heshmati, Geng, & Yu, 2013), which determine specific characteristics and patterns of change:

- Micro-level CE systems: change happens within a single organisation, household or individual. The focus is on the perspective of product, firm and consumer-centric changes (Kirchherr et al., 2017). Eco-design and cleaner production techniques are used to improve design and manufacturing of products focusing on reducing the environmental footprint of products (Ghisellini et al., 2015; Sauvé et al., 2016; Su et al., 2013). Labelling systems employed to influence individuals' behaviour and recollection of post usage resources are also micro-level initiatives (Ghisellini et al., 2015).

- Meso-level CE systems: change happens within groups of organisations in geographic proximity. The focus is on the symbiotic associations among system actors for sharing resources (Kalmykova et al., 2018; Sauvé et al., 2016). The development of eco-industrial parks and eco-agricultural systems are meso-level change (Su et al., 2013). Urban symbiosis e eco-cities, which rely on the opportunities of geographic proximity for waste management and sharing of resources (Ghisellini et al., 2015; Su et al., 2013), are also considered meso-level CE systems in this research1. Material, water, energy, and available infrastructure are among the resources shared among organisations (Ghisellini et al., 2015; Su et al., 2013).
- Macro-level CE systems: change happens in whole industries, regions or nations. The focus is on the global or national regions, considering whole production and consumption systems (Kirchherr et al., 2017). Industries such as housing, mobility, nutrition, clothing, electronics, among others are some of the value chains playing a crucial role in the transition to a Circular Economy since they represent essential societal needs while incurring large footprints globally (de Wit, Verstraeten-Jochemsen, Hoogzaad, & Kubbinga, 2019; Winans, Kendall, & Deng, 2017). At this level, the representation of consumption and production becomes integrated, encompassing the processes and interests of complex networks of actors (Sauvé et al., 2016; Su et al., 2013).

Figure 1-1 details the relationship between the three CE Systems levels and relevant aspects for the representation and understanding of these systems. The three aspects – the potential for impact, aggregation of change, and level of detail – represent a continuum to be used as a rule of thumb to address the study of CE systems. Change reaching higher system levels bring more significant potential for positive impact (Ceschin & Gaziulusoy, 2016). Systems in the macro-level are approached through a higher aggregation, where several aspects of change are grouped or considered as a whole (Borshchev & Filippov, 2004). Therefore, a lower level of detail is used to represent system elements and relationships among them (Borshchev & Filippov, 2004). When dealing with the micro-level, these aspects will most likely be positioned at the opposite limit of the rulers.

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[1] In the works developed by Ghisellini et al. (2015) and Su et al. (2013), Urban Symbiosis and Eco-cities are classified as macro-level CE systems. In this thesis, they are positioned as examples of the meso-level based on the argument that they considered change in a specific region (China) and that the discussion of transitioning entire consumption and production systems as plastics, food, fashion, and others was not in place at that time. Thus, I argue that positioning Urban Symbiosis and Eco-cities in the meso-level more adequately represents the current discussions in the Circular Economy literature.

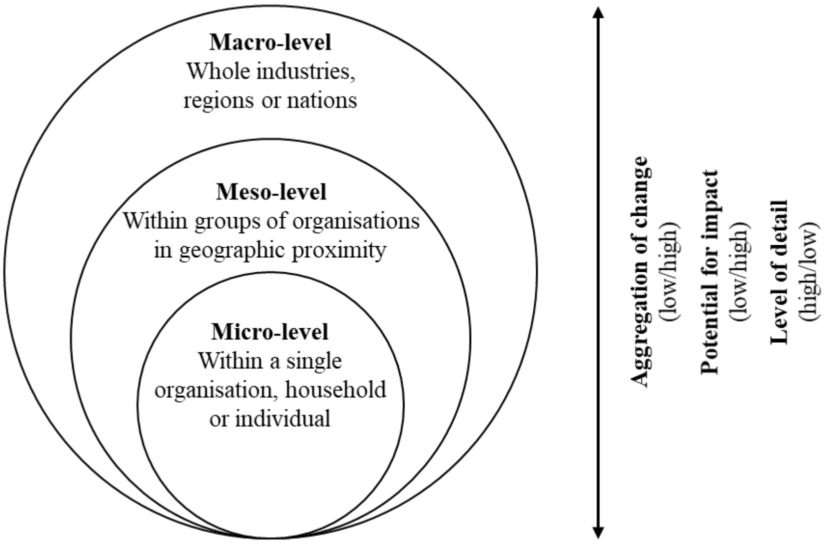

**Figure 1-1** – The three levels of CE System and relevant aspects for system understanding

Based on the characterisation, a definition for CE systems is following presented.

> *CE systems are consumption and production systems occurring in multiple levels: micro-, meso-, and macro-, that achieve enhanced positive effects to the contiguous natural and societal systems via the deceleration of the flow of resources.*

Thinking in systems (Ellen MacArthur Foundation, 2012) is at the core of CE as it relies on a paradigm shift in individuals, institutions and organisations towards a system that appreciates the causal loops between the economic and Earth systems to design more effective consumption and production systems occurring in multiple levels. Closed loops and flows are commonly embedded in CE systems definitions, and the definition provided by the Ellen MacArthur Foundation is likely the one responsible for setting the systems perspective into the core of CE discussions (Kirchherr et al., 2017). In the direction of clarifying the meaning of systems thinking for the CE concept, Webster (2013) presents a "systems language", i.e. the definition of critical concepts as feedback, resilience, effective, metabolism, and inflexion point to understand the CE through a systems perspective. Velte and Steinhilper (2016) present a list of factors of complexity that emerge from Circular Economy systems. In the closed-loop supply chain research field, Peng et al. (2020) performed a systematic review of the causes of uncertainties in the different stages: from extraction to consumption and back through repair, remanufacturing and recycling. Although stocks, flows, feedback loops and leverage points are general terms in the CE literature, still few researches strive to clarify the meaning of systems thinking, making the concept unclear and debatable in the CE literature.

More than understanding the meaning, it is crucial to empower decision-makers to deal with the increasing complexity of CE systems. Velte and Steinhilper (2016) call for the need for tools that help to reduce the uncertainty and risk perceived by decision-makers. This demand goes hand-in-hand to Linder and Williander (2015) findings, which point to inherent uncertainties in circular innovation, and that entrepreneurs need tools to reduce long term uncertainty. Hopkinson et al. (2018), too, mention the need for "tools to manage complex system dynamics and to anticipate future scenarios" in managing CE business models. However, most tools for circular innovation still have a static view of the system, capable of representing an image of the system in a moment in time (Pieroni, McAloone, & Pigosso, 2019). The CE field has an urgent need for tools to examine CE strategies configurations to enable learning about the options (Blomsma & Brennan, 2017) and permit the operationalisation of the CE concept (Geisendorf & Pietrulla, 2018). Conversely, Videira and Rouwette (2020) demonstrate System Dynamics (SD) favours the development of CE systems because it allows seeing the world as collections of the stock-and-flow structures and enables determining policies to influence the inflows and outflows of stocks. In this way, SD becomes a powerful approach to understand and facilitate decision making in CE systems.

There are a few SD modelling and simulation applications in the CE and surrounding fields that show the potential of that approach in dealing with the increasing complexity of CE systems. Asif, Lieder and Rashid (2016) applied a multi-method approach combining agent-based modelling (ABM) and SD to grasp the economic and environmental performance of circular solutions comprising the business model, product, and operations levels. Later on, Lieder, Asif and Rashid (2017) expanded the model further, considering the customers' behavioural changes to adopt a circular solution to determining pricing and marketing strategies. Franco (2019) provides an SD-based simulation model to examine the implementation of circular product design and business model initiatives and examine the combinations of circular strategies by a single firm. Gloser-Chahoud et al. (2019) provide a simulation model capable of investigating how modifications in products' lifetime and hibernation may influence the need for small consumer electronics as mobile phones, smartphones, tablets and laptops in Europe. Pinto and Diemer (2020) examine scenarios for the implementation of supply chain integration strategies in the European steel industry and the effects in iron ore consumptions. Modelling and simulation initiatives within the CE scope hold the potential to facilitate decision making in the scope of a single firm to national and supra-national circumstances.

The prevailing static approach to understanding the phenomenon deals superficially with the dynamic complexities of CE systems and fail to capitalise on the interfaces with systemic approaches. On the other hand, there are some studies using modelling and simulation to deal with uncertainties, evidenced by the increased use of SD to investigate potential behaviours of those systems under the implementation of CE strategies. New theories and tools should make it possible to clarify the systemic aspects of CE systems, and allow decision making based on long-term scenarios of the use of resources that consider the causal relationships that arise when seeking to decelerate the flow of resources. The distance between the needs for decision making in CE systems and tools available paves the way for the first research gap:

**Research gap 1:** Increasing complexity emerges in CE systems, in the face of poor understanding for the sources of complexity and lack of tools to manage them.

In addition to managing dynamic complexities emerging from the deceleration of the stock-and-flow structures in CE systems, a few critical aspects emerge when we consider the transition from linear to circular systems: the change, comparative, and directional aspects. The change aspect encompasses the necessary shifts to achieve the improved modes of consumption and production. Researchers commonly state that CE systems should build upon the dominant linear models while seeking for economic, environmental and social prosperity (Kirchherr et al., 2017; Murray et al., 2015; Sauvé et al., 2016). In other words, the socio-technical regime – the locus for established practices, culture, and institutions (Geels, 2011) – is linear, and the CE transition depends on forming a new regime based on the CE principles and a transition path from the status quo. The change aspect of CE transitions positions linear systems (as-is) to be replaced and helps to determine could-be CE systems.

The comparative aspect indicates that given system compositions can lead to better possibilities for the use of resources and generation of emissions than others. To avoid incremental change under the linear economy paradigm, it is desirable to defining a future state vision for a given CE system and directing short- and medium-term action (Gorissen, Vrancken, & Manshoven, 2016). In ideal states of consumption and production systems, the access to products and services can be decoupled entirely from the inflow of resources and outflow of waste and emissions (Kjaer, Pigosso, Niero, Bech, & McAloone, 2019). Such ideal states are worth pursuing visions that permit identifying synergies for long-term collaboration towards fundamental shifts in the consumption and production system (Brown, Bocken, & Balkenende, 2019). Seeking for ideal states hold the potential of demonstrating to decision-makers the real possibilities of change within the scope of the system under investigation and thinking of options to bridging the gap among the future vision and the socio-technical regime.

The direction of change is the third key aspect of CE transitions connecting transformations happening on the micro-, meso-, e macro-levels of CE systems following Figure 1-2. CE transitions may happen through top-down initiatives, bottom-up initiatives, or combinations thereof (Lieder & Rashid, 2016; Merli, Preziosi, & Acampora, 2018). Top-down initiatives change the social and economic dynamics through legislation, fiscal incentives, investments in supporting infrastructure, and social awareness to create a good atmosphere for the implementation of CE systems (Ellen MacArthur Foundation, 2015; Geisendorf & Pietrulla, 2018; Hobson, 2015; Lieder & Rashid, 2016; Merli et al., 2018). In order to avoid short-sighted interventions, public policies should consider the total consumption and production life cycle (Zhu, Fan, Shi, & Shi, 2019). Also, policies are required in different scales to help to effectively align CE initiatives locally, regionally and internationally (Milios, 2018). Top-down interventions must be carefully designed to accelerate the transition in macro-level systems, considering the effects of incentives in the meso- and micro-levels.

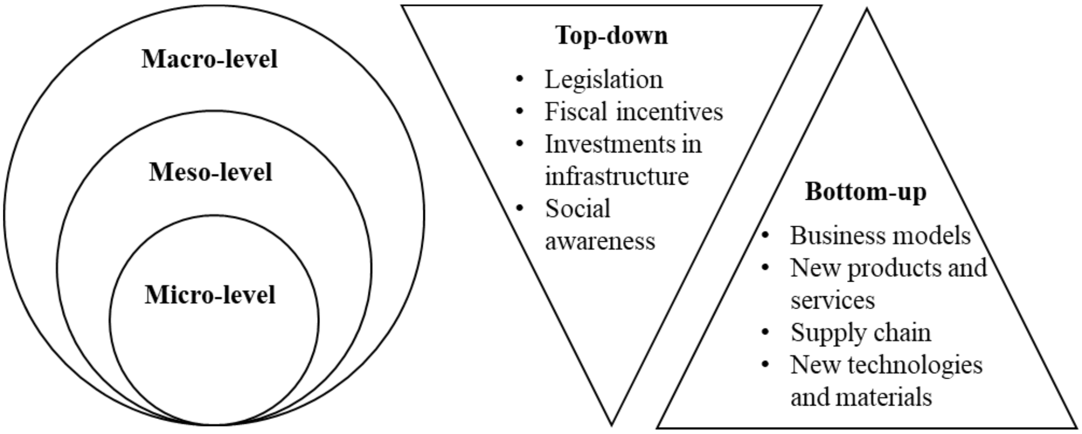

**Figure 1-2** – Bottom-up and top-down change enable and connect CE transitions in the micro-, meso-, and macro- levels.

Bottom-up initiatives implement and sustain the CE system driven by opportunities of creating, delivering and capturing value through technologies, products and services, and supply chains innovations that enable the deceleration of resource flows (Ellen MacArthur Foundation, 2015; Lieder & Rashid, 2016; Moreno, de los Rios, Rowe, & Charnley, 2016). Circular business models provide the rationale so that companies and individuals can consistently operate and benefit from product design and operational processes while leveraging the positive impacts for the environment and society (Bocken et al., 2016; Lieder and Rashid, 2016). In bottom-up change, startups and corporations play a crucial role in innovating and scaling business models that sustain enhanced modes of consumption and production. Bottom-up interventions must be carefully designed to enable the adoption of new modes of consumption and production from the product-solution fit, in the micro-level, to product-market fit and scale into regional and national adoption.

Top-down and bottom-up initiatives are complementary forces in the CE transition. The adequate definition of top-down initiatives should align the roles and expectations of the most diverse stakeholders in the socio-technical systems: governments, institutions, private companies, and the individuals taking the roles of consumers, users, citizens and decision-makers. From this, sufficient synergy can be formed between such stakeholders, allowing to sustain the adoption of bottom-up innovations, obtain sufficient market formation, and achieve the necessary leverage to reach CE regimes.

Based on the characterisation, a definition for CE transitions is following presented.

*CE transitions constitute the change process from an (as-is) linear economy system to a (to-be) CE system, ideally aiming for full decoupling of resources, where change happens through top-down initiatives, bottom-up initiatives, or combinations thereof.*

In general, there are very few quantitative studies on the CE field, which mostly focus on business model innovation (Kirchherr & van Santen, 2019). Despite the existence of studies using modelling and simulation to investigate bottom-up transitions (cf. Asif et al., 2016;

Franco, 2019; Lieder et al., 2017), there are still limitations to be addressed. In bottom-up transitions, it is possible to investigate the complexity of new collaboration networks (e.g. adoption models and behavioural changes), and the optimisation of resource use in specific cases to reduce the possibility of rebound effects. These analyses must consider the long-term use of resources linked to people's behaviour, demand for services, and the process of obsolescence of products. These are characteristics that static approaches do not allow to represent, and therefore, decision-makers are unable to examine with existing tools.

There is still less research taking a top-down perspective using modelling and simulation (cf. Pinto and Diemer, 2020). In top-down studies for policymaking, tools used in the CE field apply lifecycle assessment (LCA) and material flow analysis (MFA) to enable identifying flows, stocks and balances in the consumptions and production systems (Merli et al., 2018). The tools available still fail to address a few critical characteristics of CE systems as products' value loss and material scarcity (Merli et al., 2018). Besides, deceleration of the physical resource flows demands considering the "interests and preferences affecting and affected by the physical fluxes" (Korhonen, Nuur, Feldmann, & Birkie, 2018). When developing quantitative tools, there is an opportunity to connect the principles of LCA and MFA using SD notation to allow experimentation on a solid logical basis to assess past, present, and future stocks and flows of resources in systems.

This research regards both bottom-up and top-down transitions as a recognition of the growing institutional and consumer-led pressures to transform consumption and production systems (Ellen MacArthur Foundation, 2012; Truffer & Coenen, 2012). A proactive attitude from business practitioners and policy-makers is required to generate and sustain systemic transformations from the current consumption and production paradigm (Geissdoerfer, Naomi, Monteiro, Carvalho, & Evans, 2018; Gorissen et al., 2016). Closed-loop thinking may enable the required proactive attitude, as it enables to identify the causal feedbacks in systems structures to understand how dominance among variables might alter system behaviour through time (Sterman, 2000). A proactive attitude is necessary as damage management strategies (cf. Braungart et al., 2006) or the management of unsustainability (cf. Gorissen et al., 2016) will not be sufficient to deal with the effects of the linear form of consumption and production. The linear structure is relentless with any attempt to resolve the effects and not the causes of the current consumption and production paradigm. SD modelling and simulation matches the required proactive approach for CE transitions, as it is useful when experimenting with the real system is too costly or when the consequences of decisions take a long time to manifest (Sterman, 2002).

The need for transitioning from linear to circular systems makes it clear that there are different options to achieve improved modes of consumption and production. It is also clear that there are possibilities more or less adequate for the effective use of resources. However, these possibilities are not always clear or meet the interests of all stakeholders. CE transitions depend on the alignment of interests of different actors and the manifestation of this alignment in public policy and business actions to allow the deceleration of resource flows. Making the necessary decisions is not an easy task considering the multiple CE strategies and the vested interest of decision-makers, who will be participating in the system from a bottom-up or top-down perspective. The high costs, uncertainty, and lengthy-time interval for experimenting with the systems hinder the possibilities of acquiring validated learning, which reinforce the need to investigate the possible consequences of changes in the consumption and production system to facilitate decision making. When considering the characteristics of CE transitions against existing tools that can help decision making, the second research gap emerges.

**Research gap 2:** Available tools insufficiently address the experimenting needs of decision-makers in bottom-up and top-down CE transitions.

The theoretical foundations and complimentary research gaps presented in this section pave the way for the research questions and goals addressed in this research.

## 1.2 General research question and goals

A general research question and two complimentary goals were defined to tackle the two research gaps identified when taking the perspective of systems thinking for investigating Circular Economy systems and transitions. The general research question is following outlined.

**General research question (GRQ):** How can a systems approach help decision-makers to understand and facilitate CE transitions?

The GRQ embraces the CE field perspective, which is under rapid development and is the primary beneficiary of the contributions in this thesis. The general research question is deliberately open, as this is the question that emerges from the current level of knowledge found in the CE field concerning systems thinking.

As outlined in the previous section, there is little understanding of the meaning of systems thinking in the CE field, and there is plenty of room for the application of systems approaches to facilitating CE transitions. Two complementary research goals are derived from the general research question. They constitute a theoretical goal and a practical goal, aiming to direct the thesis to contribute to academia and practice, as follows.

**Theoretical goal (TG):** Interpret CE transitions through a systems perspective;

**Practical goal (PG):** Generate tools to facilitate decision-making in CE transitions.

The general research question and the two complementary goals sustain the research efforts following described.

## 1.3 Research methodology

In this section, the methodology is presented following the Design Research Methodology (DRM). Work packages (WPs) positioned in the DRM are presented to facilitate the understanding of the results of this research. The research questions, methods and outcomes are following detailed for each WP.

The DRM was employed to guide the research in the thesis. The DRM aims to develop and validate support based on a sound understanding of theories and empirical knowledge to improve the design of systems (Blessing & Chakrabarti, 2009). The DRM contains four research stages (Blessing & Chakrabarti, 2009): **(1)** Research Clarification, **(2)** Descriptive Study 1, **(3)** Prescriptive Study, and **(4)** Descriptive Study 2. The research aims and activities for each of the four stages are outlined according to Blessing and Chakrabarti (2009). In the Research Clarification stage, researchers aim to formulate realistic and worthwhile research goals considering resources available. In the Descriptive Study 1, researchers describe their understanding of the phenomenon under study until there is enough clarity to start developing support. In the Prescriptive Study, researchers use the increasing understanding of the phenomenon under investigation to develop practical support that enables the realisation of an improved situation in practice. Finally, in Descriptive Study 2, researchers investigate the ability of the support to realise an improved situation.

**Table 1-1 –** Work packages structure followed in this research.

| **Research Stage** | **Research goals** | **Work Packages (WPs)** | | | | |
|---|---|---|---|---|---|---|
| Research Clarification (RC) (set research scope) | Interpret CE transitions through a systems perspective (Theoretical)<br>Generate tools to facilitate decision-making in CE transitions (Practical) | WP1 Setting the research scope | | | | |
| Descriptive Study 1 (DR1) (understand the phenomenon) | Develop the foundation for an SD simulation tool that enables experimenting and discussing CE transitions | WP2 Developing research foundation | WP3 Modelling and simulation case 1 (Article 1) | WP4 Modelling and simulation case 2 (Article 2) | | |
| Prescriptive Study (PS) (develop practical support) | Generate a tool capable of facilitating decision-making in CE transitions | | | | WP5 Modelling and simulation case 3 (Article 3) | WP6 Cross-case analysis |
| Descriptive Study 2 (DS2) (investigate effects of support use) | Discuss the insights SD modelling and simulation can provide in CE transitions | | | | | |

The four DRM stages were employed in this research. Table 1-1 presents the six work packages (WP) developed to resolve the specific goals developed for each research stage. The six work packages were designed to connect theory and practice, developing tools to facilitate CE transitions and demonstrating their application while creating knowledge for theory building. The outcomes of WPs 1, and 2 are presented in the two initial sections of this thesis, and they embrace the research scope and initial understanding of the phenomenon. The outcomes of WPs 3, 4, and 5 are the three articles that form this thesis. The outcomes of WP 6 are guidelines, exhibited in section 6, that allows to connect and expand the knowledge contained in the articles.

The use of the DRM approach was iterative, meaning that learnings from one stage shaped all other stages and that there was not a rigid order in the activities concerning the four stages within WPs. In other words, understanding of the phenomenon, development of practical support and investigation of the effects of the use of the tools occurred concomitantly.

The first work package (**WP1**) consisted of setting the research scope as an effort for Research Clarification – see Table 1-2. The two research gaps identified in the literature were translated into the general research question (GRQ), orienting paths for investigation, and guiding the search for possible answers. The two complementary goals delimited the practical and theoretical intention followed in work packages 2 to 6. A thorough literature review was performed to sustain the research gaps and to elaborate the research questions and goals of the following work packages. Additionally, a second literature review was carried out alongside to promote a rich understanding of the potential of the modelling and simulation techniques employed in the thesis. The research scope and structure contained in this first section of the thesis are the Outcomes of WP1.

**Table 1-2 –** WP1 - Description of research questions and research outcomes.

| DRM | Research goals | WP | Research Questions (RQs) | Research Outcomes (ROs) |
|---|---|---|---|---|
| **RC** | Interpret CE transitions through a systems perspective (Theoretical)<br>Generate tools to facilitate decision-making in CE transitions (Practical) | WP1 Setting the research scope | GRQ[2]: How can a systems approach help decision-makers to understand and facilitate CE transitions? | RO1.1: Research scope and structure |

Towards a profound understanding of CE transitions, **WP2** aimed to build the theoretical foundation required to sustain the modelling and simulation performed in the case studies. As presented in Table 1-3, the research question addressed is RQ2.1: “What are the key concepts and requirements for an SD-based tool to understand and facilitate CE transitions?”. This WP was required, due to the recognition of the dynamic and systemic perspective of the CE transition as an emerging research area, where the body of the literature is still limited. The literature review was used to organise the knowledge of the relevant related fields that contributed to the development of conceptual models to support explaining the phenomenon (J. Webster & Watson, 2002). As previously presented in the introduction, CE systems and transitions are characterised in this thesis under a systems perspective, therefore, this WP aimed at the comprehension of the concept of dynamic complexities of Circular Economy transitions

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[2] GRQ stands for General Research Question

(Outcome 2.1). As it will be presented in section 2.1, the dynamic complexities are able to reveal the reasons for uncertainty in CE transitions. Finally, to develop the SD simulation tool, it was necessary to systematise the specific requirements for an SD-Based tool to facilitate CE transitions (Outcome 2.2). The systematisation was based on literature review and is presented in section 2.2.

**Table 1-3** – **WP2 -** Description of research questions and research outcomes.

| **DRM Research goals** | | **WP** | **Research Questions (RQs)** | **Research Outcomes (ROs)** |
|---|---|---|---|---|
| **DS1** | Develop the foundation for an SD simulation tool that enables experimenting and discussing CE transitions | WP2 Developing research foundation | RQ2.1: What are the key concepts and requirements for an SD-based tool to understand and facilitate CE transitions? | RO2.1: The sources of dynamic complexity in CE transitions |
| | | | | RO2.2: Requirements for an SD-based tool |

**WP3** comprised the first SD modelling and simulation investigation and culminated in the research article 1. Such investigation aimed at understanding the dynamic complexity aspects in CE systems influencing decision-makers in practice, and identifying potential paths for using modelling and simulation. The exploratory approach in this WP is justified as it was necessary to understand the relationship between the modelling and simulation scope and which elements of dynamic complexity could be tackled in a real case. As presented in Table 1-4, the first research question addressed is RQ3.1: "What are the dynamic aspects determining the use of resources when adopting a circular business model?". Modelling systems with dynamic behaviour and presenting elements of complexity may require understanding the sub-systems that constitute the phenomenon under investigation. In this way, identifying and using sub-models allows managing the complexity in each sub-system to integrate them later. The four sub-models determining resource use (Outcome 3.1) detail the breadth of aspects that bring dynamic complexity when examining the effects of behavioural changes in the use of resources in a real case within the micro-level system. The interaction between these sub-systems enables investigating changes in the flow of resources due to the adoption of new behaviour.

The second research question addressed in this investigation was RQ3.2: "In which manners SD modelling and simulation can be used to demonstrate the effects of the adoption of a circular business model in terms of resources use?". Two research outcomes respond to this research question:

- A model detailing effects of adopting a sharing platform built through causal loop diagrams – CLDs[3] (Outcome 3.2) communicate the reasons for changes in the flow of resources due to new system behaviour.
- The simulation tests of the adoption of the sharing platform by one company considering durables and consumables (Outcome 3.3) demonstrates the potential of using simulation models to experiment with CE systems.

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[3] Causal loop diagrams (CLDs) represent the causal relationships and feedback loops within a system (Lane, 2000). CLDs assist in understanding and communicating about a system since the causal relationships define most of the potential behaviour of the system.

In this work package, the usage of CLDs and SFDs – stock and flow diagrams – allowed exploring possibilities to develop practical support via the two complementary modelling paradigms in SD. Although CLDs are powerful in communicating the reasons for the behaviour of systems, the use of simulation models supported by SFDs prevailed in the following WPs.

**Table 1-4** – **WP3 -** Description of research questions and research outcomes

| DRM | Research goals | WP | Research Questions (RQs) | Research Outcomes (ROs) |
|---|---|---|---|---|
| **DS1** | Develop the foundation for an SD simulation tool that enables experimenting and discussing CE transitions | WP3 Modelling and simulation case 1 (Article 1) | RQ3.1: What are the dynamic aspects determining the use of resources when adopting a circular business model? | RO3.1: The four sub-models determining resources use |
| **PS** | Generate a tool capable of facilitating decision-making in CE transitions | | RQ3.2: In which manners SD modelling and simulation can be used to demonstrate the effects of the adoption of a circular business model in terms of resources use? | RO3.2: CLD of the effects of the adoption of a sharing platform<br>R3.3: Simulation tests of the adoption of a sharing platform by one company |

The following SD modelling and simulation investigation, **WP4,** bridges the understanding of CE transitions, the proposition of a tool to investigate transitions in the EEE industry and the investigation of the tool use from a macro-level perspective. The WP4 culminated in the research article 2. Table 1-5 presents the research questions and outcomes of WP4. Driven by the finding that there was no conceptual model capable of representing the potential for deceleration of CE systems using SD notation, the first research question covered is RQ4.1: "How can SD modelling be used to represent the potential for decelerated flow of resources of CE systems?". Making use of hybrid SD modelling, a conceptual model detailed CE system anchored in the CE and industrial ecology fields (Outcome 4.1). Using stocks, flows and auxiliaries, the conceptual model details the logics behind the deceleration of resource flows in CE systems, and positions the CE strategies according to the flows they slow, narrow, or close, working as the foundation for designing the simulation model.

The second research question addressed in the investigation of WP4 was RQ4.2: "How can a simulation model provide knowledge of the effects of the implementation of CE strategies on nationwide stocks and flows of EEE?". Three research outcomes respond to this research question:

- The Circular EEE SD model (Outcome 4.2) developed is a simulation model capable of examining the effects of CE strategies implementation on the stocks and flows of durable goods, taking a macro-level perspective. The Circular EEE SD model is available on GitHub[4] with guidance for calibration and use by researchers and practitioners.
- Scenarios obtained from using the model are the Outcome 4.3. These scenarios represent the examination of the effects of specific strategies to slow or close the

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[4] Model and documentation available on GitHub: https://github.com/danguzzo/CircularEEE_SDModel

resource flows and demonstrate the nationwide effects of CE strategies implementation for flat display panel TVs in the Netherlands.

- Recommendations for advancing the Circular EEE SD model (Outcome 4.4) complements the response to RQ4.2 as it communicates opportunities for further developing practical support.

In addition to presenting the stocks and flows in different configurations of CE systems, the use of the Circular EEE SD Model enables responding to RQ4.3: "How a simulation model that exposes the effects of the implementation of CE strategies on nationwide stocks and flows of EEE can help in CE transitions?". The use of scenarios for transitions, the sources of complexity that can be managed by using modelling and simulation, and the potential of using the Circular EEE SD Model in policymaking and business decision making are some of the discussions connecting the scenarios obtained using the simulation model to the capability of enabling CE transitions (Outcome 4.5).

**Table 1-5** – **WP4 -** Description of research questions and research outcomes

| DRM | Research goals | WP | Research Questions (RQs) | Research Outcomes (ROs) |
|---|---|---|---|---|
| **DS1** | Develop the foundation for an SD simulation tool that enables experimenting and discussing CE transitions | WP4 Modelling and simulation case 2 (Article 2) | RQ4.1: How can SD modelling be used to represent the potential for decelerated flow of resources of CE systems? | RO4.1: Conceptual model for CE systems |
| **PS** | Generate a tool capable of facilitating decision-making in CE transitions | | RQ4.2: How can a simulation model provide knowledge of the effects of the implementation of CE strategies on nationwide stocks and flows of EEE? | RO4.2: Circular EEE SD model<br>RO4.3: Scenarios for the nationwide effects of CE strategies implementation for flat display panel TVs in the Netherlands<br>RO4.4: Recommendations for advancing the Circular EEE SD model |
| | | | RQ4.3: How a simulation model that exposes the effects of the implementation of CE strategies on nationwide stocks and flows of EEE can help in CE transitions? | RO4.5: Discussions about the use of SD modelling and simulation in CE transitions |

**WP5** consisted of the last SD modelling and simulation investigation contained in this thesis, where the Circular EEE SD model is used to examine potential effects of collection interventions within the scope of a national public policy and discuss the use of modelling and simulation for top-down CE transitions. WP4 culminated in the research article 3. It was clear that the Circular EEE SD model was capable of investigating CE systems and transitions in the macro-level, so it held the potential for investigating nationwide policies. As presented in Table 1-6, the first research question addressed is RQ5.1: "How can a simulation model capable of

representing the nationwide stocks and flows of EEE be used to investigate public policies?". Two research outcomes respond to this research question:

- The adaptation of the Circular EEE SD model to investigate the BIAEEE case (Outcome 5.1) shows the rationale for modifying the model to the purpose of public policy investigation. The adaption process comprises all the steps for calibrating the model to a baseline scenario and the development of scenarios for examining EEE collection interventions within the industrial agreement.
- Recommendations for the use of modelling and simulation to governing the BIAEEE implementation (Outcome 5.2) provides additional prescriptive input to RQ5.1. Such recommendations comprise possibilities for the continuous use of the model to enable decision-making by policymakers and business practitioners.

The second research questions addressed in this investigation was RQ5.2: "What are the potential outcomes of interventions focused on the collection of products at the end of life in meeting the Brazilian industrial agreement for EEE?". Using the model permitted exploring scenarios to represent the effects of the implementation of collection interventions for meeting the BIAEEE targets (Outcome 5.3). The scenarios represent different post-use EEE collection interventions as to the coverage increase and distribution of collection points and the existence of rewards for collection.

**Table 1-6** – **WP5 -** Description of research questions and research outcomes

| DRM | Research goals | WP | Research Questions | Research Outcomes |
|---|---|---|---|---|
| PS | Generate a tool capable of facilitating decision-making in CE transitions | WP5 Modelling and simulation case 3 (Article 3) | RQ5.1: How can a simulation model capable of representing the nationwide stocks and flows of EEE be used to investigate public policies? | RO5.1: Circular EEE SD model adapted to the BIAEEE case<br>RO5.2: Recommendations for the use of modelling and simulation to governing the BIAEEE implementation |
| DS2 | Discuss the insights SD modelling and simulation can provide in CE transitions | | RQ5.2: What are the potential outcomes of interventions focused on the collection of products at the end of life in meeting the BIAEEE? | RO5.3: Effects of the implementation of collection interventions for meeting the BIAEEE targets |
| | | | RQ5.3: What is the potential of modelling and simulation to assist public policy investigation in the context of CE transitions? | RO5.4: Recommendations for the BIAEEE |

The third research question was RQ5.3.: "What is the potential of modelling and simulation to assist public policy investigation in the context of CE transitions?". The scenarios clarify trade-offs in the choices that influence the capillarity of the system and customer engagement to the reverse logistics system. Also, results show the limitation of the instruments contained in the BIAEEE as they comprehend collection for recycling only. Such trade-offs and limitations are communicated in the form of recommendations for the public policy based on model use considering critical aspects for post-use EEE collection (Outcome 5.4).

The final work package, **WP6**, consisted of cross analysing the modelling and simulation cases on the light of the research foundation contained in this thesis. Table 1-7 summarises the work package 6, containing the final research question; RQ6.1: "How examine CE transitions using SD modelling and simulation?". The knowledge accumulated with the development and application of the tools in the three research articles allowed the development of guidelines for experimenting with CE transitions using SD (Outcome 6.1), which are made available in the section 6 of this thesis.

**Table 1-7** – **WP6 -** Description of research questions and research outcomes

| DRM | Research goals | WP | Research Questions | Research Outcomes |
|---|---|---|---|---|
| **PS** | Generate a tool capable of facilitating decision-making in CE transitions | WP6 Cross-case analysis | RQ6.1: How to examine CE transitions using SD modelling and simulation? | RO6.1: Guidelines for experimenting with CE systems using SD |

In **WPs 3, 4 and 5**, multiple model-based studies (Kopainsky & Luna-Reyes, 2008) were used (1) to bring clarity to the phenomenon under investigation, (2) to allow the creation of tools to help with CE transitions and (3) to provide insights to researchers and practitioners by experimenting with the simulation models created. Multiple case studies can describe a phenomenon grounded in empirical experience of multiple sources that permit broad exploration of research questions for more robust knowledge creation (Eisenhardt & Graebner, 2007).

The three articles uncover CE transitions occurring at different scales and taking different perspectives regarding the direction of change as detailed in Table 1-8. Article 1 deals with a CE system in the micro-level, as it reports the adoption of a sharing platform in one healthcare institution and the effects in the use of resources. This first article comprises bottom-up change as it investigates a transition led by the adoption of a circular business model. Article 2 investigates the system behaviour in the macro-level perspective, with a higher degree of aggregation, examining the effects of the nationwide adoption of CE strategies in the stocks and flows of a EEE product type (flat-panel TVs) in the Netherlands. Finally, article 3 is an extension of the second article, detailing interventions focused on the collection of EEE products (smartphones) at the end of life to examine its effects in the use of resources and for meeting the targets of the Brazilian industry agreement for EEE (BIAEEE). In this way, article 3 consists of an investigation at the macro-level with a top-down perspective for CE transition. The meanings of the arrows presented in Table 1-8 are: ↑ indicates bottom-up change, ↓ indicates top-down change, and – indicates neutral change. Neutral change happens when the interventions are not detailed as part of business model innovation nor public policies alteration.

**Table 1-8** – Scales of CE systems addressed in the articles 1, 2 and 3

| **Scales of CE systems** | Article 1 | Article 2 | Article 3 |
|---|---|---|---|
| **Micro-level:** Within a single organisation, household or individual | X ↑ | | |
| **Meso-level:** Within groups of organisations in geographic proximity | | | |
| **Macro-level**: Whole industries, regions or nations | | X – | X ↓ |

The criteria for case selection for investigation were the possibility of application of CE strategies in that system, the potential for insights from the modelling and simulation effort, and the potential for positive environmental impacts from the transition in that system. The research contained in the first article contributes to the discussion of the potential of sharing strategies for the use of resources. The adoption of one organization to sharing durable goods and consumables can bring limited gains in the use of resources. However, a better understanding of the effects of sharing can help to spread the adoption of this strategy in other organizations and leverage impacts. The second and third articles contribute to the discussion of stocks and flows of electronics, a sector that demands a systemic transition and that demands adjustments throughout the value chain. The insights of the second article are to investigate and potentially coordinate different CE strategies to enhance the deceleration in the flow of resources. In the third article, the insights emerge from detailing, from a public policy perspective, the interventions necessary for a CE strategy to be successfully implemented.

System Dynamics modelling and simulation processes were employed in the three articles. The process proposed by Pruyt (2013) guided the first article, while the process prescribed by Sterman (2000) guided the two following articles. Both approaches are based on similar characteristics and provide similar steps.

Figure 1-3 represents the five iterative stages following Sterman (2000): **(i)** Problem articulation, **(ii)** Formulation of Dynamic Hypothesis, **(iii)** Formulation of a Simulation Model, **(iv)** Testing and **(v)** Policy Design and Evaluation. As represented, SD modelling and simulation is an iterative process, starting with a conceptual representation of the problematic system. This conceptual representation is translated into a simulation model when equations determine the relationships among variables. Simulation runs are then used to calibrate the behaviour of stocks and flows to available data and model users' expectations. Different scenarios enabled by altering the values of parameters or model structures can be used to learn about the possible results of changes in the model, and thus, the system. The whole process is designed to increasing trust in the model adequacy to representing the system, from conceptual foundations to equations, and to provide insights based on the behaviour of stocks and flows.

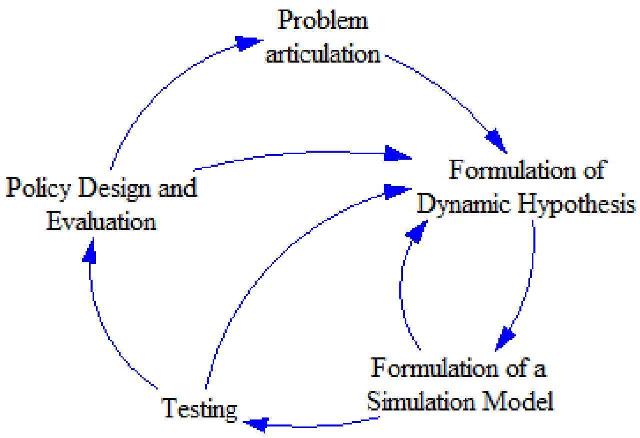

**Figure 1-3** – Steps for System Dynamics modelling and simulation following Sterman (2000)

The three articles combine developing the fundamentals for investigating CE transitions using SD modelling and simulation (Descriptive Study 1), followed by the proposition, application and testing of a simulation model (Prescriptive Study) to allow gaining insights on the implications of model use in specific aspects of such transitions (Descriptive Study 2). The three articles achieved varying levels of description of the phenomenon, prescriptive investigation, and knowledge generation. In all works, there are elements of Prescriptive Study as simulation models support results. From article 1 to article 3, there is a clear evolution from the description of the current understanding regarding the system to descriptions that address the effects of using the tools generated. The efforts contained in this thesis are built on literature review and SD modelling and simulation to resolve the theoretical and practical goals set for the research. The DRM details the six work packages (WPs) culminating in the three articles and the additional sections contained in this thesis. In the following section, the research fields contributing to the investigation are outlined.

## 1.4 Research fields

The novelty of the CE concept is widely debated since its definition and principles are supported by several other fields that have been discussing the potential of treating industrial systems as closed systems, accounting for the impacts during the whole lifecycle of products, or the possibility of the complete servitisation of the economy. A conciliatory proposition for this debate is to understand CE as an umbrella concept (Blomsma & Brennan, 2017), relying on several research fields (Kalmykova et al., 2018), such as notions of the limits of economic growth[5], general systems theory[6] and system thinking[7], industrial ecology[8], Cradle to Cradle[9], regenerative design[10], performance economy[11], and biomimicry[12].

For academic research, the synthesis[13] of one field from others brings opportunities and challenges. The opportunity is to take advantage of the interest of industry and academia for the theme and seek to combine and reframe concepts established in the fields covered by the umbrella concept. There is plenty of opportunities to generate or resignify knowledge from the fields covered by the umbrella concept while connecting them with the current challenges of organisations and society. The challenge is to carry out these activities sparingly, as each of these research fields presents a series of principles, tools, and previous investigations to be considered to allow relevant contributions. Risks lie in both superficially understanding the fields that support CE and in being paralysed by the multitude of possibilities.

Figure 1-4 presents the logic model connecting the research themes and research fields considered in this research. Three research themes underpin this research and set the research scope: Circular Economy, systems theory, and modelling and simulation. In the figure, research themes contain and connects the research fields. Circular Economy represents a research theme in the figure because it is a synthesis of other research fields, making use of knowledge from such fields and providing new sense to their meaning by connecting them. Systems theory is another research theme in the figure because there are several research fields treated as systems thinking or theory in the literature. Several modelling and simulation approaches can help to understand systems, which is, therefore, another theme in the figure. The positioning of the

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[5] In a report developed for the Club of Rome, Meadows and Meadows (1972) have applied System Dynamics to model and simulate the behaviour of population, industrialization, pollution, food production, and consumption of non-renewable resources to represent and understand whether and when the limits to growth will be reached in different scenarios. Although a condition for ecological and economic stability could be achieved, most of the scenarios led to collapse.

[6] In the *Economics of the Coming Spaceship Earth*, Kenneth Boulding (Boulding, 1966) discourses on the transition of mankind perception of living in a virtually illimitable planet to a closed and limited system - the Spaceship Earth - where all its composing systems are interconnected. From an economic viewpoint, facing Earth as a closed system demands mankind to distinguish economic success derived from exhaustible and inexhaustible resources.

[7] Joel de Rosnay (1979) discusses scientific knowledge development of the infinitely great through the figurative use of the Telescope and the infinitely small through the Microscope and proposing the necessity to understand the infinitely complex. The Macroscope is then set as a symbolic instrument to make sense of elements, relationships and interactions of complex systems.

[8] Industrial ecology is concerned to materials and energy flows through local, regional, and global economies and confront completely linear systems that entirely rely on external resources and sinks for emissions with the possibility of entirely circular systems self-sustained by the internal flow of resources (Lifset & Graedel, 2002)

[9] Cradle to Cradle aims at reconciling the flows of manmade technological nutrients to the flows of nature made biological nutrients by eliminating the concept of waste, where nutrients should be continuously used in their cycles (McDonough & Braungart, 2002).

[10] Regenerative design aims at integrating human processes to natural process by using renewable resources considering renewal cycle times and minimizing use of fossil fuels and non-renewable resources (Lyle, 1996). A system where the effects of human activity resonates to Earth systems and capable to regenerate these systems is envisioned.

[11] The Performance Economy is an economic system which aims to uncouple wealth creation from resource throughput by focusing on selling the function of products instead of selling goods (Stahel, 2010). Stahel's previous works are commonly mentioned as basis for the Product-Service System literature, which also sustains a service-oriented economy.

[12] Biomimicry or biomimetics is a concept disseminated by Janine Benyus (1997), which systematically observes and analyses models, systems and elements of nature to look for ingenious analogical resolutions for human problems.

[13] It is important to mention that the definitions provided by the Ellen Macarthur Foundation, which is a third sector institution, shaped the core principles of the Circular Economy, by placing the systems perspective at the centre of the discussion (Kalmykova et al., 2018; Kirchherr et al., 2017). Semi- and non-governmental organizations such as the Ellen Macarthur Foundation, the OECD (Organisation for Economic Co-operation and Development), and the World Bank play an important role to connect the public power and companies, and to disseminate good CE practices through the globe (Hobson, 2015).

circles represents the status of connection among each field and the three themes based on evidence from prior research. The literature shows that some fields contribute to more than one of the themes, explaining the reason for positioning some circles within themes. For example, System Dynamics is a research field recognised as a modelling and simulation approach that allows enhanced systems thinking. Also, it supports conceptual definitions within CE and has already been applied in a few studies. Thus, SD is positioned within the three themes, but with a greater interface with the themes of systems theory and modelling and simulation. Finally, the figure legend shows at what level each of the fields contributed to the research efforts contained in this thesis.

The logic model clarifies that there were other possibilities to answer the general research question: "How can a systems approach help decision-makers to understand and facilitate CE transitions?". The goal of generating a tool to facilitate decision-making in CE transitions brought modelling and simulation to the centre of this research. There were, however, multiple paths to generate tools to facilitate decision-making in CE transitions that would not involve modelling and simulation. For instance, fields as General Systems Theory and Biomimicry present concepts using the definition of systems and could provide different perspectives for a systems approach to understand and facilitate CE transitions. In this way, different combinations of the research fields contained on the themes – specifically Circular Economy and systems theory – would allow for alternative research pathway to answering the GRQ.

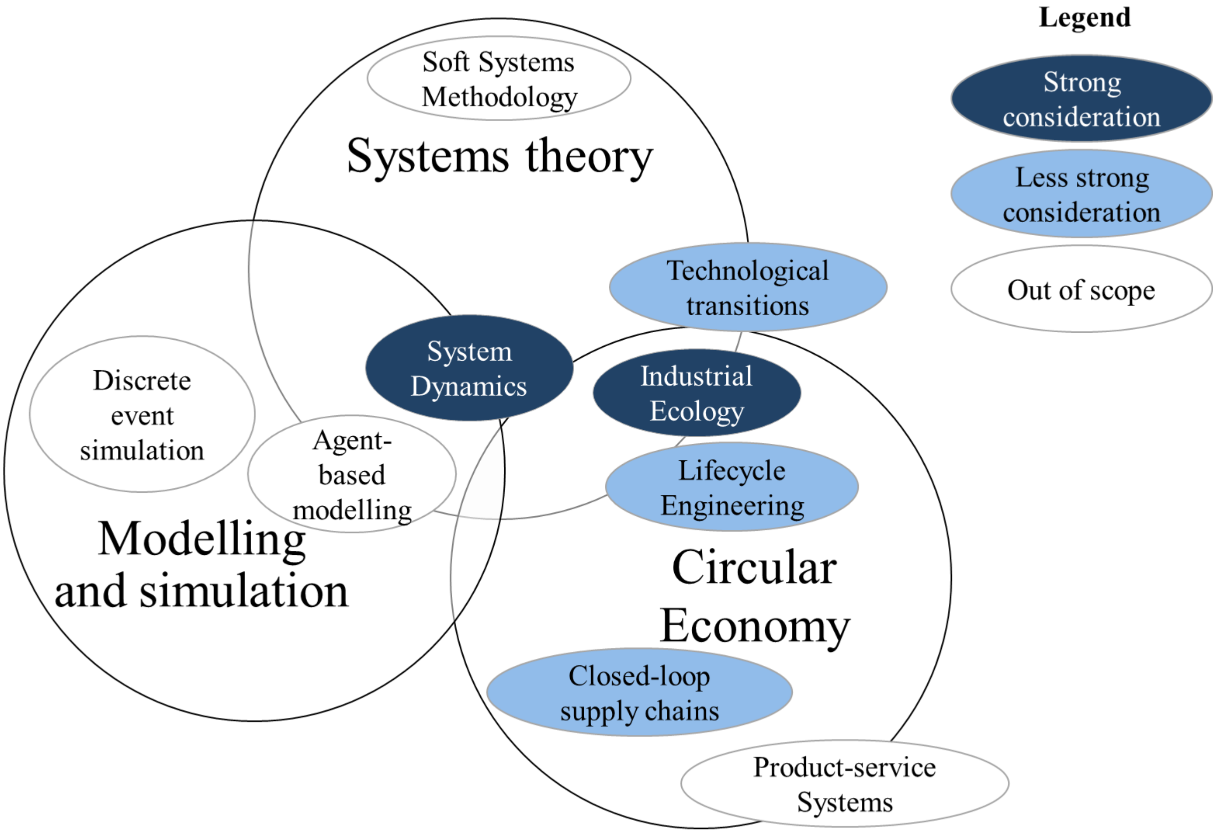

**Figure 1-4** – Logic model displaying the relation among research themes and fields considered in this thesis

In this thesis, Circular Economy is the central research field, since it is the leading research field investigated for setting the research scope. All research objectives, from Research Clarification to Descriptive Study 2, consist of interpreting, facilitating, experimenting, or discussing CE transitions. Therefore, this research is designed to provide most of the contributions to the CE field.

System Dynamics is a guiding thread in the development of knowledge in the thesis. SD fulfils the role of systemic thinking and is the modelling and simulation used as a research method to answer the research questions in the three research articles. System Dynamics modelling and simulation was used for theory development in this research following the argument of Davis et al. (2007), that simulation it is useful to understand and experiment with phenomena that contain characteristics of complex systems: multiple feedback relationships among its components, and time delays and non-linear effects in the interactions among them. Simulation allows experimenting with models that represent the system in question and to develop an understanding of the behaviour of the system.

Industrial ecology (IE) is essential to sustain the theoretical foundations of the tools provided, in particular in articles 2 and 3. The interactions of the anthroposphere and the biosphere have been a matter of concern in the IE field (cf. Ayres, 1994; Lifset & Graedel, 2002). The IE field is at the roots of the CE field, which appropriated the principle of mimicking nature's material and energy cycles for the technical cycles managed by humans (Blomsma & Brennan, 2017; Korhonen, Nuur, et al., 2018). While IE may have the most substantial influence in sustaining the CE field (Merli et al., 2018), the theoretical foundation link between the two fields needs to be strengthened (Homrich, Galvão, Abadia, & Carvalho, 2018). In this thesis, IE connects the Descriptive Study 1 to the Prescriptive Study, as it determines the conceptual model for CE Systems alongside SD. In the conceptual model, knowledge stemming from the IE field provides the theoretical framework for understanding systems with the potential for decelerated flow of resources. The knowledge from the IE field is complementary with that of SD, allowing an avenue of connection between the understanding of resource flows and the societal flows that permeate decision making in institutions, organisations and individuals.

Research fields such as Lifecycle Engineering and Closed-loop supply chains were instrumental in detailing the models, providing support to delimit the behaviour of specific CE strategies, such as sharing, second-use, remanufacturing, recycling, and others. These fields complemented the principles of IE, allowing to identify structures and formulations in the models to define product obsolescence and the operation of particular strategies for slowing, narrowing, and closing the flow of resources.

The technological transitions field, more specifically, the portion focused on sustainability transitions complements the systems view followed in this thesis. The possibility of top-down, bottom-up, and combinations underpin central discussions in the sustainability transitions field (Geels, 2011; Verbong & Geels, 2010). Understanding the dynamics of systems (Loorbach, 2007) and the multiple interactions within systems (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007) is determinant in the shift to more sustainable modes of production. There is also a growing interest in modelling and simulation to aid decision making in the sustainability transitions field (Holtz et al., 2015; Köhler et al., 2019) including in the use of SD (Papachristos, 2019; Raven & Walrave, 2020). In this way, knowledge of the field of sustainability transitions supports the understanding of essential aspects of the CE transitions concept and allows discussing the simulation results more extensively.

The interplay of fields investigated and applied in practice enables a systems perspective on CE transitions. In the following section, the potential benefit to knowledge creation and the practical use of the knowledge generated in this thesis is outlined.

## 1.5 Research justification to academia and practice

From the perspective of knowledge generation, the CE is a concept which is stimulating discussions and conjunct action among academia, civil society, and companies from all over the world. It is noteworthy the rising interest by academia to comprehend and develop the CE field. The number of publications in the Web of Science using ‘Circular Economy’ has increased from 18 in 2006 to 1,597 in 2019. Circular Economy special issues emerged in the recent years in respected journals, including the Journal of Industrial Ecology, the Resources, Conservation & Recycling journal, and the Journal of Cleaner Production. Apart from the sustainability-oriented journals taking an engineering perspective, the concept is under discussion in the strategy (e.g. Business Strategy and the Environment journal), economics (e.g. Ecological Economics journal), innovation (e.g. Research Policy journal) and social sciences (e.g. Technological Forecasting and Social Change journal) areas as well. The congregation of different perspectives to ground the debate contribute to the development of CE as a promising research field to guide urgent discussions between the diverse macro-areas of knowledge and help achieving sustainable development.

As previously argued, the CE is grounded in knowledge from a multitude of fields. Several existing concepts must still be translated into this emerging field. For example, the intersection of systems theory and the Circular Economy demands clarification. This thesis contributes to the academy by clarifying the potential of System Dynamics to understand and facilitate CE transitions. Discussing CE from the perspective of sources of dynamic complexities, stocks and flow structures, and the effects of system change through simulation enrich to the debate. Besides, relying on sustainability transitions and industrial ecology fields allowed for a more comprehensive and grounded reasoning about the meaning of systems thinking concerning CE systems and transitions.

The Circular Economy concept is not only being discussed by the academy but is under extensive practical application. Governments, business, consultancies and think thanks are discussing and applying the CE principles to foster a sustainable future in different regions and industries. Exemplary cases of application of CE strategies in businesses are widely reported. Many tools for business model and product design are available. Besides, local, regional, and international policies continue to be widely discussed, designed, and implemented. However, for the time being, we are still far from reaching a consumption and production system that allows for sustainability.

In addition to refine the concepts still in formation and disseminate validated knowledge, the academy must create tools to help business practitioners and policymakers to make the right decisions in CE transition. In this thesis, the choice to develop a tool was deliberate because it aims not only to understand further what CE transitions are but also to create ways to facilitate change. It is expected that the tools proposed here, as well as the reported applications, can be replicated and further developed to investigate and facilitate CE transitions in different systems, taking a dynamic approach.

## 1.6 Thesis structure

The structure of the thesis is following detailed, along with identifying the research outcomes contained in each section. Section 1, Introduction, contains the theoretical foundation sustaining the research gap, goals, questions, and methodology. Also, the research fields and justification are detailed.

The second section provides supplementary descriptive information that sustains all three research articles. The sources of dynamic complexity in CE transitions and requirements for an SD-based tool are described in section 2.

The three articles are presented in section 3, 4, and 5. Although article 2 presents knowledge that sustains much of the conceptual development of the application of SD and IE for CE systems, the studies presentation follow the order in which they occurred. The order of occurrence is maintained as it better portrays the research journey. Thus, the order of the sections follows Table 1-9, which details the title of the three articles.

**Table 1-9** – The title and section of each article

| **Section** | **Title** | **Article** |
|---|---|---|
| 3 | The use of System Dynamics to verify long-term behaviour and impacts of circular business models: a sharing platform in healthcare | 1 |
| 4 | A systems representation of the Circular Economy: Transition scenarios in the electrical and electronic equipment (EEE) industry | 2 |
| 5 | Analysis of national waste management policies for Circular Economy transitions: Modelling and simulating the Brazilian industry agreement for electrical and electronic equipment (BIAEEE) | 3 |

Section 6 contains the guidelines for examining CE transitions based on the accumulated knowledge from the three research articles. Finally, section 7 contains the final considerations for the thesis, highlighting contributions to academia and practice, alongside further avenues of investigation.

# 2 ADDITIONAL FUNDAMENTAL BACKGROUND

This section contains foundation knowledge to understand Circular Economy (CE) systems and transitions not included in the three research articles nor in the introduction. In section 2.1, the sources of dynamic complexity in CE transitions are categorised. The sources of dynamic complexities are specific behaviour observed in the literature that enable to understand the phenomenon of CE transitions as complex systems. In section 2.2, the characteristics of CE systems and transitions described in section 1.1 and the sources of dynamic complexities determine the elicitation of the requirements for a System Dynamics-based tool.

## 2.1 The sources of dynamic complexity in CE transitions

The closed-loop, stock optimisation and multi-level characteristics of CE systems added to the change, comparative and directional aspects of CE transitions mean that we are dealing with situations full of complexity. Resistance to change may occur to new modes of consumption and production due to the counterintuitive behaviour that can arise from the increase in complexity. Dynamic complexities, or the counterintuitive behaviour of complex systems, stem from the many causal relationships among elements, the process of accumulation and the delays and non-linearities in system behaviour over time (Sterman, 2000). The behaviour is counterintuitive when we use static or reductionist models to understand such complex systems (Sterman, 2001). Handling dynamic complexities is a crucial skill for CE transitions (Velte & Steinhilper, 2016). Table 2-1 organises an analysis of the sources of dynamic complexity in CE transitions.

The table presents the characteristics of complex systems that can be found in CE systems and transitions. Complex systems are considered dynamic, governed by feedback, counterintuitive, policy resistant, characterised by trade-offs, among other characteristics. A characteristic of CE systems that leads to potential counterintuitive behaviours is that these systems frequently rely on the combination of CE strategies implementation, which can lead to essential trade-offs (Brennan, Tennant, & Blomsma, 2015; Reike, Vermeulen, & Witjes, 2018; Zink & Geyer, 2017). The trade-offs among CE strategies demonstrates one of the dynamic characteristics of these systems, where changes taking place in different parts of the system and at different scales often interact (Sterman, 2000). Also, there are tensions between short-term gains and long-term opportunities for companies when considering a CE transition (Hopkinson et al., 2018). This characteristic reinforces tensions among long-run and short-run responses to an intervention. These are two examples that illustrate the sources of dynamic complexity in CE transitions organised in the table.

**Table 2-1** – The sources of dynamic complexity in CE transitions

| Characteristic of complex systems | Definition following Sterman (2000) | Occurrence in Circular Economy transitions | Reference |
|---|---|---|---|
| Dynamic | Change in systems occurs at many time scales, and these different scales sometimes interact. | Change occurs on different levels simultaneously – in the micro-level of, e.g. product design and use, in the meso-level of inter-organisation innovation, and the macro-level through the implementation of advanced policy systems in whole regions—changes in one level influence changes in the other. | (Ghisellini et al., 2015; Kirchherr et al., 2017; Su et al., 2013) |
| | | Circular Economy systems involve implementing combinations of CE strategies, and there are potential synergies and trade-offs among the options | (Brennan et al., 2015; Reike et al., 2018; Zink & Geyer, 2017) |
| Tightly coupled | The actors in the system actively interact with one another and with the natural world. | The concept of Circular Economy considers the relations of the consumption and production system with the adjacent systems, seeking to enhance environmental quality, economic prosperity, and social equity. The Circular Economy can be seen as a condition for sustainability, as well as bringing essential trade-offs to achieve it. | (Ellen MacArthur Foundation, 2012; Geissdoerfer et al., 2017; Kirchherr et al., 2017) |
| | | Collaboration and synergies identification are necessary towards "win-win-win" settings in ever more complex networks of stakeholders – circular innovations ought to deliver positive value for individuals, organisations, society and the environment. | (Antikainen & Valkokari, 2016; Brown et al., 2019; Geissdoerfer et al., 2018) |
| | | In CE systems, consumption and production relationships change profoundly, moving away from ownership models to service models. Consumers become users, and transactional relationships become longer-term relationships among providers and customers. | (Ellen MacArthur Foundation, 2012; Preston, 2012; Stahel, 2016) |
| Governed by feedback | One's decisions alter the situation, triggering others to act, giving rise to a new situation which then influences one's next decisions. | CE transitions rely on the coordination of interests by stakeholders with different interests: consumers, producers, legislators, citizens. Change happens in different directions, mutually influencing each other. For instance, bottom-up transitions are empowered when the value chain achieves a scalability level that enables replacing business as usual. Many times, the market formation will only happen if top-down initiatives are put in place concomitantly. | (Brown et al., 2019; Gorissen et al., 2016; Lieder & Rashid, 2016) |
| Non-linear | The effect is rarely proportional to cause. | The need for a Circular Economy starts by acknowledging that the linear economy paradigm causes the poor use of resources and disproportional levels of emissions, challenging the possibilities to achieve prosperity within planetary boundaries. There is significant uncertainty in transgressing the boundaries, which can lead to catastrophic events to the natural systems and to human well-being. | (Rockström et al., 2009; Wit et al., 2019) |

| Characteristic of complex systems | Definition following Sterman (2000) | Occurrence in Circular Economy transitions | Reference |
|---|---|---|---|
| | | Tipping points, or points which small changes become significant enough to cause more substantial change, are used to communicate that initiatives that seem incremental can lead to a rapid shift towards CE systems if well articulated in several fronts. | (Stahel, 2016; Webster, 2013) |
| History-dependent | Previous decisions made in the past defines the set of decision available. | The linear economy is built on production chains based on mass production, low labour costs and economies of scale, which are very difficult to challenge when seeking to internalise environmental and social impacts. | (EMF2012, Webster2013) |
| | | The physical production, distribution and consumption infrastructure of the linear economy model is highly dependent on fossil fuels and geared towards ownership-based models. For instance, we have been developing forward logistics infrastructure and capabilities for years, while CE systems require reverse logistics. Also, businesses that achieved the leading position tend to continue doing things as they currently do than embracing change, unless it is needed. | (Korhonen, Honkasalo, & Seppälä, 2018; Lüdeke-Freund, Gold, & Bocken, 2018; Preston, 2012) |
| Self-organising | The dynamics of a system arise from its internal structure. | Although we know the effects of the linear economy, if the structure of the socio-technical system does not allow it, the behaviour of a few organisations and people will not be enough to achieve CE transitions. In this context, there is continuous work within the growing CE community that is worth mentioning: the initiatives of non-governmental organisations focusing on the need for change and facilitating public discussions on the topic; the academy seeking to give theoretical support for the concept; members of the top management of companies adhering change; and the emergence of increasingly robust local and regional initiatives. The current phase of the Circular Economy is the scale-up of business models and public policies. | (Ellen MacArthur Foundation, 2012; Kirchherr et al., 2017) |
| Adaptive | The capabilities and decision rules of agents change over time. | CE transitions rely on fundamental changes from consumers – e.g. returning of products and parts, and acceptance of remanufactured or upgraded products, and from providers – e.g. manage the financial risks of assets ownership. Individuals and organisations take time to learn to behave in a new way. | (Linder & Williander, 2015; Planing, 2015) |
| | | People and organizations develop intrinsic motivation (energizing behaviour that comes from within the individual or organization) and extrinsic motivation (behaviour that comes to earn an external reward or avoid punishment) to engage in Circular Economy innovations. | (Brown et al., 2019, fig. 2) |

| Characteristic of complex systems | Definition following Sterman (2000) | Occurrence in Circular Economy transitions | Reference |
|---|---|---|---|
| Counterintuitive | Causes and effects are distant in time and space, hindering learning. | Aiming for CE system, the adequate boundary for the impacts of consumption and production systems encompasses the whole lifecycle of products, meaning the beginning of life – BOL, middle of life – MOL, and the end of life – EOL. Many times, the impacts of material extraction, or hindrance of eco-systems services due to deforestation are disregarded in designing new solutions as they are out of designers' mental models. | (Homrich et al., 2018) |
| | | Designers need to account for the environmental and business impacts of multiple lifetimes and lifecycles of products already in the early design phase. For instance, if multiple restoration activities will occur during the lifetime of a product offered as a service, the costs and impacts emerging from these activities should be accounted for when comparing with an ownership-based model. | (den Hollander, Bakker, & Hultink, 2017; Linder & Williander, 2015) |
| Policy resistant | Many obvious solutions fail or worsen the situation. | Circular strategies adoption may lead to a localised increase of resource effectiveness while resulting in unexpected impacts through the shift of economic activity – i.e. the potential occurrence of rebound effects. | (Bocken et al., 2016; Ghisellini et al., 2015; Korhonen, Honkasalo, et al., 2018; Reike et al., 2018) |
| | | Consumers and users present resistance to change purchasing behaviour due to habits and routines, subjective norms and social norms. While habits and routines may be easier to change, social norms are imposed by society and may not change in the short term. Individuals may take time to internalise the benefits of adhering to a CE system. | (Planing, 2015) |
| | | Resistance to change also occurs within organisations as there is a natural reluctance by employees to cultural and organisational changes for new modes of behaviour and the development of new business models. | (Brown et al., 2019; Korhonen, Honkasalo, et al., 2018; Pieroni et al., 2019) |
| Characterised by trade-offs | Long-run response to an intervention is different from its short-run response. | There are multiple types of stakeholders which captures different types of value. For instance, customers may capture functional and emotional values from solutions, costs, and risks are essential to organisations, and resource use and emissions matter to the environment. There are potential trade-offs and delays in value capturing by the different stakeholders that should be accounted for when designing CE systems. | (Bocken et al., 2016; Geissdoerfer et al., 2018) |
| | | There are tensions between short-term gains and long-term opportunities for companies, especially when (and if) particular technologies and operational practices reach scale. | (Hopkinson et al., 2018) |

## 2.2 Requirements for a System Dynamics-based tool

The characteristics of CE systems and transition and the sources of dynamic complexity in CE transitions help to determine Requirements for an SD-based tool. The envisioned tool should:

- Enable users examining the behaviour of resources – products, components, materials, and energy – within a system through time;
- Enable users examining the effects of different CE strategies adoption concomitantly and learn about the possibility of eventual rebound effects;
- Enable users defining and comparing scenarios for different consumption and production system configurations (as-is vs could-be);
- Enable users investigating systems under a time range adequate to the scale of change, covering the transition to a new equilibrium;
- Enable users examining the possibility of eco-economic decoupling to assist determining ideal states;
- Enable users examining the positive and negative effects of system change from the perspective of different stakeholders, including the environment and society;
- Facilitate decision-making for top-down and bottom-up transitions;

The requirements for an SD-based tool translate the descriptive knowledge about CE systems and transitions to guide the tool's development efforts in the three studies to be following presented.

# 3 ARTICLE 1: THE USE OF SYSTEM DYNAMICS TO VERIFY LONG-TERM BEHAVIOUR AND IMPACTS OF CIRCULAR BUSINESS MODELS: A SHARING PLATFORM IN HEALTHCARE

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**Abstract:** Static approaches for business modelling cannot cope with the increased complexity commonly linked to Circular Business Model (CBM) innovation. In this research, we aim to investigate whether System Dynamics (SD) modelling is suitable to verify the long-term behaviour and impacts of CBMs by applying it to a particular case study. The dynamics of a closed sharing platform for healthcare institutions are modelled and simulated. The dynamics of sharing durables and consumables is represented through (1.) a causal explanation of the behaviour, (2.) the structure of stock and flows and (3.) verification through simulation. Results indicate substantial potential impacts for durable products. Products lifecycle time and the number of use cycles determine this behaviour. The use of SD enables experimenting with CBM in this case by connecting the dynamics of sharing to the use of resources and its impacts. Further research should verify the possibilities to design enhanced CBMs from interventions evidenced by modelling.

**Keywords:** Circular Economy; Business Model Innovation; Experimentation; System Dynamics

**Status:** Accepted for publication at the 3rd Product Lifetimes and the Environment (PLATE) conference – Berlin, 2019.

## 3.1 Introduction

Business model innovation is the bottom-up engine towards a Circular Economy (CE). Circular business models (CBMs) provide the rationale so that companies and individuals can consistently operate and benefit from value retained in products and materials (Bocken, de Pauw, Bakker, & van der Grinten, 2016; Lüdeke-Freund, Gold, & Bocken, 2018). Increased complexity is commonly linked to CBM innovation. It arises from the need for collaboration in ever more complex networks of stakeholders (Geissdoerfer, Vladimirova, & Evans, 2018), the possibility of rebound effects (Bocken et al., 2016), and from increased risk due to capital tied up in resources and reliance in future people behaviour inherent to solutions of increased lifetimes (Linder & Williander, 2015).

Still, business modelling methods rarely focus on sustainability (Evans et al., 2017) and current research still offers a static view of business model innovation for sustainability (Roome & Louche, 2016). In this work, we aim to investigate whether System Dynamics (SD) modelling is suitable to verify the long-term behaviour and impacts of CBMs by applying it to a case study of a closed sharing platform for healthcare institutions. SD, a modelling paradigm used in environmental sciences (Meadows, Meadows, Randers, & Behrens III, 1972) and business management (Sterman, 2001), is used to demonstrate the potential impacts of CBMs while decreasing the efforts and risks of experimentation. Through modelling and simulation, the multiple parties involved in business model innovation can further understand the potential impacts and its reasons when aiming for long-term sustainability.

## 3.2 Background

System Dynamics (SD) is a continuous modelling approach capable of representing and simulating specific aspects of systems based on feedback-rich structures and delays among decisions and their effects (Sterman, 2001). Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (SFDs) are the two major diagramming conventions in SD. CLDs use variables and links to represent the feedback structure of a model (Lane, 2000). SFDs enable simulations of stock accumulations over time, according to structures of inflows and outflows (Lane, 2000). While the former is effective in communicating and explaining the system’s behaviour, the latter enables verification of behaviour through time.

The SD lenses can be used to make sense of the Circular Economy. The CE is a regenerative system where the flow of resources, waste and emissions are minimised through circular initiatives (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). Stocks can be used to represent the many types of resources in a system. Products, parts, consumables constitute some of the stocks to be maintained in a CE. By contrast, flows depict the transformation processes that affect such stocks: extraction, manufacturing, discarding.

The circular initiatives, in fact, slow or narrow the flow of resources and closing their loops (Bocken et al., 2016; Geissdoerfer et al., 2017). In other words, the CE involves both creating mechanisms to delay flows of resources as to enabling outflows of a given stock to be used as inflow of a less aggregated one. In order to slow the flow of resources, delay systems can be conceptualised to decrease throughput, retaining the value of products. Maintenance services work as delays for functional products to become obsolete, increasing their lifetime as useful stocks. In order to close the loops, outflows of a given resource become inflow of a less aggregated one, retaining value in the parts or materials levels. Recycling makes use of the outflow of obsolete products to be used as inflow of material production.

This resource-oriented perspective, if connected to the dynamics of a given business model, enables the capability of verifying and potentially experimenting with the impacts of CBM implementation through the application of SD.

## 3.3 Research Methodology

A case study of long-term behaviour and impacts of the sharing platform provided by Company A for healthcare institutions was performed. The scope of analysis is the use of a sharing platform in a small-sized hospital with 400 employees.

Medical devices contribute to the high use of resources and waste generation in diverse ways (Moultrie, Sutcliffe, & Maier, 2015): through recyclable uncontaminated devices ending up treated as hazardous waste, the release of toxic substances from the end-of-life of PVC-based devices, and the Waste Electrical and Electronic Equipment (WEEE) from electromedical equipment. Sharing assets is one of the CE strategies that can be applied to the medical industry towards a more sustainable healthcare system.

A protocol using the SD modelling process proposed by Pruyt (2013) was applied. The following steps were employed: problem identification, model conceptualisation, model formulation and model testing. The sustainable business model canvas presented in Bocken et al. (2015) was applied in order to set the scope of inquiry. Interviews (four) with the platform co-founder, press releases and secondary sources as research papers from the medical and SD knowledge areas were used for model conceptualisation and testing. Stock and Flow Diagrams (SFDs) were developed to simulate model behaviour over time. Causal Loop Diagrams (CLDs) were employed to highlight the structure originating such behaviour. The reasons for the simulated long-term behaviour are discussed. Recommendations for intervention in the real system and initiatives for model enhancement are pointed out. These are derived from the increased understanding enabled by modelling and simulation.

## 3.4 Results

### *3.4.1 Problem identification: articulating the issues to be addressed*

In the platform, different types of resources can be shared: from low-value single-use products to highly complex electromedical devices. Two types of sharing platforms are available: (i.) Closed sharing platforms - where customer companies pay a tailoring fee and annual maintenance fee for a platform to be used by internal teams, and (ii.) Open sharing platforms - where customer companies pay a monthly fee to access products from a network of healthcare institutions. Following five years of market experience, where they mainly acted as evangelists of Circular Economy and Sharing Economy to clarify their business model, Company A is focusing on implementing closed sharing platforms in Hospitals.

Their current challenges towards expansion are:

- Understand the dynamics of sharing in a closed platform;
- Connect the dynamics of sharing to potential environmental impacts of platform use;

Identify levers so that the potential positive impacts of sharing can be consistently improved.

### *3.4.2 Model conceptualisation: a theory of behaviour*

The model structure about the dynamic aspects of product use dealt by the sharing platform is represented in Figure 3-1.

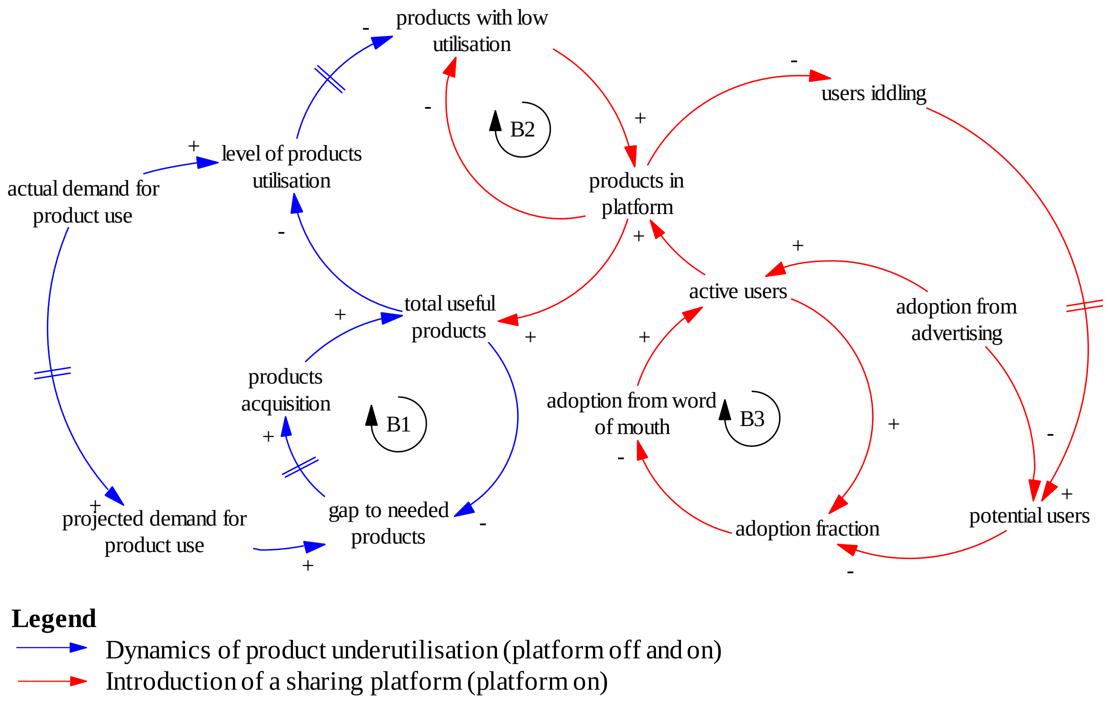

**Figure 3-1** – Causal Loop Diagrams (CLD) of sharing platform use

Low utilisation occurs when the actual demand for product use is lower than the total amount of useful products. Products become underutilised after a while in that condition. It is worth distinguishing durables and consumables. Durables may not be used often – way less than their capacity, and consumables may be kept away from use while approaching the end of their shelf life.

In a hospital which does not use a sharing platform, these underutilised products become obsolete after little use, and the number of total useful products is balanced by acquiring new products to meet projected demand – see B1 in Figure 3-1.

By contrast, in a hospital with a sharing platform in place, products with low utilisation can be turned into useful products for users that otherwise would not have been able to access them. This mechanism is of limited impact because it is a balancing loop – see B2. Active users in the platform register products and make use of them. The mechanism of internal user acquisition is thus critical. Users adopt the platform through two mechanisms: word of mouth and advertising. Adaption through advertising occurs mainly exogenously. Word of mouth is a powerful mechanism, which is balanced when the adoption fraction is high – represented by B3. Finally, users may get idle and stop using the platform for some time when they have a negative experience, i.e. when they cannot find products they want in the platform. Some idle users may never try the sharing platform again because of the bad experience.

### *3.4.3 Model formulation: a simulation model of the theory of behaviour*

Towards simulation, the model is organised into four sub-models on the sector diagram represented in Figure 3-2. Sub-models are parts of the model that could be conceptualized and tested separately, so that modelers could deal with less complexity before assembling the full model. It helps to provide a general description of the Stock and Flow Diagram (SFD) model. Sub-models are: ‘use of resources’, ’users in platform’, ‘sharing within a platform’ and ‘KPI system’. Variables that connect sub-models are made explicit.

The ‘use of resources’ connects the model to the CE framework by making the stocks the and flows of resources explicit in a healthcare institution. It contains the total stocks of functional, underutilised, and obsolete resources. Acquisition, obsolescence, utilisation and discarding are the main flows.

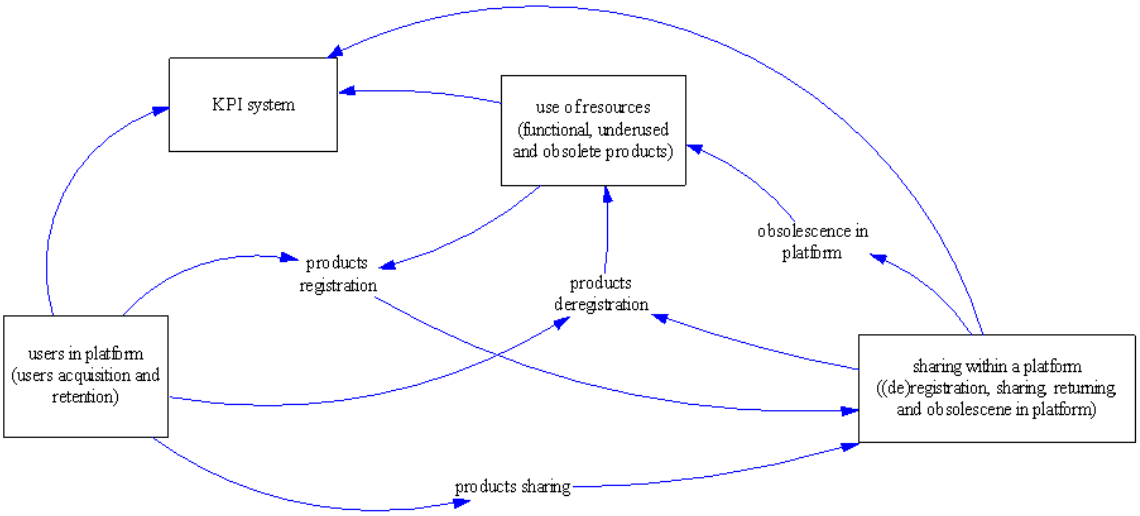

**Figure 3-2** – Sector diagram of the four conceptualised sub-models and relationships among them

The ‘users in platform’ represent the mechanisms for user acquisition and retention in a closed platform. The Bass diffusion model (Borshchev & Filippov, 2004; Sterman, 2001) is applied to represent the mechanisms of word of mouth and saturation in such a process. Advertisement efforts pushed forward by Company A are used to initiate/reinforce such dynamics.

The ‘sharing in platform’ represent the flow of underutilised assets being registered in the platform and their consecutive sharing. It connects the two sub-models previously presented. Products registration by users into the platform work as a delay to products acquisition as it rapidly balances the total number of functional products. A balanced ratio of products per users is necessary to enable sharing. When users leave the platform, the products under their responsibility are automatically deregistered and become underused again.

Finally, impacts are represented by the 'KPI system' sub-model, which is fed by all the other sub-models. Total sharing events, total products acquired and discarded, and total unmet demand are some of the KPIs defined to assess resource effectiveness.

### *3.4.4 Model testing: assessing whether the model is fit for purpose*

**Table 3-1** shows the parameters used to model the behaviour of durables and consumables in the 400 employees hospital using a closed sharing platform. Durables account for electromedical machines like MRI, Computed Tomography, X-ray, and Mammography machines. Consumables are single-use devices such as sutures, syringes, and gloves. The variables and parameters used represent the demands and lifetimes of products – durables and consumables.

Durables hold a high lifetime. They get the status of 'underutilised' after 18 months of low utilisation level and the decisions involved in acquisition take longer. Consumables hold shorter lifetimes and a safety stock policy is maintained. Lifetimes of durables are drawn based on the age profiling of imaging equipment in Europe (COCIR, 2016).

Product acquisition is defined by the projected demand for product use. Random time series are used to simulate actual demand for product use. The projected demand is a delayed response to actual demand, considering the time to acquire the product. The actual and projected demands were defined based on a case study for demand forecasting in healthcare (Cote & Tucker, 2001).

For the sharing platform, registration relies on the density of underutilised products per users. Sharing relies on the probability of desired product availability, which depends on the types of products within a category – durables or consumables. Finally, only durables are returned as available products in the platform for further sharing events. Consumables are used only once.

Figure 3-3 and Figure 3-4 show the simulation runs for the input parameters for durables and consumables of a small-sized hospital. Two scenarios are presented for each type of product: one representing no sharing platform and another with the sharing platform in place.

**Table 3-1** – Initial parameters to simulate the behaviour of durables and consumables[14]

| **Variables** | **Parameters for Durables** | **Parameters for Consumables** |
|---|---|---|
| simulation time (Month) | 120 | 120 |
| hospital employees (People) | 400 | 400 |
| product lifetime (Month) | 120 | 12 |
| time to underuse (Month) | 18 | 6 |
| time to acquire (Month) | 3 | 1 |
| actual demand for product use (Product) | Random time series – mean value of 20, standard deviation of 4 | Random time series – mean value of 3000, standard deviation of 600 |
| projected demand for product use (Product) | Information delay of the actual demand for product use considering time to acquire | Information delay of the actual demand for product use considering time to acquire |
| initial Functional (Product) | 19 | 2800 |
| initial Underutilised (Product) | 1 | 200 |
| Safety stock (Product) | 0 | 300 |
| ratio of returning (Dmnl) | 1 | 0 |

For durables and consumables, the actual and projected demand is the same when the platform is on or off (see Figures 3-3.a and 3-4.a). Following Figures 3-3.b, and 3-4.b, when the platform is on, users become active, and after a while, an increasing fraction becomes idle. In both cases, when the platform is off, all types of users remain zero. As shown in Figures 3-3.c and 3-4.c, total useful products are higher when the platform is on for both cases. Nevertheless, it is more relevant for durables. The total number of acquired products is relevantly lower to durable products when the sharing platform is in place (see Figures 3-3.d and 3-4.d).

Furthermore, the sharing platform enables meeting some demand that would otherwise not receive treatment. The total unmet demand decreases when the platform is on. Potential increased capacity is, again, more significant to durable products than to consumables (see Figures 3-3.e and 3-4.e).

Based on the experiment, the potential impacts of implementing a sharing platform in the context of one small hospital are substantial. Impacts of sharing durables and consumables in hospitals vary according to factors such as demands for product use, lifecycle time of products and the number of use cycles. The potential is higher for the sharing of durables.

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[14] Further details on the model choices can be obtained by contacting the corresponding author

## Durables: simulations platform on and off

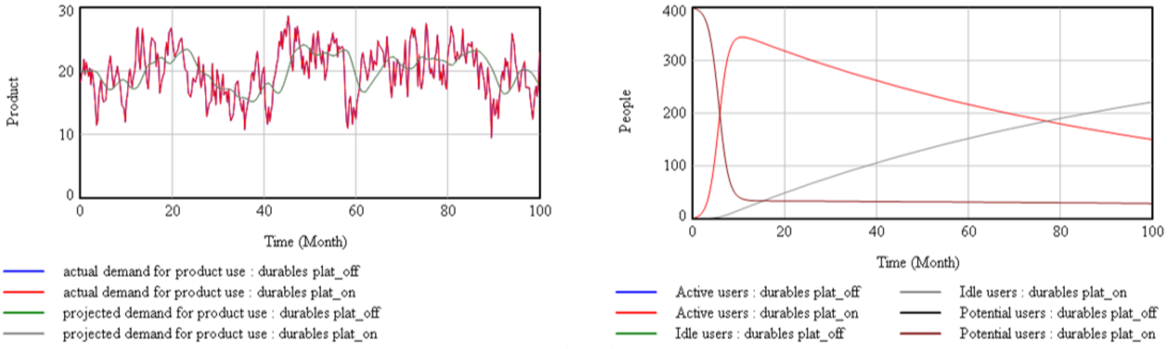

**Figure 3-3.a – actual and projected demand for durables**

**Figure 3-3.b – potential, active and idle users in platform**

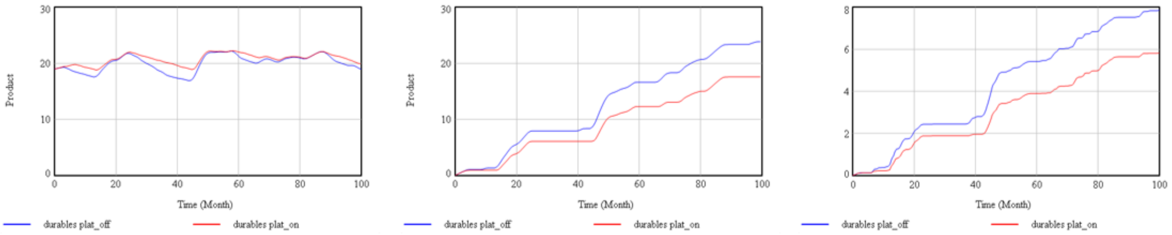

**Figure 3-3.c – total useful products**

**Figure 3-3.d – total acquired products**

**Figure 3-3.e – total unmet demand**

**Figure 3-3** – Simulation of durable products in a small hospital with and without sharing platform

## Consumables: simulations platform on and off

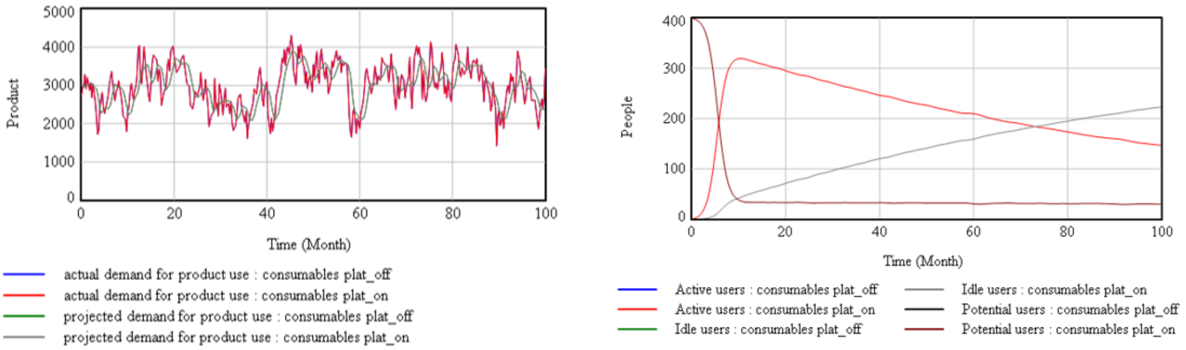

**Figure 3-4.a – actual and projected demand for consumables**

**Figure 3-4.b – potential, active and idle users in platform**

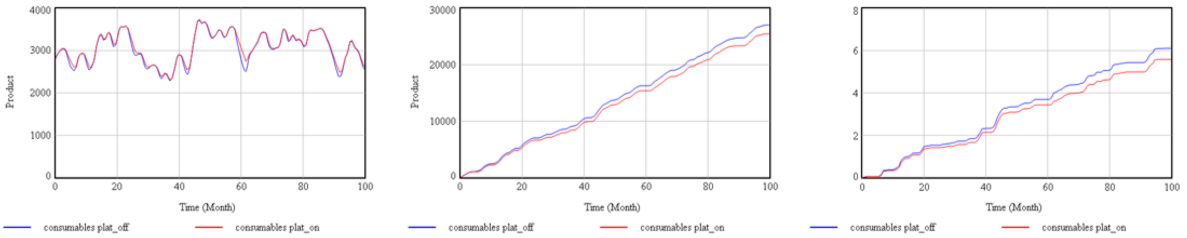

**Figure 3-4.c – total useful products**

**Figure 3-4.d – total acquired products**

**Figure 3-4.e – total unmet demand**

**Figure 3-4** – Simulation of consumable products in a small hospital with and without sharing platform

## 3.5 Discussion

The model can represent the long-term behaviour and impacts of sharing durables and consumables in the scope of one small hospital. It can, thus, influence the adoption of the sharing platform by a potential client. Also, it can assist Company A to communicate or even improve its solution. New mechanisms to improve environmental impacts of this CBM can be enabled by, e.g. expanding platforms for neighbour hospitals or improving the fit to demand by further understanding the reasons for underuse.

Nevertheless, some model limitations must be considered. First, we assume that products become useful as soon as they are added to the platform in the presented model. The actual stock of use cycles of products is not considered. Addressing this could provide a more accurate measure of the level of use for durables. Also, CO2 consumption during the use phase could be investigated. Second, item degradation because of underuse or careless sharing was not considered. Third, the parameters and dynamics of user acquisition need to be further investigated in practice. Nevertheless, the diffusion behaviour works similarly to research pieces used as references, i.e. Borschev and Filippov (2004) and Sterman (Sterman, 2001). Fourth, the model is still not connected to Company A’s operations, costs and revenues. These aspects of the company might influence the overall dynamics of sharing, and these processes should be explicitly considered in the model. This is key to understand the path to enabling the scale-up of Company A’s business model. The dynamic business modelling approach presented by Cosenz and Noto (2018) can help in that direction.

## 3.6 Conclusion

In this work, we have experimented with a CBM in healthcare to verify its long-term impacts. Through the case study of a sharing platform, the dynamics of sharing durables and consumables is represented through (1.) the causal theory of sharing, (2.) a stock and flow model and (3.) verification through simulation. Scenarios based on a plausible set of variables lead to increased understanding of the CBM under research. A contribution of this research is thus to provide evidence that SD modelling and simulation can inform decisions i the adoption of business models aiming for long-term sustainability. The method presented in this research is useful to conceptualise a Circular Economy connected to the dynamics of business models. It can be used to verify the impacts of potentially circular business models in further applications. Directions to expand the model purpose are provided. It holds the potential to inform the design of CMBs by evidencing interventions for more positive impacts.

### Acknowledgements

The authors acknowledge the efforts of Emmanouil Leontaris and Fabio Tejedor for their assistance to build the first version of the model. We acknowledge the contribution of professor Erik Pruyt for guidance for building and understanding SD models. Finally, we are grateful to Vinicius Picanço Rodrigues for reading and contributing to this manuscript.

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# 4 ARTICLE 2: A SYSTEMS REPRESENTATION OF THE CIRCULAR ECONOMY: TRANSITION SCENARIOS IN THE ELECTRICAL AND ELECTRONIC EQUIPMENT INDUSTRY

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**Abstract:** The electrical and electronic equipment (EEE) industry requires a Circular Economy (CE) transition, and decision-makers need support to deal with the complexities of such change. The goal of this research is: (1) providing an SD-based conceptual model for CE systems that clarifies their potential for decelerated flow of resources; (2) providing a simulation model that enables gaining knowledge of the effects of the implementation of CE strategies on nationwide stocks and flows of EEE; and (3) discussing the capabilities of such a model to facilitate CE transitions. The System Dynamics (SD) methodology is used to conceptualise and operationalise CE systems grounded on adjacent theories as industrial ecology (IE) and sustainability transitions. In this research, the resulting Circular EEE SD Model used data from publicly available sources to represent the long-term (1980-2050) adoption of flat display panel TVs in the Netherlands in different scenarios. Diverging restoration infrastructure levels and diverging product lifetimes were examined. Results show that although no scenario led to full eco-economic decoupling, the Circular EEE SD Model enables decision-makers to create "what-if" scenarios to test their assumptions about the potential effects of CE strategies to achieving transitions. The model is fully available for verification, modification, and use.

**Keywords:** sustainability; systems-thinking experimentation; forecasting; business policy; public policy

**Status:** Available online at the Technological Forecasting and Social Change journal.

**List of abbreviations**

| | |
|---|---|
| CE | Circular Economy |
| CLD | Causal loop diagram |
| EEE | Electrical and electronic equipment |
| IE | Industrial ecology |

| | |
|---|---|
| MFA | Material flow analysis |
| PPP | Purchasing power parity |
| SD | System Dynamics |
| SFD | Stock and flow diagram |
| WEEE | Waste of electrical and electronic equipment |

## 4.1 Introduction

For the last several decades, the great acceleration of socioeconomic activities has led to an intense expansion of resource usage and emissions into the Earth system (Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015). An additional 2 billion people on Earth by 2050 and expanding per capita consumption may aggravate the situation. In this context, the Circular Economy (CE) is set as an advanced production and consumption system that may lead humanity towards sustainable development (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). It relies on the systematic application of strategies that can decelerate the flow of resources while enabling enhanced value creation (Bocken, de Pauw, Bakker, & van der Grinten, 2016). CE systems have the potential of breaking the mass-value-carbon nexus by decoupling the access to products and services from the inflow of resources and outflow of emissions (de Wit, Verstraeten-Jochemsen, Hoogzaad, & Kubbinga, 2019). Transitioning to a CE system requires a profound rethinking of the prevailing take-make-dispose linear model. Such transition calls for thinking in systems (Ellen MacArthur Foundation, 2012) and systemic transformations (Gorissen, Vrancken, & Manshoven, 2016).

Being able to handle complexity is a critical competence for decision-makers when transitioning to CE systems (Velte & Steinhilper, 2016). Complexity arises due to the characteristics of CE systems and the required process of change. There are several sources of complexity: first, CE systems occur at multiple levels – micro, meso, and macro – and change is simultaneous (Lieder & Rashid, 2016). Simultaneous change leads to mutual influences and feedback among the processes of an individual firm to the use of resources in entire nations. Second, CE interventions depend on positive reinforcement in increasingly more complex networks of stakeholders seeking to benefit individuals, organisations, society and the environment (Antikainen & Valkokari, 2016; Geissdoerfer, Naomi, Monteiro, Carvalho, & Evans, 2018). Third, in the early phases of the design process, decision-makers need to account for the multiple lifetimes and lifecycles of products (den Hollander, Bakker, & Hultink, 2017; Linder & Williander, 2015). Finally, the fourth source of complexity we highlight is that the adoption of circular strategies may lead to rebound effects when additional impacts hinder or even suppress a localised enhancement of resource effectiveness from new behaviours (Bocken et al., 2016; Ghisellini, Cialani, & Ulgiati, 2015; Zink & Geyer, 2017). There is a clear knowledge gap in this matter, needing to be filled to provide support to decision-makers in redesigning the prevailing production and consumption system.

Modelling and simulation is a tool to facilitate learning about the behaviour of such complex systems, and System Dynamics (SD) is used to study and learn from their long-term counterintuitive behaviour (Senge & Sterman, 1992; Sterman, 2001). It can also help identify where to intervene in a system, which can lead to more desired states (Meadows, 1999). Recently, applications of SD modelling and simulation have examined policy options for transitioning away from using fossil fuels in vehicles (Lu, Liu, Tao, Rong, & Hsieh, 2017) and overcoming policy resistance that inherently arises in sustainability transitions (de Gooyert, Rouwette, van Kranenburg, Freeman, & van Breen, 2016). This is an effective approach to dealing with the complexities arising from CE transitions.

One industry requiring such a transition to a CE is the electrical and electronic equipment (EEE) industry, grounded in a take-make-dispose rationale (Ellen Macarthur Foundation, 2018). EEE plays a central role in society as it facilitates day-to-day tasks, improves living conditions and work environments, and facilitates communication. The aforementioned growing world population, emerging middle class, and increased urbanisation are among the factors affecting the growth of EEE consumption (Baldé, V., Gray, Kuehr, & Stegmann, 2017; Forti, Baldé, Kuehr, & Bel, 2020).

Limited or unreachable supplies of materials and limited recovery capacity of such materials lead to scenarios of scarcity for many of the elements used to produce EEE (European Chemical Society, 2019). Only 17.4% of worldwide waste of electric and electronic equipment (WEEE) is recycled appropriately (Forti et al., 2020), while large amounts of used EEE and WEEE flow from developed to less-developed countries (Wang, Zhang, & Guan, 2016). Indications of a decreasing lifespan for EEE as customers encounter few incentives to acquire more durable options (Prakash, Dehoust, Gsell, & Schleicher, 2015) are likely to aggravate the situation. Also, accelerating technology waves pushes customers to replace still-functional products with new product versions holding increased perceived value (Baldé et al., 2017). Such a production and consumption structure in EEE generates vast amounts of WEEE. Therefore, efforts should be aimed at investigating how the CE concept can assist in decelerating the flow of EEE while supporting its benefits to society.

Per the complexity involved in CE transitions, the key research question addressed in this research is this: *Is it possible to build a model that provides scenarios for Circular Economy transition in a specific industry to support decision-making?* This study tackles the following research gaps. First, from a CE perspective, there is a lack of sector-specific research and very few *quantitative* studies on the CE field, with a disproportionate amount of research focusing on business model innovation (Kirchherr & van Santen, 2019). Second, the study can contribute to the urgent need for tools for learning about configurations of resource-effective strategies under the CE umbrella (Blomsma & Brennan, 2017). Third, this research is positioned within the field of sustainability transitions as a recognition of the growing institutional and consumer-led pressures to transform production and consumption systems (Ellen MacArthur Foundation, 2012; Truffer & Coenen, 2012). Finally, a systemic perspective of the different lifecycle phases and CE strategies in researching the EEE industry is also lacking (Bressanelli, Saccani, Pigosso, & Perona, 2020).

We establish three complementary goals to tackle the research question. Therefore, we aim at **(1)** providing an SD-based conceptual model for CE systems that clarifies their potential for decelerated flow of resources; **(2)** providing a simulation model that enables gaining knowledge of the effects of the implementation of CE strategies on nationwide stocks and flows of EEE; and **(3)** discussing the capabilities of such a model to facilitate CE transitions. In this research, the model's scope of application is the adoption of flat display panel TVs in the Netherlands and the corresponding CE scenarios. The concepts, models, and discussions presented in this research should contribute to the systems perspective required in transitioning away from the currently take-make-dispose rationale.

## 4.2 Literature Review

### *4.2.1 System Dynamics to enable sustainability and Circular Economy transitions*

Two approaches are commonly adopted to introduce the phenomenon of sustainability transitions: (i) the multi-level perspective (MLP) and (ii) the technological innovation systems (TIS). From the MLP point of view, sustainability transitions occur through dynamic processes in three levels: the regime (i.e., dominant institutionalised structures), the niche (i.e., protected spaces for innovation), and the landscape (i.e., the societal setting that influences both the regime and niche) (Loorbach, 2007). The means a sustainability transition can be top-down, bottom-up, or a combination (Verbong & Geels, 2010). From a TIS perspective, sustainability transitions occur around the development and diffusion of innovations that can lead to a reduced footprint in comparison to the current conditions (Walrave & Raven, 2016). The TIS approach is particularly effective if aimed at redesigning the entire production and consumption systems (Truffer & Coenen, 2012).

Sustainability transitions are multiple-feedback systems where the interactions among system elements determine the current behaviour and the necessary conditions for structural change (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). Feedback occurs both endogenously in the system, involving socio-technical regimes and niches, as well as exogenously from the landscape (Köhler et al., 2018; Papachristos, 2014). Transitions concomitantly occur in the different levels, leading to different time ranges and spatial settings (Raven, Schot, & Berkhout, 2012; Turnheim et al., 2015). They typically start slow due to inertia in the old regime (Köhler et al., 2018) and, when the right conditions are in place, change accelerates and stabilises again, reaching a new state of dynamic equilibrium (Loorbach, 2007). Modelling and simulation methods are, therefore, suitable to cover the complexities of such transitions (Köhler et al., 2019). These methods also support decision-makers in testing their intended interventions in the system through time (Jacobsson & Bergek, 2011), and to envisioning "major transformations of society-nature relations" (Fischer-Kowalski, 2011, p. 158). Within the field of quantitative modelling and simulation methods, SD is a particularly promising approach to understand and analyse sustainability transitions (Köhler et al., 2018).

SD is a continuous-time modelling approach capable of representing and simulating feedback-rich structures, with the presence of delays between decisions and their effects

(Sterman, 2001). Causal loop diagrams (CLDs) and stock and flow diagrams (SFDs) are the two most established diagramming conventions in the field of SD. CLDs represent the fundamental feedback structures of a system, where reinforcing and balancing loops determine the behaviour of the system (Lane, 2000; Senge & Sterman, 1992). Simulations are enabled by SFDs through differential equations and numerical methods that quantify the relationships in structures and represent the behaviour of particular stocks accumulating and depleting over time (Lane, 2000; Senge & Sterman, 1992). Model users interpret the results of those simulations, compare them to what they believe should happen, and learn from this process. In this sense, SD modelling and simulation can enable fast learning about a particular system's behaviour and the identification of leverage points which lead to desired behaviours in the long-term (Sterman, 2001).

Complex systems are composed of a multitude of actors with multiple links of causes and consequences for even small changes, which occur in different time scales in different parts of the system (Sterman, 2000). This definition for complex systems fits modelling, simulation and understanding of circular and sustainability-driven transitions. CE systems present multiple levels of implementation, forms of providing stakeholder value, products with varying lifetimes and lifecycles, and the possibility of rebound effects from circular strategies implementation, as presented in the Introduction. Sustainability transitions also involve feedback-rich systems, occur in multiple levels or scales, and require the rearrangement of the incumbent structure and continuous replacement by a more sustainable regime.

Several studies in the fields of sustainability transitions, business models for sustainability, and CE have employed SD modelling and simulation. In the sustainability transitions field, CLDs have been used to describe the positive feedback-loop systems that enable a Technological Innovation System to mature, named 'motors of sustainable innovation' (Suurs & Hekkert, 2012). Walrave and Raven (2016) developed SFD models of such motors of innovation to investigate transition pathways through simulation under different conditions. De Gooyert and colleagues (2016) have applied group model building techniques to represent and explain the sources of policy resistance in sustainability transitions.

In the business models for sustainability field, the conceptual model presented by Abdelkafi and Täuscher (2015) shows the influence of entrepreneur and customer behaviour to enable sustainable value creation. In turn, Cosenz, Rodrigues and Rosati (2019) provide a conceptual model to represent the feedback structures that emerge when considering environmental, social and economic value in sustainable business modelling. Both conceptual models enable the representation of the concurrent perspective of individuals, organisations and the environment in bottom-up innovation.

In the CE literature, Asif, Lieder and Rashid (2016) applied a multi-method approach combining agent-based modelling (ABM) and SD to grasp the economic and environmental performance of circular solutions comprising the business model, product, and operations levels. Later on, Lieder, Asif and Rashid (2017) expanded the model further, considering the customers' behavioural changes to adopt a circular solution to determining pricing and marketing strategies. Finally, Franco (2019) provides an SD-based simulation model to examine the implementation of circular product design and business model initiatives. In her investigation, the behaviour of short-lifetime and long-lifetime enables testing the combinations of circular strategies by a single firm.

Modelling and simulation through SD have enabled discussing transitions to more effective systems. Nevertheless, there is no framework to conceptualise CE systems and their multiple sources of dynamic complexities. Also, only a few of the identified modelling initiatives get to test the behaviour of resources through simulation, while none of them makes a systematic application of real data to do it. Besides, none of these initiatives permits the examination of nation-wide resources dynamics as they focused on bottom-up innovation. In the following section, a conceptual model applying the concepts of stocks, flows and causal links describe CE systems.

### *4.2.2 The Circular Economy: decelerating the flow of resources*

The CE represents a systemic perspective of the production and consumption systems that can lead humanity to a sustainable future. It responds to what Stahel (1997) named as “the linear structure of the industrial economy” by envisioning a closed system that permits only certain types of transfer with the surroundings. CE systems make use of notions of ecosystem ecology to confront completely linear systems that rely on external resources and sinks for emissions with the possibility of entirely circular systems self-sustained by the internal flow of resources (Lifset & Graedel, 2002).

Some principles enable achieving CE systems (Ellen MacArthur Foundation, 2013): first, only renewable sources of energy and material can enter a CE system; second, the circular flows of resources permit the CE system to attend people’s needs continuously; third, as output, there are no such concepts as negative externalities or waste. According to these three principles, resources are stocks to be kept in use as effectively as possible, renewables should be primarily considered as inflows to the system, and the outflows should either get back to the system as a nutrient or cause no harm to Earth systems. Stocks and flows are commonly embedded in CE systems definitions, and the definition provided by the Ellen MacArthur Foundation is likely the one responsible for setting the systems perspective into the core of CE discussions (Kirchherr, Reike, & Hekkert, 2017).

Figure 4-1 details an initial conceptual model for CE systems. In this conceptual model, resources flow from the biosphere towards the customer in the anthroposphere. The boundaries of the production and consumption systems (indicated by the clouds) represent the biosphere. Circular strategies permit the effective use of resources by narrowing, closing and slowing their flows (Bocken et al., 2016; Geissdoerfer et al., 2017). This categorisation for CE strategies developed by Bocken and colleagues (2016) is fundamental for several subsequent categorisations and is capable of expressing the essential structure of stocks and flows in a CE. However, the continued lack of a representation in the appropriate notation was an obstacle to further operationalisation. The combination of CE strategies aims at enabling the constitution of a *"lake economy"*, where decreased throughput of resources and emissions leads to increased value creation (Stahel, 1997, 2016).

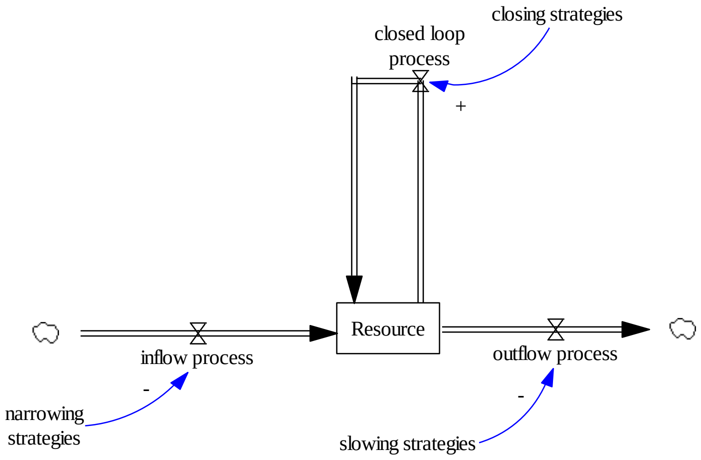

**Figure 4-1** – System Dynamics conceptual model for a Circular Economy system

The stocks in the diagram are resources in their multiple states – products, parts and materials – and they might accumulate or deplete over time (Thierry, Salomon, Van Nunen, & Van Wassenhove, 1995). While consumables are degraded or absorbed by consumers in the moment of benefit, durable products provide benefits through services enabled by them. As resources have specific toxicity affecting biological systems, consumables should be conceived as part of the biological metabolism, and durables as part of the technical metabolism (Braungart, Mcdonough, & Bollinger, 2006). In a CE, when products become obsolete, i.e. when they lose perceived value, they are 'presources'[15] for other products, parts and materials depending on the possibilities for recovery (den Hollander et al., 2017).

The flows determine the rates of change of stocks. The former represent particular processes that shape the availability of resources. Humans are the primary catalyst for such processes – we represent labour that enables value creation activities and the demand for consumption or use (Ayres, 1994). Humans are also highly involved in the obsolescence process. The customer holds an active role in obsolescence when consuming or using the product. In such a process, products lose their perceived value over time (den Hollander et al., 2017). Perceived value brings customer perception to the process, where obsolescence may or may not occur as a result of reduced functionality (Burns, 2010).

Obsolescence can be resisted, postponed or reversed (den Hollander et al., 2017). In this sense, the CE strategies influence the inflow-outflow structures decelerating the flows of resources. Slowing strategies help to decrease either the outflow processes by preventing failure or the inflow processes by enhancing the level of use. Closing strategies enable the

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[15] den Hollander and colleagues have coined the term 'presource' to characterise "obsolete products awaiting for recovery", where products are considered on their multiple states – products, parts, and materials.

restoration of presources to return to customers' direction. Therefore, products may hold multiple use cycles and even multiple lifetimes according to the recovery operations put into practice (den Hollander et al., 2017). In turn, narrowing[16] strategies make use of abundant, non-toxic resources, aiming at a net-positive impact.

Figure 4-2 details the conceptual model employing specific CE strategies from multiple studies (Bocken et al., 2016; Guzzo, Trevisan, Echeveste, & Costa, 2019; Lüdeke-Freund, Gold, & Bocken, 2018). Various specific CE strategies are mentioned in the literature. In the figure, some of the strategies, such as servitising, maintenance, reprocessing, and recycling, exemplify the possible structures for achieving a decelerated flow of resources. The initial and final states of resources and the processes these strategies influence determine their positioning in the figure. The causal links indicate if they positively influence the desired restoration process or if they negatively influence resources' obsolescence or toxicity. The detailed model conceptually describes the use of strategies that, if systematically combined, may enable fully CE systems. When fully circular, these systems would not lead to additional extraction or discarding that negatively impact Earth systems.

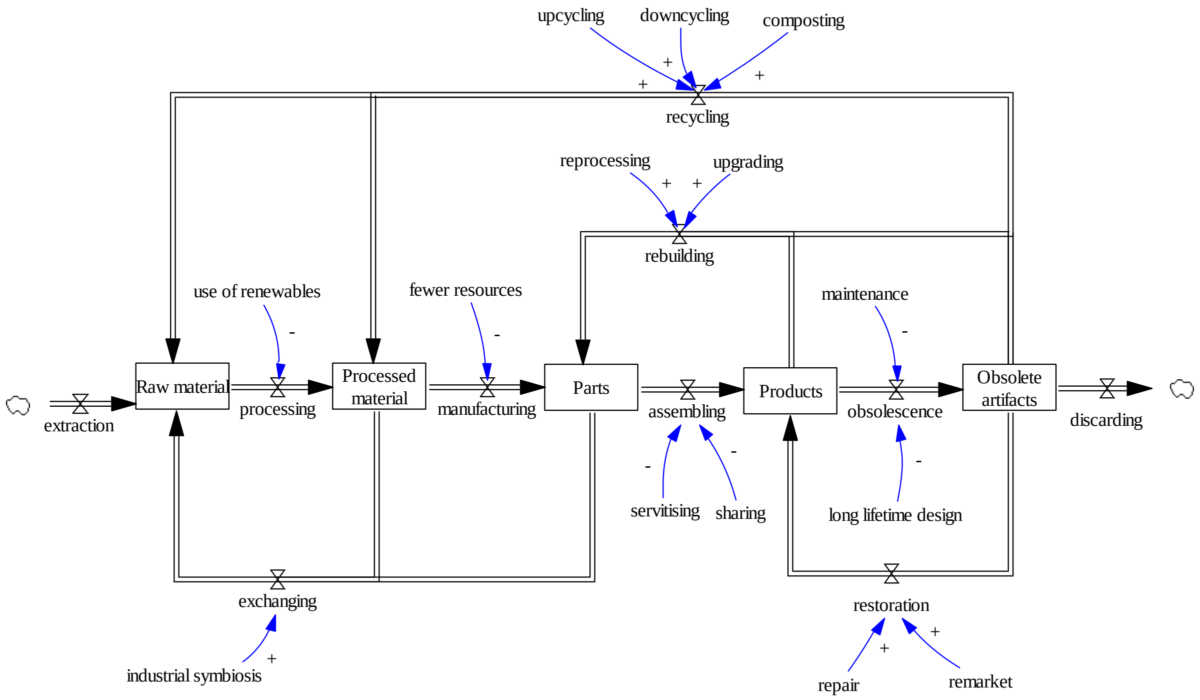

**Figure 4-2** – System Dynamics detailed model for a Circular Economy system

The two aggregate SD conceptual models presented in this section represent crucial aspects of industrial ecology (IE) and CE definitions. They allow the investigation of the influence of CE strategies on stocks and flows of resources. The identified gaps in systems

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[16] 'Narrowing' has been employed in research to describe CE strategies for the inflow of resources. However, one may consider Braungart and colleagues (2006) who argue that the quality of processes outflows – and not their quantities – are the main issue in a production and consumption system. They go further by envisioning that such systems should aim at increasing the value of stocks through time. In such a scenario, accelerating the flow of resources is even desired.

transitions and the conceptual models proposed ground the effort to develop a simulation model for nationwide stocks and flows of resources under specific CE strategies.

## 4.3 Material and Methods

System Dynamics enables experimenting with the behaviour of systems with interconnected causality to develop theory about patterns of systems behaviour (Davis, Eisenhardt, & Bingham, 2007). It combines deduction and induction to enable theory building from existing theory and available empirical data (Schwaninger & Grösser, 2008). The construction of models occurs mainly from deductive reasoning by formalising theory through the modellers' mental models. Validation relies on empirical data to test the assumptions that were defined when developing the model. SD modelling is particularly useful to develop middle-range theories, providing empirical ground and step-by-step validation to connecting theory and practice (Schwaninger & Grösser, 2008). In this research, SD is used to conceptualise and operationalise CE systems grounded on the theories of IE and sustainability transitions.

This research followed the standard and general process prescribed by Sterman (2000) for SD modelling and simulation based on the following 5 steps: **(1)** *Problem articulation*, **(2)** *Formulation of Dynamic Hypothesis*, **(3)** *Formulation of a Simulation Model*, **(4)** *Testing* and **(5)** *Policy Design and Evaluation*. This general process for SD modelling aims at clearly identifying and defining a problem within the system boundaries. The scope of the investigation must hold the potential for both theory building and operationalisation. Developing qualitative models assists in identifying variables and potential system behaviours. Enhanced understanding of the system behaviour over time largely depends on the development of working simulation models based on mathematical formulations to connect the variables. Testing the model against expected behaviour and existing data enables modellers, model users, and other stakeholders to develop trust in the model's mechanics and the generated results. Finally, the use of the models enables model users to evolve their understanding of a particular system and identify places to intervene towards more desirable behaviour of the real system. Following we describe the application of the 5-step general SD modelling process in this research.

The first step, *problem articulation*, determined the purpose and scope of the modelling effort. The purpose of our model is to represent long-term nationwide dynamics of EEE stocks and flows when introducing specific interventions for CE strategies implementation. The scope of analysis is the long-term (1980–2050) use of specific EEEs, such as flat display panel TVs and refrigerators, nationwide.

The second step, *formulation of dynamic hypothesis*, encompasses the definition of primary endogenous concepts, structures and hypotheses. This step follows the approach defined by Richmond (1994) using both knowledge from extensive academic research and publicly available data for robust conceptualisation. Knowledge from dynamic material flow analysis (MFA), reliability engineering, closed-loop supply chains and the CE conceptual model described in Section 2.2 underpin the Circular EEE SD Model. Time series and data from WEEE studies and publicly available national and international statistics organisations supported the calibration of the model.

As for the third step, *formulation of a simulation model*, new and existing standard structures available in the SD literature – for example, in the *Business Dynamics* reference book (Sterman, 2000) and *The Molecules of Structure* (Hines, 1996) – were adapted to formulate the simulation model. The simulation model was developed with Vensim DSS Version 8.0.4. Two connected versions of the simulation model describe the behaviour of the system over the defined time span (1980-2050): a *retrospective* model pre-processes the data from 1980 until 2015 and drives the *prospective* model.

The fourth step, *testing*, was iteratively developed with the previous formulation step. The simulation model started with simple structures and a group of exogenous variables, which were then gradually developed into more complex sub-models whenever necessary. The model's behaviour was then continuously tested against available data and modellers' expectations for subsystems' behaviour as this entails a good practice in SD modelling (Pruyt, 2013, p. 87). To enhance validity, model testing for contextual, structural and behavioural validity followed Sterman's (2000) and Schwaninger and Groesser's (2016) guidelines. Tests such as the mass-balance check to verify any gain of mass in the model (Dangerfield, 2014; Schwaninger & Groesser, 2016) and the use of Theil inequality statistics (Oliva, 1995; Sterman, 2000) to verify bias, unequal variation, and unequal covariation of variables during calibration enabled increased confidence in the model. The results of calibration to a baseline scenario, of the mass balance tests and of the Theil inequality statistics are available in this article's Appendix, alongside a compilation of all the testing activities undertaken – see Figure 4-10, Figure 4-11, Table 4-4, and Table 4-5.

Reports obtained from using the SDM-Doc documentation tool (Martinez-Moyano, 2012) provide overview information about the Circular EEE SD Model – all model views and a detailed description of each variable. The model and its documentation, including SDM-Doc reports, tests performed, datasets used, model limitations and a step-by-step guide for model calibration and use are available in an open-access GitHub repository to enhance transparency (access https://github.com/danguzzo/CircularEEE_SDModel ).

The fifth and last step, *policy design and evaluation*, informed the development of specific scenarios for CE strategies regarding the adoption of flat display panel TVs in the Netherlands. Flat display panel TVs are an adequate choice given the significant number of LCD screens sold in the last years, these TVs' emerging replacement by LED screens, and the implementation of underdeveloped restoration processes (Cucchiella, D'Adamo, Lenny Koh, & Rosa, 2015). The adoption exercise constitutes the full adoption of one type of technology, enabling the understanding of the resource flow from initial adoption to stabilisation. The reliable public data on EEE and WEEE use and collection for the Netherlands (Prakash et al., 2015, chapter 4.6.1) justify the choice for the country.

We developed 8 scenarios to demonstrate the use of the model. A baseline scenario was developed based on secondary research. The scenario represents a business-as-usual one for the use of resources to sustain flat display panel TVs in the Netherlands. Scenarios for different levels of CE strategies implementation were designed to demonstrate slowing and closed-loop strategies. The behaviour of stocks and flows in the different scenarios allows comparison and discussions on the structure of CE systems and their potential paths for transition.

## 4.4 Results

### *4.4.1 The Circular EEE SD Model*

The Circular EEE SD Model is a dynamic MFA model, which aims to assess future stocks and flows of resources in the anthroposphere based on past information (Bergsdal, Brattebø, Bohne, & Müller, 2007; Müller, Hilty, Widmer, Schluep, & Faulstich, 2014; Pauliuk & Müller, 2014). The proposed model is composed of four sub-models: (1) technology adoption, (2) EEE obsolescence, (3) EEE and WEEE flows, and (4) material supply. Figure 4-3 represents the major subsystems of the model and their interconnections.

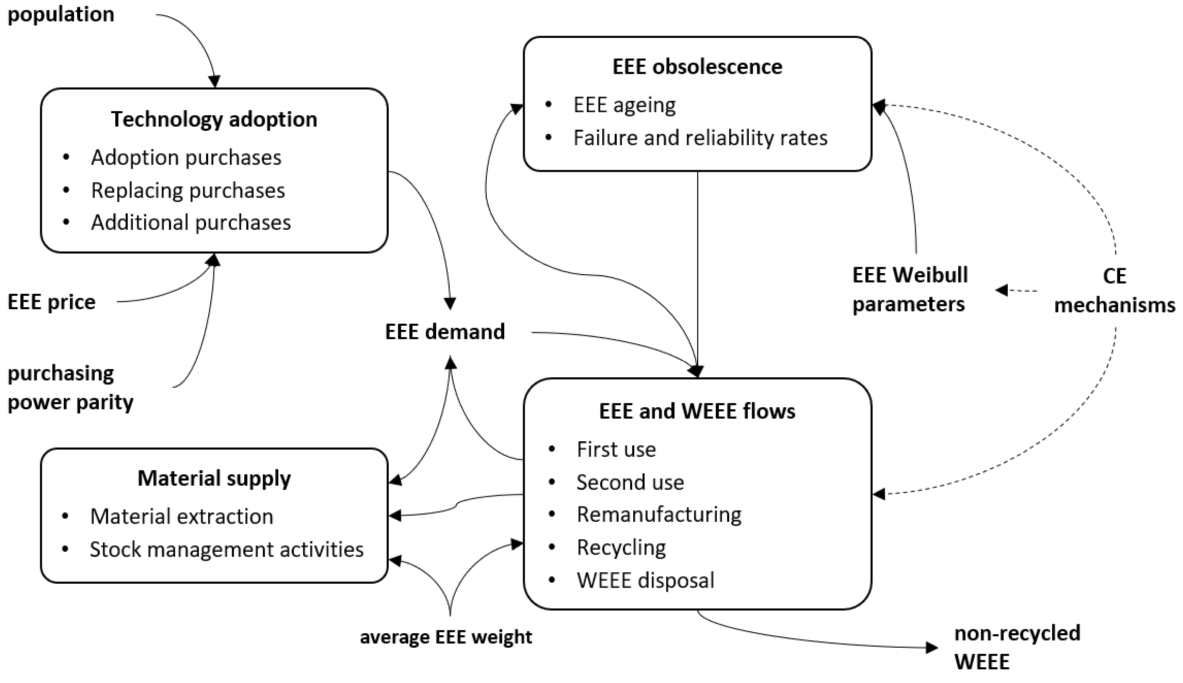

**Figure 4-3** – The Circular EEE SD Model composition: The four sub-models of the Circular EEE SD Model and relationships

The technology adoption sub-model generates demand through adoption, replacement and additional purchases from adopters. Functional EEE products in first and second use represent the unities of electronics artefacts that meet adopters' demand. In this research, EEE products are the flat display panel TVs. The EEE obsolescence process makes use of product-specific Weibull parameters to determine the failure and reliability rates of products in the system while considering the ageing process. EEE products can follow different outflows. They may maintain product status through second use or remanufacturing or be converted into material through disposal and potential recycling. The decisions for which path resources follow depend on products' available lifetime, restoration capabilities and infrastructure available. CE mechanisms are exogenous variables capable of adjusting CE strategies implementation, i.e., influencing obsolescence or restoration capabilities in the model. Non-recycled WEEE is the "sink" of the system, i.e., products achieving the status of waste and not recycled back into material accumulate as non-recycled WEEE. Finally, the material supply subsystem determines material extraction based on stock management activities and the average EEE weight.

Table 4-1 details the modelling assumptions that underpin the four sub-models. The sub-models are described in the following sections.

**Table 4-1** – Modelling assumptions to formulate the simulation model

| Sub-model | Assumption | Reference |
|---|---|---|
| Technology adoption | A Bass diffusion model is adequate to represent the adoption of technology. | (Bass, 1969; Benvenutti, Ribeiro, & Uriona, 2017; Hines, 1996; Rogers, 2003; Sterman, 2000) |
| | Socioeconomic information as purchasing power parity per capita, population and price are adequate variables to define the adoption of an EEE technology. | (Müller et al., 2014; van Straalen, Roskam, & Baldé, 2016) |
| | There are three different types of purchases: first purchases, replacing purchases, and additional purchases. | (Sterman, 2000; Waldman, 2003) |
| | First use and second use EEE equally address the demand for EEE products. | (Müller et al., 2014) |
| EEE obsolescence | The Weibull distribution functions are adequate to determine the probabilities for product failure. | (Müller et al., 2014; Murakami, Oguchi, Tasaki, Daigo, & Hashimoto, 2010; Oguchi, Murakami, Tasaki, Daigo, & Hashimoto, 2010) |
| | The Weibull shape and scale parameters remain constant over time. | *Assumption made by the modellers* |
| | Co-flows are adequate structures to model the average age of stocks. | (Hines, 1996; Spengler & Schröter, 2003; Sterman, 2000) |
| EEE and WEEE flows | All decommissioned products become available for second use and remanufacturing before disposal as WEEE. Products will preferably move into second use, then remanufacturing, then recycling. | *Assumption made by the modellers* |
| | The infrastructure level of second use and remanufacturing networks define the coverage and capacity of such restoration processes. | (Govindan, Soleimani, & Kannan, 2015) |

| Sub-model | Assumption | Reference |
|---|---|---|
| | The concept of virtual age is applied to model the average lifetime after the repairing and remanufacturing processes. | (Proske, Winzer, Marwede, Nissen, & Lang, 2016; Yañez, Joglar, & Modarres, 2002) |
| | No imported used EEE is admitted into the system. | *Assumptions made by the modellers* |
| | The infrastructure level of recycling defines the coverage and capacity of such restoration processes. | |
| | The recyclability and remanufacturability parameters remain constant over time. | |
| | Non-recycled WEEE stock is the sink of the system. | (Ayres, 1994) |
| Material supply | A supply chain structure is adequate to model the acquisition of inputs into a process and the stock management task. | (Hines, 1996; Sterman, 2000) |

### *4.4.1.1 Technology adoption sub-model*

The technology adoption is defined by a diffusion of innovation (DoI) model, which is an adequate structure to represent the adoption of a given technology in a specific region (Bass, 1969; Benvenutti et al., 2017; Hines, 1996; Rogers, 2003; Sterman, 2000). This sub-model represents the dynamics of adopters through time to obtain the demand for products. Figure 4-4 represents the structure used to determine EEE demand from the diffusion model.

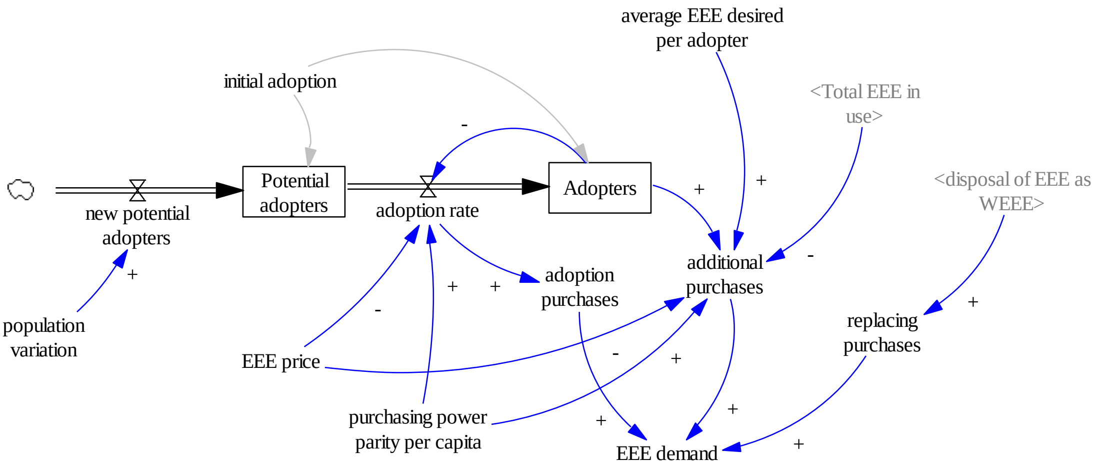

**Figure 4-4** – Technology adoption in the Circular EEE SD Model

In the Circular EEE SD Model, demand is a result of three types of purchases: adoption purchases, replacing purchases and eventual additional purchases of that given technology (Maier, 1998; Sterman, 2000). Adoption purchases happen when the population adopt the technology – in the case of EEE for individual use, the number of inhabitants matters; in the case of EEE for collective use, the number of households is of concern. Replacing purchases are a result of the products leaving the system as WEEE. Additional purchases emerge from adopters that need more than one product at a time.

Socioeconomic variables are broadly used in dynamic MFA models to determine market demand (Müller et al., 2014). In our model, the PPP per capita and the EEE price determine the fraction of the population that is willing to adopt the technology. If prices are adequate to what people can pay, they will become adopters of that technology. The demand for additional purchases also relies on the purchasing power of the population and the EEE price. Finally, the population variation over time defines growth in the size of the market.

#### *4.4.1.2 EEE obsolescence sub-model*

The obsolescence sub-model determines EEE products decommissioning based on the average age of products. Decommission in the model means to withdraw from active service. Similar structures determine the decommissioning of products in first and second use. Specifying the average age of products is a challenge in MFA models as EEE products may pass through many stages, from production to eventual disposal, holding multiple references to define their lifespans (Murakami et al., 2010). In the Circular EEE SD Model, the reference to specify the average age is the period from commissioning – or product activation – until the present time. A co-flow, i.e. parallel stock and flow structures, determines the EEE ageing process. Co-flows are frequently used to model the dynamic characteristics of stocks (Hines, 1996; Spengler & Schröter, 2003; Sterman, 2000). Figure 4-5 represents the structure used to determine the decommissioning probability from the flow of EEE products.

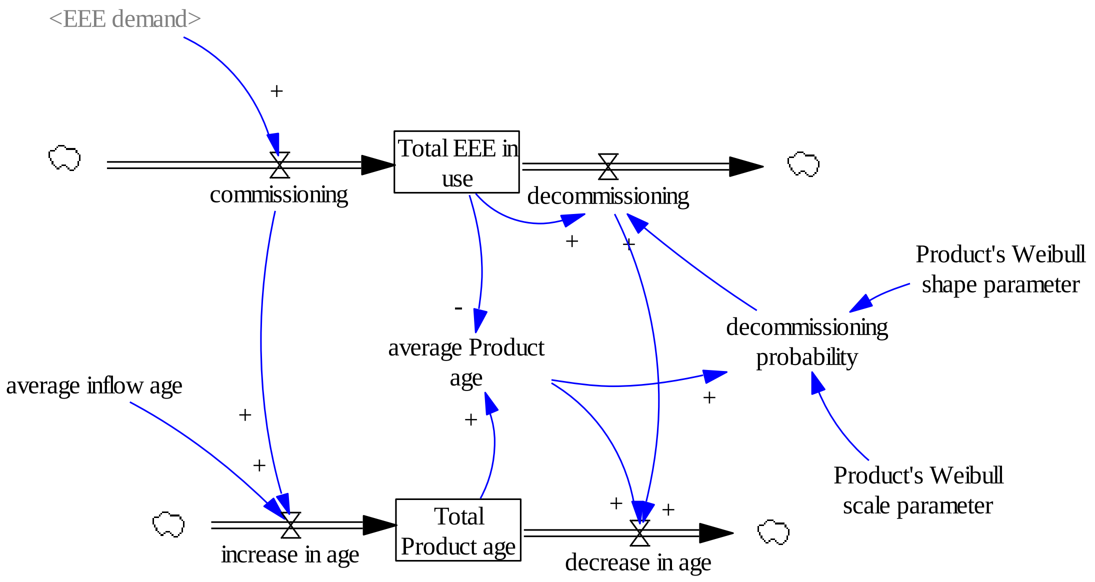

**Figure 4-5** – EEE obsolescence in the Circular EEE SD Model

In dynamic MFA models, the use of lifetime distribution equations is essential to quantify the outflow of durable goods, and Weibull distribution functions are commonly employed (Müller et al., 2014; Murakami et al., 2010; Oguchi et al., 2010). Weibull distribution functions originate from the reliability engineering field to forecast failures (Kapur & Pecht, 2014). Two parameters characterise the distribution: scale (α) defines the lifetime at which 63.2% of units will fail, and shape (β) identifies the pattern of failure over time. In other words, the shape parameter determines if a given type of product presents decreasing ($\beta<1$), constant ($\beta=1$), or increasing ($\beta>1$) failure rates over its lifetime. The Weibull failure rate function determines decommissioning probability in the Circular EEE SD Model considering the average age of EEE products. This function represents the probability of failure at time *t*, considering the sample of products that have already survived to time *t* (Kapur & Pecht, 2014).

In the Circular EEE SD Model, the failure rate considers the average age of products to determine the decommissioning probability. Obsolescence regards only resources holding product status. When restored products flow back as useful products, their rejuvenated age is tracked (see subsection below). The failure rate also defines the second use decommissioning probability. Products decommissioning from first and second use accumulate as available used EEE.

#### *4.4.1.3 EEE and WEEE flows sub-model*

The EEE and WEEE flows sub-model enables decommissioned EEE to enter the restoration market. If products do not fit second-use and remanufacturing markets, EEE products are disposed of as WEEE reacquiring a material status. Disposal means the moment when EEE products lose their functionality and become WEEE. It is critical to note that although remanufacturing and refurbishment hold different meanings in the literature[17], the term remanufacturing is generically used in the model to cover both processes. Figure 4-6 represents the paths for available used EEE and WEEE considering the influence of CE mechanisms.

Three factors define whether available used EEE will ever be reused or restored in the Circular EEE SD Model.

The first factor is the coverage and capacity of collection and redistribution networks, critical in making the presources available for restoration (Govindan et al., 2015). In the model, an infrastructure level index that ranges from 0 to 4 defines the coverage and capacity for second use, remanufacturing and recycling. For instance, when setting the second-use infrastructure level to 2, 40% of the available used EEE will be accessible for the second-use market.

The quality expected by the customer for repaired and remanufactured products in comparison to the quality providers can reach through restoration are critical elements (King, Burgess, Ijomah, & McMahon, 2006). Two other key factors emerge – restoration effectiveness and the expected lifetime for the use of restored products. Zero to 4 repairing and remanufacturing infrastructure levels define restoration effectiveness. In the Circular EEE SD

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[17] According to King and colleagues (2006) remanufacturing leads to product recovery to at least as-new performance, whereas through refurbishment only faulty components (or near to the point of failure) are restored.

Model, restoration processes rejuvenate used products using the concept of the virtual age of goods. Virtual age is the calculated age of the asset after a recovery process (Yañez et al., 2002). Customers compare the virtual age of products after recovery to their expectations for a minimum time of use after purchasing remanufactured or second-use products. Available used EEE embark into new useful lives according to survival probability to the minimal expected lifetime after restoration, calculated using the Weibull conditional reliability function.

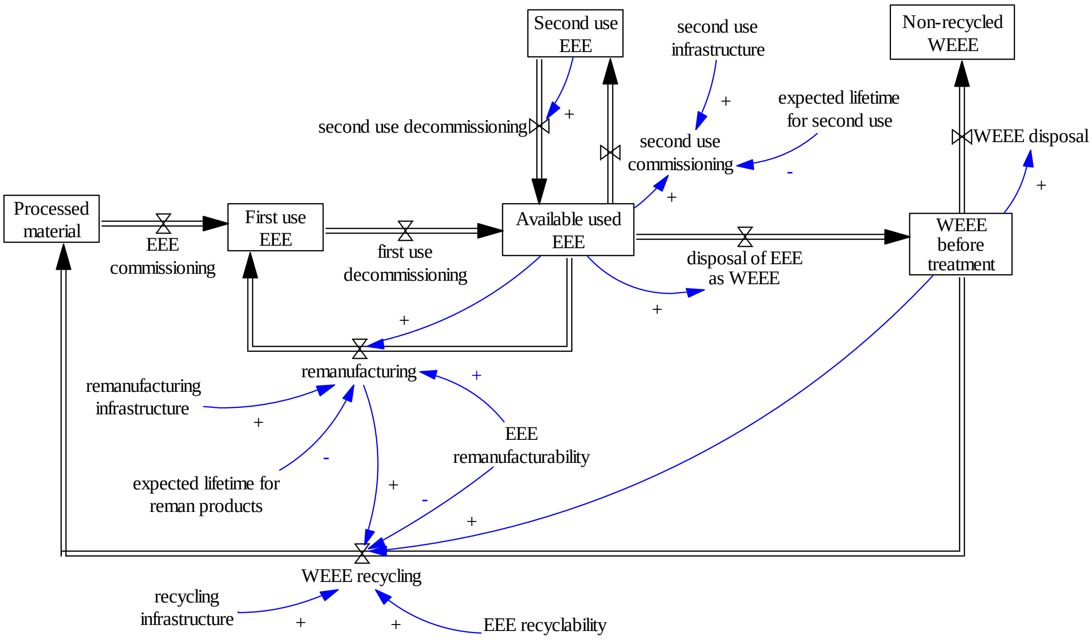

**Figure 4-6** – EEE and WEEE flows in the Circular EEE SD Model. In the figure, second use and remanufacturing infrastructure comprise the coverage and capacity of such processes as the restoration effectiveness

Available used EEE are eventually disposed of and accumulate as WEEE before treatment. Apart from the coverage and capacity of collection infrastructure, the recyclability of WEEE (Zeng & Li, 2016) defines the fraction of material that is recycled. The remanufacturing process also feeds recycling. Such spillover is defined by the product remanufacturability (Ardente & Mathieux, 2012), that considers some products entering the remanufacturing process are broken beyond restoration or will be broken during the process. All recycled material feeds the stock of processed material, decreasing the need for extraction.

Following the law of conservation of mass, *“there are only two possible long-run fates for materials: dissipative loss and recycling or reuse”* (Ayres, 1994, p. 31). In the model, accumulated WEEE that is not handled by the recycling markets ends as non-recycled EEE. The paths of non-recycled EEE flowing into mixed residual waste, incineration, landfilling and exporting are not detailed. Imported used EEE or WEEE is disregarded, too.

### *4.4.1.4 Material supply sub-model*

The material supply sub-model determines the demand for processed material. A stock management structure (Hines, 1996; Sterman, 2000) defines the extraction rate of material relying on adjustments to expected losses of material from the system, expected EEE demand and the desired stock of processed material drives extraction – see Figure 4-7.

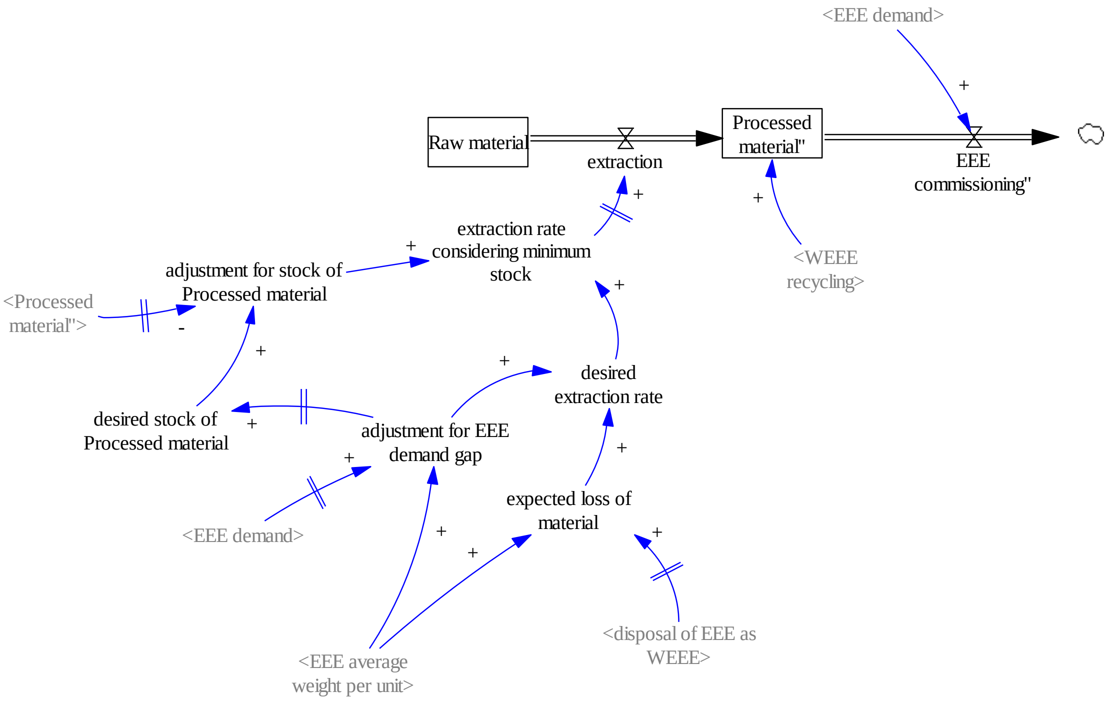

**Figure 4-7** – The material supply chain in the Circular EEE SD Model. Double line marks across an arrow represent information delays. Such representations specify measurement, reporting and perception delays inherent to the stock management process

The expected loss of material from the system and adjustments to attending EEE demand compose the desired extraction rate. In other words, if possible, the ones leading the process would only extract material to meet the actual demand in addition to material lost from the system. However, the delays in obtaining supply chain information and the delay of the extraction process – from orders until the actual extraction of material – are considered. Additionally, a stock of processed material minimises the odds of material shortage.

In the model, products are considered in unities of equipment while the material is considered in kilograms. When EEE is put on the market, the average weight of equipment defines the quantity of material used. The same applies when EEE become WEEE. The initial stock of material available in the simulations does not represent any real available stock of material used in EEE production. Instead, a value that facilitates presenting and discussing the results was employed.

### *4.4.2 Simulation of CE implementation scenarios*

The Circular EEE SD Model uses time series for nationwide information about EEE from the Global E-waste Monitor 2017 (Baldé et al., 2017; Forti, Baldé, & Kuehr, 2018) and from the Waste over Time model developed by Statistics Netherlands (van Straalen et al., 2016). Socioeconomic information such as population and number of households, PPP per capita, and EEE prices are input as exogenous variables from publicly available national and international statistics organisations. The variables, ranges and sources for data preparation to run the model are available in Table 4-2.

Variables are classified into country-specific – meaning they constitute information for the region; EEE-specific – constituting information for that type of product; and country- and EEE-specific – constituting information for that type of product in that region.

**Table 4-2** – Variables and sources for data preparation

| Class | Variable | Type | Availability Range | Source |
|---|---|---|---|---|
| Country-specific | PPP per capita | f(t) | 1980–2050 | International Monetary Fund (2019); PricewaterhouseCoopers (2017) |
| Country-specific | total households | f(t) | 1980–2050 | Statistics Netherlands (n.d.) |
| Country-specific | Population | f(t) | 1980–2050 | Statistics Netherlands (n.d.) |
| EEE-specific | EEE average weight per unit | f(t) | 1980–2024 | van Straalen et al (2016) |
| EEE-specific | Weibull scale | constant | 2016 | Forti et al. (2018) |
| EEE-specific | Weibull shape | constant | 2016 | Forti et al. (2018) |
| EEE-specific | recyclability | constant | 2016 | Zeng and Li (2016) |
| EEE-specific | EEE unit price | Lookup | 1980–2015 | Morrison (2017) |
| Country and EEE-specific | historic annual EEE put on the market | f(t) | 1980–2021 | van Straalen et al. (2016) |
| Country and EEE-specific | historic annual disposal of EEE | f(t) | 1980–2024 | van Straalen et al. (2016): |

Eight different scenarios show the flow of resources under different levels of CE strategies for flat display panel TVs in the Netherlands. Scenarios differ in the level of infrastructure for the second use, repairing, remanufacturing and recycling regional capabilities. Moreover, a lifetime ratio enables testing EEE designed for increased and decreased lifetimes. These strategies are extensively discussed in the CE literature and demonstrate slowing (longer lifetime design) and closed-loop (reuse, remanufacturing, and recycling) structures. Each scenario represents a different regime of CE strategy implementation and runs as follows:

**S1. Linear economy (NL408_LE):** scenario applying null restoring capabilities. In this scenario, products are introduced in the market disregarding any of the circular strategies considered in the model;

**S2. Baseline (NL408_Baseline):** scenario representing the expected restoring capabilities in the Netherlands. The second use and repairing infrastructure are obtained based on Huisman et al. (2012), the remanufacturing infrastructure based on Parker et al. (2015), and the recycling infrastructure based on Huisman et al. (2015). This scenario presents a baseline for comparison to other simulated conditions;

**S3. Advanced Second Use (NL408_advSU):** scenario representing a mature market for used products, where the network of buying and selling used goods is available to 80% of the household. It is considered a significant capacity to repair products – products rejuvenate in 40% when repaired. Other capabilities follow the Linear Economy scenario;

**S4. Advanced Remanufacturing (NL408_advRM):** scenario representing a mature take-back network that enables manufacturers to access 80% of the available used EEE. The manufacturer holds a significant remanufacturing capability – products rejuvenate in 90% when remanufactured. Other capabilities follow the Linear Economy scenario;

**S5. Advanced Recycling (NL408_advRC):** scenario representing a mature compliant recycling network that enables recyclers to collect 80% of the stock of WEEE before treatment. Other capabilities follow the Linear Economy scenario;

**S6. Shorter lifetime (75%) (NL408_0,75life):** in this scenario, products are designed for a shorter life with a similar failure rate pattern through time to the baseline. Other capabilities follow the Linear Economy scenario;

**S7. Longer lifetime (150%) (NL408_1,5life):** in this scenario, products are designed for a longer life with a similar failure rate pattern through time to the baseline. Other capabilities follow the Linear Economy scenario;

**S8. Advanced CE (NL408_advCE):** scenario making use of the best-implemented conditions for CE mechanisms from other scenarios.

Table 4-3 shows the variables input that defines each scenario (white fields) and the value of the variables they influence (grey fields) that are relevant for simulation outcomes for each scenario (S1 through S8). The EEE recyclability is set at 37% for flat display panel TVs (Zeng & Li, 2016), and remanufacturability is set at 80% for all simulation runs. Finally, a minimal remaining lifetime fraction after restoration determines the flow of products into second use and remanufacturing: minimal remaining lifetime is 50% for second-used and 80% for remanufactured products in all scenarios.

**Table 4-3** – Constant variables input for scenarios composition. White fields represent the inputted variable for scenarios, and grey fields represent the value of the variables they influence.

| Variable \ Scenario | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| lifetime ratio (dimensionless) | 1 | 1 | 1 | 1 | 1 | 0.75 | 1.5 | 1.5 |
| Weibull scale (dimensionless) | 11.75 | 11.75 | 11.75 | 11.75 | 11.75 | 8.81 | 17.63 | 17.63 |
| second use level (dimensionless) | 0 | 3 | 4 | 0 | 0 | 0 | 0 | 4 |
| fraction EEE second-hand market can handle (dimensionless) | 0 | 0.2 | 0.8 | 0 | 0 | 0 | 0 | 0.8 |
| repairing level (dimensionless) | 0 | 2 | 4 | 0 | 0 | 0 | 0 | 4 |
| average repair effectiveness (dimensionless) | 0 | 0.2 | 0.4 | 0 | 0 | 0 | 0 | 0.4 |
| lifetime fraction for second use (dimensionless) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| expected lifetime for second use (year) | 5.21 | 5.21 | 5.21 | 5.21 | 5.21 | 3.90 | 7.81 | 7.81 |
| reman level (dimensionless) | 0 | 2 | 0 | 4 | 0 | 0 | 0 | 4 |
| fraction EEE reman market can handle (dimensionless) | 0 | 0.2 | 0 | 0.8 | 0 | 0 | 0 | 0.8 |
| average reman effectiveness (dimensionless) | 0 | 0.3 | 0 | 0.9 | 0 | 0 | 0 | 0.9 |
| remanufacturability EEE (dimensionless) | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| lifetime fraction of reman products (dimensionless) | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| expected lifetime of reman products (year) | 8.33 | 8.33 | 8.33 | 8.33 | 8.33 | 6.25 | 12.49 | 12.49 |
| recycling level (dimensionless) | 0 | 3 | 0 | 0 | 4 | 0 | 0 | 4 |
| fraction of WEEE formally collected (dimensionless) | 0 | 0.5 | 0 | 0 | 0.8 | 0 | 0 | 0.8 |
| recyclability of EEE (dimensionless) | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 |

Figure 4-8 shows the behaviour of six critical stocks and flows for the eight defined scenarios: (4-8.a) Availability of Raw material (kg); (4-8.b) Material extraction (kg/year); (4-8.c) EEE commissioning (unit/year); (4-8.d) Total EEE in use (units); (4-8.e) Disposal of EEE as WEEE (unit/year) and (4-8.f) WEEE recycled (kg). In all cases, the system is already close to dynamic equilibrium in 2030, after achieving full adoption of the technology. While market saturation is low, most purchases come from first-time purchasers adopting the technology. In saturated markets, new purchases mainly indicate old product replacement and marginal population increments. Dynamic equilibrium indicates a saturated market where purchases are made to replace obsolete products. Results are presented ranging from 1990 to 2040 to improve visualization, with no conclusions being altered.

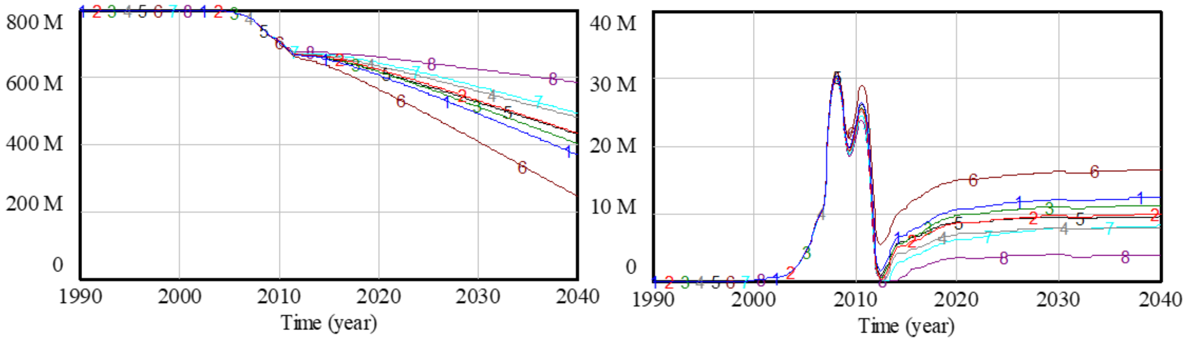

**Figure 4-8.a – Availability of Raw material (kg)**

**Figure 4-8.b – Material extraction (kg/year)**

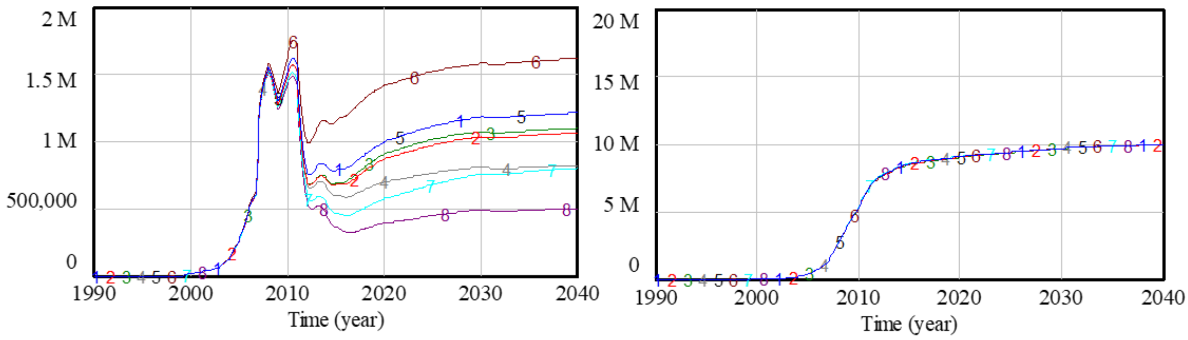

**Figure 4-8.c – EEE commissioning (unit/year)**

**Figure 4-8.d – Total EEE in use (unit)**

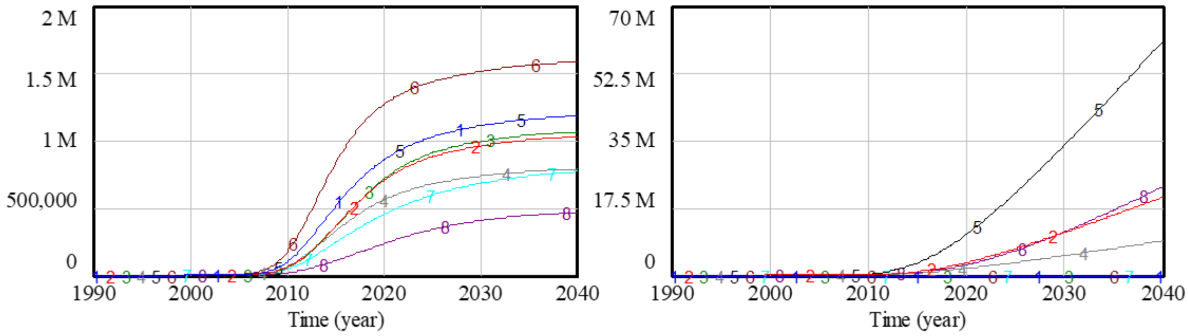

**Figure 4-8.e – Disposal of EEE as WEEE (unit/year)**

**Figure 4-8.f – WEEE recycled (kg)**

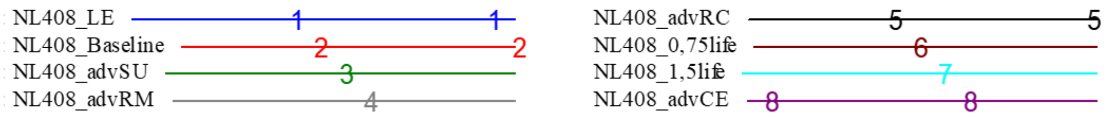

**Figure 4-8** – Critical stocks and flows for the eight defined CE scenarios for flat display panel TVs in the Netherlands. (8.a) Availability of Raw material available in kg; (8.b) Material extraction in kg per year; (8.c) EEE commissioning in unit per year; (8.d) The Total EEE in use in unit; (8.e) Disposal of EEE as WEEE in unit per year; and (8.f) WEEE recycled in kg.

Figure 4-8.a shows the different availabilities of raw material stock for each scenario. Comparing the S2. Baseline with the S8. Advanced Circular Economy scenario, the inflow of raw material was more than double the baseline in the best-case scenario. The worst-case scenario for the raw material stock is S6. It has a 25% shorter lifetime, which led to almost 30% more material extraction by 2040. The gap between the worst- and best-case scenarios is an increase more significant than 150% in the inflow of material in the system.

Figures 4-8.b and 4-8.c show similar shapes among extraction and commissioning, as the stock management structure adapts to the EEE demand. Figure 4-8.d shows that the demand for EEE is met in all scenarios, as represented by the similar curves. The Disposal of EEE as WEEE presented in **Figure 4-8**.e represents the total flow of products that will not be restored as a product and should follow adequate disposal, preferably by full recycling. In the S2. Baseline scenario, we may expect around 1 million flat display panel TVs yearly requiring adequate disposal in the Netherlands alone after 2030.

The combined analysis of Figures 4-8.e and 4-8.c reveals that the EEE is disposed of in similar order of magnitude as they are commissioned after its average lifetime, considering eventual additional lives. The process of EEE obsolescence smooths the peak of EEE commissioning seen in 2010. Although Figure 4-8.f presents S5. Advanced Recycling with the best prospects for total WEEE recycled, S7. Longer lifetime (150%) and S8. Advanced Circular Economy are the ones that minimise the inflow of materials in the system (Figure 4-8.b), and thus, the need for raw material (Figure 4-8.a).

Figure 4-9 outlines products and material flows for each scenario from 1990 to 2040. The scenarios, S1. Linear economy (Figure 4-9.a) and S6. Shorter lifetime (75%) (Figure 4-9.f), present the worst cases in terms of material extraction and EEE production. Only the S4. Advanced Remanufacturing (Figure 4-9.d), S7. Longer lifetime (150%) (Figure 4-9.g) and S8. Advanced Circular Economy (Figure 4-9.h) scenarios provide better results than the S2. Baseline (Figure 4-9.b) in terms of raw material use. Scenario S5. Advanced Recycling (Figure 4-9.e) leads to similar needs for the inflow of material to the S2. Baseline (Figure 4-9.b).

The value of restoring products to as close as possible to an as-new condition before a new use cycle is evident when comparing the S4 – Advanced Remanufacturing – scenario (Figure 4-9.d) and the S3 – Advanced Second Use – scenario (Figure 4-9.c). Although S3 (Figure 4-9.c) shows a substantial commissioning of products to second use, only a limited impact in material extraction is observed since second-use products have shorter use times when compared to new products. Remanufacturing (Figure 4-9.d) influences both commissioning and extraction to a greater extent because of the high restoration capabilities. While S3 (Figure 4-9.c) leads to a worse situation than the baseline in terms of material extraction and production, S4 (Figure 4-9.d) is the third-best scenario.

The comparison between the S6 – Shorter lifetime – scenario (75%; Figure 4-9.f) and the S7 – Longer lifetime (150%; Figure 4-9.g) shows that changes in the lifetime ratio significantly influence the need for EEE commissioning in the long run and, thus, material extraction. This reinforces the value of slowing strategies when looking for CE transitions and increases attention to the effects of developing products with lower lifetimes.

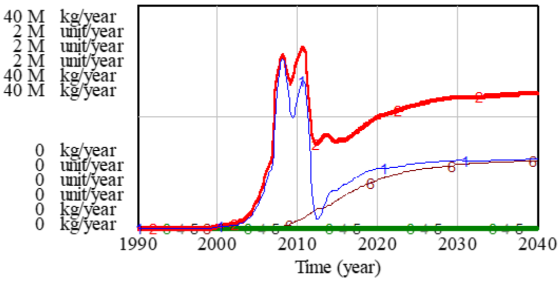

**Figure 4-9.a – S1. Linear economy (NL408_LE)**

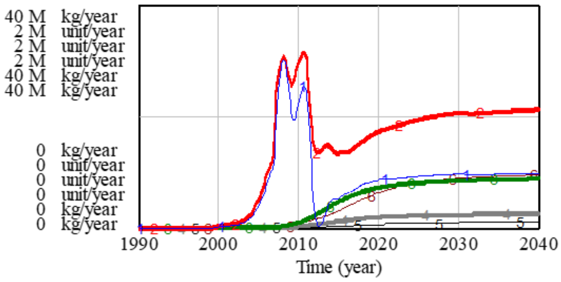

**Figure 4-9.b – S2. Baseline (NL408_Baseline)**

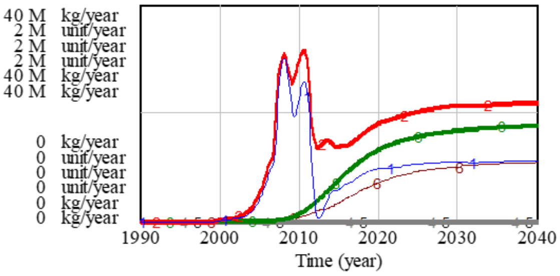

**Figure 4-9.c – S3. Advanced Second use(NL408_advSU)**

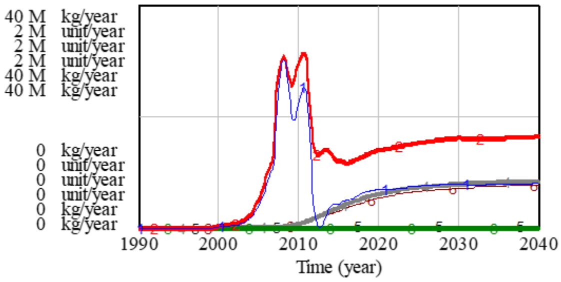

**Figure 4-9.d – S4. Advanced Remanufacturing (NL408_advRM)**

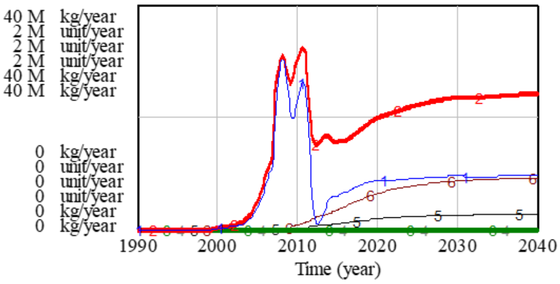

**Figure 4-9.e – S5. Advanced Recycling (NL408_advRC)**

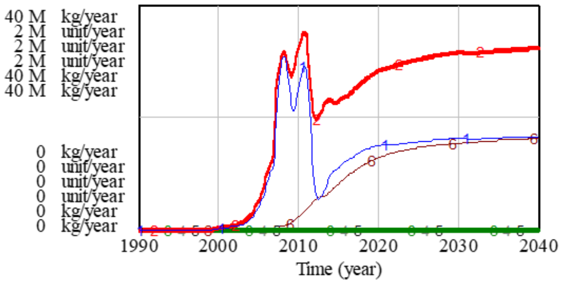

**Figure 4-9.f – S6. Shorter lifetime (75%) (NL408_0,75life)**

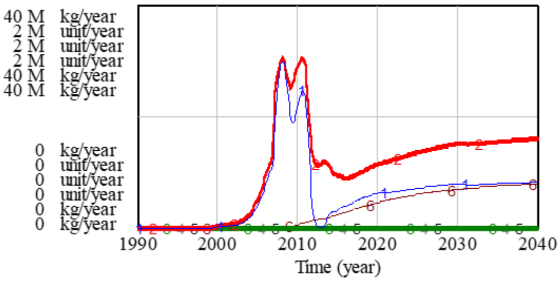

**Figure 4-9.g – S7. Longer lifetime (150%) (NL408_1,5life)**

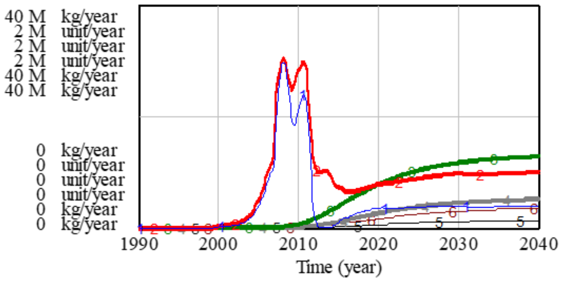

**Figure 4-9.h – S8. Advanced Circular Economy (NL408_advCE)**

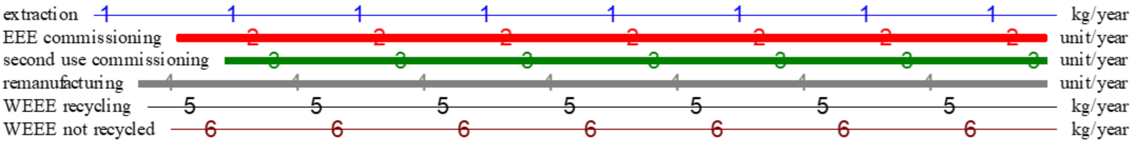

**Figure 4-9** – The products and material flows for the eight defined CE scenarios for flat display panel TVs in the Netherlands. Products – unit/year – are represented in thicker lines and material – kg/year – in thinner lines to facilitate reading.

The S5 – Advanced Recycling – scenario (Figure 4-9.e) influences only the flow of materials, presenting remarkable impacts in the extraction and the amount of non-recycled WEEE. If the recyclability of products is low (37%, in this study), high amounts of WEEE are not recycled even with an extensive collection infrastructure. Therefore, collection capacity and recycling capabilities are essential to fully close the loop of materials when the implementation of other CE strategies are not capable of retaining products fully.

As expected, S8. Advanced Circular Economy leads to the best overall results (Figure 4-9.h). In that scenario, products hold 150% of the actual lifetime, are subject to high coverage of second-use and remanufacturing markets with strong restoration capabilities, and the recycling market formally collects most of the WEEE. Only that scenario was able to get close to rely exclusively on the products and materials already available in the system after the complete adoption of the technology. Although such a high level of infrastructure and enhancement on the product design was not enough to create a closed system for EEE, it was adequate to decrease the inflow of resources to less than half of the scenario S2. Baseline (Figure 4-9.b).

## 4.5 Discussion

The application of the SD model for flat display panel TVs (UNU 408) in the Netherlands allows for experimentation with their stocks and flows in different scenarios of CE strategies. The behaviour of this type of EEE in the Netherlands represents the full adoption of durable products technology, meaning that it started with zero EEE adopters, grew to a maximum and stabilised at a given adoption fraction. Eight plausible scenarios show the behaviour of stocks and flows of EEE under different levels of CE strategies for repairing, remanufacturing, recycling, second use, and designing for a longer (or a shorter) lifetime. They demonstrate structures and behaviours of closing the loop and slowing strategies. Individually, designing for longer lifetime enabled the most promising scenario in terms of material extraction, followed by remanufacturing, recycling, and finally second use. The Advanced Circular Economy scenario, which combines the implementation of the strategies, presents the best scenario. These results should be regarded in the light of the modelling choices and assumptions.

The results achieved by the simulation model enable two threads of discussion: (**i**) the use of modelling and simulation to support CE transitions and (**ii**) the identification of opportunities for the Circular EEE SD Model to be further developed and applied. Arguments in the following two sections underpin these discussion threads.

### *4.5.1 SD modelling and simulation to support CE transitions*

In terms of transitions, each of the eight scenarios enable a dynamic perspective of resources in different regimes. Scenarios range from a linear economy regime, where no CE strategies take place, and a baseline regime denoting the flows of resources based on data from the current situation, to an advanced CE regime, combining high implementation levels of CE strategies. Scenarios are useful to foresee desired future states allowing for sustainability transitions to take place (Papachristos, 2014). Within such context, these eight scenarios allow foreseeing and discussing the goals of CE implementation for a particular type of product (flat display panel TVs) in one specific country (the Netherlands).

Comparing the behaviour and the orders of magnitude of stocks and flows over time is the primary source of insights. It allows for the development of “what-if” scenarios to test the users’ assumptions about the effects of circular strategies. The model use enables decision-makers to evolve their mental models about interventions in the system by a continuous testing process (Sterman, 2000). For instance, second-use strategies could lead to a more substantial reduction of the use of resources, as the CE literature preconises prioritising reuse over both remanufacturing and recycling (Kirchherr et al., 2017). However, the simulations show a rather low impact in terms of material inflow in the advanced second-use scenarios. The fact that products in second use have shorter lives than those in first use can explain that behaviour. Results indicate that combining second use with a more robust repairing infrastructure or prioritising remanufacturing is a desirable strategy in terms of further circularity adoption.

Full decoupling was not achieved in any of the scenarios, as material extraction and WEEE generation happens in all cases – however, the S8. Advanced Circular Economy matches the behaviour of a sustainability transition envisioned by Papachristos (2014) as the material intensity decreases after reaching a peak. An advanced CE regime should keep inflows of resources low even considering a technological replacement of flat display panel TVs. The reduced need for resources inflow will happen if the CE principles endure the next generation of EEE, i.e. if the next generation encompasses extensive second use, recycling, and remanufacturing and follows long-life design. With a Baseline or a Linear Economy structure, we can expect a sharp increase in material use for when deploying new technologies, as it tends to accelerate product replacement when users adopt the new technology.

More than a representation of possible regimes, the Circular EEE SD Model tackles some of the sources of complexities involved in transitions. First, the multiple lifetimes and lifecycles of products are a conceptual foundation of the model. The simulations allow the quantification of products in different states and the qualification of their average age. With that, it is possible to analyse the number of products and their condition over time, along with the amount of resource needed to sustain them. These capabilities provide decision-making information for CE transition from the perspective of multiple stakeholders, including policy-makers and business practitioners.

From the perspective of the direction of the transition, the results presented in this paper do not represent specific bottom-up or top-down change. The Circular EEE SD Model can assist in both directions if the assumptions for system change are modelled. Simulation results may ground policy-making decisions in terms of which type of restoration process to foster and at which intensity while examining the systemic costs and benefits. These analyses are particularly beneficial for policy-makers, as they can experiment with different policies without having to commit resources up front. The definition of scenarios may inform both the particular targets of policies and the implementation strategy.

Organisations aiming to design CE solutions can use the model to assess market opportunities for CE-enabled businesses. For instance, a business practitioner may be interested in verifying the market potential and potential outcomes of a recycling factory. In this case, the business model structure (Cosenz et al., 2019) enables investigations of the mechanisms for value creation, delivery, and capture that permits a company to prosper while decelerating the flow of resources. Additional efforts to connect the nationwide implementation of CE systems to particular business initiatives, public policies or incentives can support the assessment of the potential impacts of specific endeavours. The Circular EEE SD Model is one building block towards investigating CE transitions.

### *4.5.2 Advancing the Circular EEE SD Model*

In terms of the foundations for this modelling effort, industrial ecology (IE) and SD are fundamental knowledge areas for the conceptualisation of CE from a dynamic point of view. Features as the implementation of the closed system concept (Ayres, 1994; Lifset & Graedel, 2002), the representation of the multiple lifetimes (den Hollander et al., 2017; Murakami et al., 2010) and the use of MFA principles (Bergsdal et al., 2007; Müller et al., 2014; Pauliuk & Müller, 2014) materialise the application of IE knowledge contributing to a CE tool (Blomsma & Brennan, 2017). From an SD perspective, features as the application of the Bass diffusion model to represent the adoption of technology (Bass, 1969; Benvenutti et al., 2017; Hines, 1996; Rogers, 2003; Sterman, 2000) and the application of a co-flow structure to model the average age of stocks (Hines, 1996; Spengler & Schröter, 2003; Sterman, 2000) strengthen model foundations. Besides, the simulation model clarify the structure of stocks and flows when aiming for resource flows deceleration.

The model and discussions thereof are relevant to the sustainability transitions field as well. Integrating SD, IE and transitions has been recommended to support the attainment of sustainability-oriented goals (Williams, Kennedy, Philipp, & Whiteman, 2017). The model fulfils a quantitative system modelling approach for transitions (Turnheim et al., 2015) and contributes to the challenge of integrating modelling and simulation to investigate them (Köhler et al., 2019).

The Circular EEE SD Model can expand in a few directions aimed at investigating topics of interest not covered in this research. First, the MFA-based circular indicators pointed out by Pauliuk (2018) can be connected to verify and enhance its IE foundation. Second, non-transaction circular strategies, such as sharing and servitisation, can be introduced by endogenising the rationale of the level of service of products. Furthermore, the co-flow structure that measures the age of products in their different states can be adapted to analyse lifetime monetary value, lifetime quality, modularity and repairability of products through time. Measuring additional product characteristics can provide further insights into product design changes influencing CE systems implementation.

From the point of view of individuals, there is an opportunity to integrate people's reasons and motivations to engage in CE solutions. The consumer perspective has the potential to demonstrate the influence of user behaviour in the effectiveness of take-back programs and the acceptance of remanufactured products. Also, there are material, functional, psychological and economic reasons for EEE obsolescence (Prakash et al., 2015; Proske et al., 2016; Wilson et al., 2017), and the use of the Weibull distribution could include multiple failure modes of products as Elmahdy (2015) indicates. The individual behaviour change process described by Abdelkafi et al. (2015) can provide insights if integrated into the simulation model.

The simulation results presented in this paper are an initial step to enabling system change. Continuous development of simulation models throughout the design, implementation and evaluation of incentives is needed to help decision-makers dealing with uncertainty and complexity (Wiek, Binder, & Scholz, 2006). Continuous model calibration is a possibility to enable assessing real development and to enhance the structures employed. Efforts should focus on tracing the amount and age of products flowing into different parts of the system by, for example, systematically collecting data from households, collection points and WEEE consolidation facilities in urban settings (Forti et al., 2018). A handful of methods to estimate life and use of products from primary data are available (Kumar, Holuszko, & Espinosa, 2017; Prakash et al., 2015). These can be used to examine the real average age of products when reaching those states and feedback those values into the model. Continuously calibrating the model based on empirical data enables the comparison between the expected behaviour from interventions and the learning about the implementation of CE strategies. Also, efforts aiming at decreasing the delay between taking action and assessing the results allows for timely corrective action, which will potentially increase the probability and velocity of positive change towards a Circular Economy.

## 4.6 Conclusion

The goal of this research was threefold: (1) providing an SD-based conceptual model for CE systems that clarifies their potential for decelerated flow of resources; (2) providing a simulation model that enables gaining knowledge of the effects of the implementation of CE strategies on nationwide stocks and flows of EEE; and (3) discussing the capabilities of such a model to facilitate CE transitions. A conceptual model grounds the Circular EEE SD Model and demonstrates the adoption of a given technology focused on the nationwide dynamics of stocks and flows of EEE considering specific scenarios for CE strategies. Scenarios results range from 1980 until 2050, using empirical data for exogenous variables. The long-term behaviour of stocks and flows determines desired future situations for more effective use of resources.

From a theoretical perspective, this work contributes to filling the gap for quantitative studies in the CE field. It details the structure for CE systems in the scope of durable goods, which are part of the technical metabolisms of the CE, enabling demonstration, discussion and prioritisation of CE strategies implementation within that scope. The paper also tackles crucial characteristics that bring uncertainty and complexity to the study of CE transitions. Ties with sustainability transitions, IE and SD, are tightened through this work.

From a practical perspective, the Circular EEE SD Model contributes as a readily available tool to enable the proposition of scenarios and discussion of potential pathways for the transitions to occur. The possibility of identifying and discussing business and public policies to enable industry-wide future situations is a significant contribution for practitioners. The simulation model might enable enhanced coordination among private and public institutions, as more effort is necessary from both parties. Practitioners from public and private institutions can learn the particular causal mechanism, leading up to the most effective use of resources and designing business and public policies accordingly. Moreover, the Circular EEE SD Model can be used to examine these policies beforehand, identify potential discrepancies when compared to the expected behaviours, and act upon the discrepancies.

The Circular EEE SD Model is publicly available for scrutiny and additional modelling efforts. The results from using the model rely on the conditions of each country relative to a given EEE technology. Adapting the model for different types of EEE and regions depends on the availability of empirical data for the time range or wide access to qualitative data produced by experts and specialised organisations. To enable theoretical and practical developments, the steps for data preparation, calibration and simulation are thoroughly described to enable behaviour examination in this and other cases.

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# Appendix

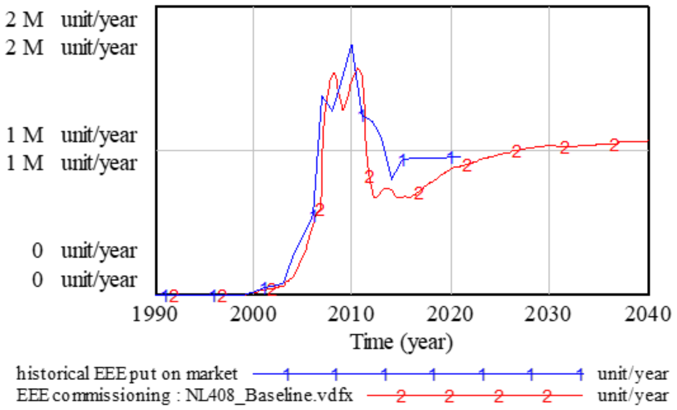

Figure 4-10.a – EEE commissioning fit

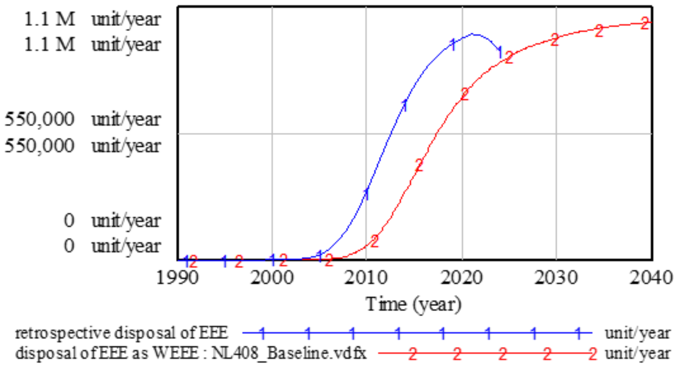

Figure 4-10.b – EEE disposal fit

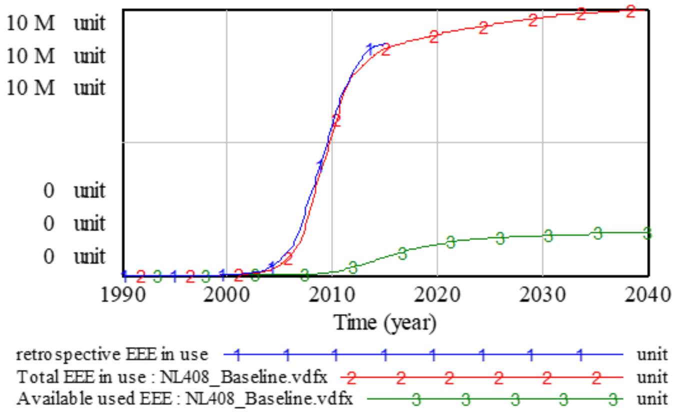

Figure 4-10.c – EEE in use fit

**Figure 4-10** – Calibration results for the baseline scenario. Subfigure a represents the comparisons of historical and simulated EEE put on the market. Subfigure b represents the comparison of EEE disposal from the retrospective model and the prospective model. Subfigure c represents the comparison of EEE in use in the retrospective model and the prospective model.

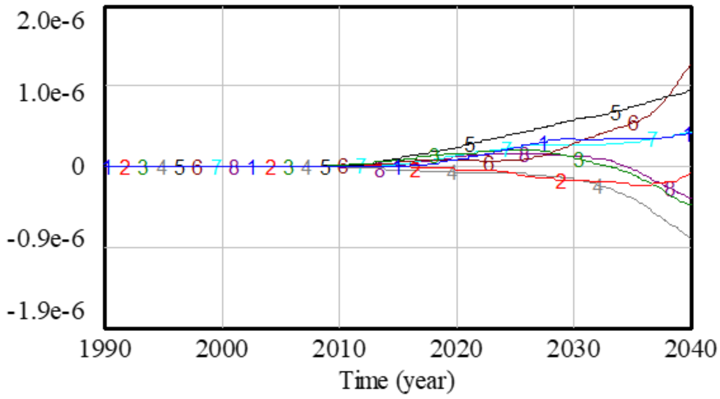

**Figure 11.a – Mass balance EEE (unit)**

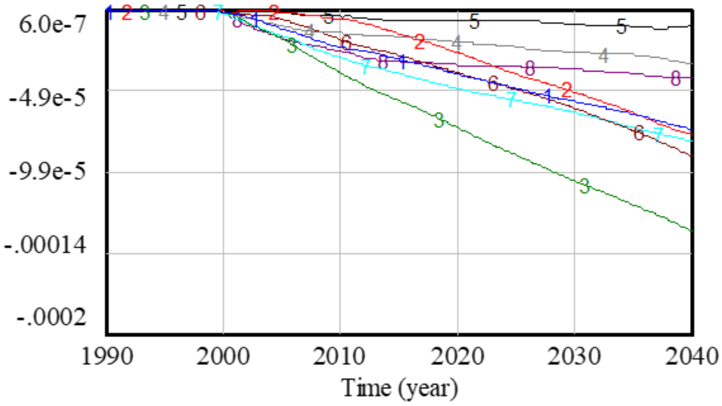

**Figure 4-11.b – Mass balance material (kg)**

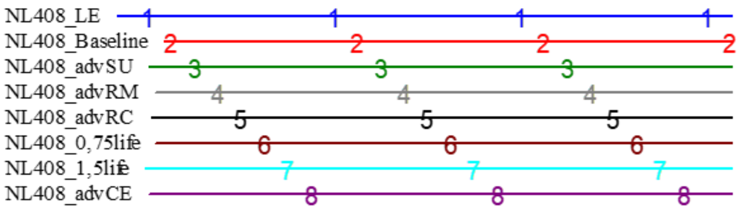

**Figure 4-11** – Results of product and material mass balance tests

**Table 4-4** – Error analysis of simulated and historic EEE commissioning. The values for 2015 are the last historic values provided by van Straalen et al. (2016), whereas the values from 2015 to 2022 are extrapolations. Bias ($U^M$) represents 13.18% of error in 2015 and 21.69% of error in 2022. Unequal covariation ($U^C$) causes 75.58% of error in 2015 and 64.81% of error in 2022, meaning mainly unsystematic error. Unequal variation ($U^S$) is low comparing data in both years.

| **Year** | $U^M$ | $U^S$ | $U^C$ |
|---|---|---|---|
| 2015 | 0.1318 | 0.1124 | 0.7558 |
| 2022 | 0.2169 | 0.135 | 0.6481 |

**Table 4-5** – List of testing activities performed and modelling outcomes obtained

| Test type | Test description | Modelling outcomes |
|---|---|---|
| Boundary adequacy | Model boundary chart development | Facilitates to identify relevant structures to model. Reliable data is available for most of the exogenous variables. |
| | Model expansion to include the Adoption sub-model | Enables prospective simulation from historical data. |
| Structure assessment | Subsystem diagram development | Represents the main concepts and feedback structures in the model. |
| | Model conceptualisation following the dynamic material flow analysis (MFA) concept | Conservation of matter is embedded in the model structure. Non-recycled WEEE stock is the sink of the system. |
| | Application of the mass-balance check (Dangerfield, 2014; Schwaninger & Groesser, 2016) to products and materials | Enables examining gains or losses of materials and products in the model. Total gains should be zero. |
| | Development and testing relevant sub-model parts in isolation | Enables building confidence in plausible behaviour of sub-models before aggregate analysis. |
| | Experimentation with stocks in varied conditions to identify negative values | Identification of variables to constrain, e.g., limiting the flows into second use, remanufacturing and recycling (in that order of preference) to prevent negative values of Available use-EEE. |
| Dimensional adequacy | Use of parameters with real-world meaning when modelling | Name and description clearly identify variables' meaning. There are a few ad hoc variables as 'effect of PPP on the average number of EEE per household'. |
| Parameter assessment | Elaboration of a step-by-step guide to calibrating relevant partial models | Enables calibration of the behaviour of EEE adoption from retrospective data from 1980–2015 to obtain the behaviour from 1980–2050. |
| Extreme conditions | Bounding the use of the model by levels of CE mechanisms implementation | The 0 to 4 infrastructure level indexes bound the model. |
| | Bounding auxiliaries and flows with potential extreme behaviour | Combination of MIN and one-minus function to prevent negative values. E.g., "fraction of decommissioned EEE introduced to WEEE". |
| | Shocks and extreme condition testing | It is possible to examine the inflow of a shipment of used products as "Available used-EEE" with a given average age in a moment in time, mimicking what happens in countries under development. Mass balance is maintained. |

| Test type | Test description | Modelling outcomes |
|---|---|---|
| Integration error | Testing the model using RG4 of 1 year to 0.125-year time steps | Results are not sensitive to these choices in the time step. Nevertheless, the supply chain delays are proportional to the time step. |
| Behaviour reproduction | Setting up a dashboard to fit the prospective model to external data and data calculated in the prospective model | Helps to calibrate the model through behaviour reproduction of the following variables: “EEE commissioning” and “historic annual EEE put on market”; “Total EEE in use” and “R EEE in use”; “disposal of EEE as WEEE” and “historic disposal of EEE”. |
| | Application of descriptive statistics tools to calibrate the model – Theil inequality statistics (Oliva, 1995; Sterman, 2000) | A structure to verify bias, unequal variation, and unequal covariation of simulated and input variables enables verifying the fit among two variables. |
| Family member test | Using Netherlands (NL) and Estonia (EST) data for Fridges (UNU 108) | Calibration is possible from retrospective data in both cases (NL108 and EST108). EST data closer to 1980 is harder to obtain. Although NL and EST are from different stratum in van Straalen et al. (2016), they are both mature markets for fridges. Comparing EEE dynamics in both cases does not provide much insight. |
| | Using (Netherlands) NL data for Fridges (UNU 108) and Flat Display Panel TVs (UNU408) | Calibration is possible from retrospective data in both cases (108NL and 408NL). The adoption curve for Flat Display Panel TVs enables more general discussion of CE strategies implementation as it shows the full adoption of a technology. |

# 5 ARTICLE 3: 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.

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

**Status:** Submitted to the Waste Management journal.

**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 |

## 5.1 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 et al., 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 (*Política Nacional de Resíduos Sólidos*, 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 et al., 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 et al., 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 et al., 2021). 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.

## 5.2 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[18] 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., 2021) 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 5-1 shows the references used for modelling, simulating, and discussing the BIAEEE.

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

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[18] 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'.

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 Figure 5-6 (Appendix).

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.

**Table 5-1 –** 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 et al., 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) |

The model structure, calibration and use are following described.

## 5.3 System description

### *5.3.1 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 5-1 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.

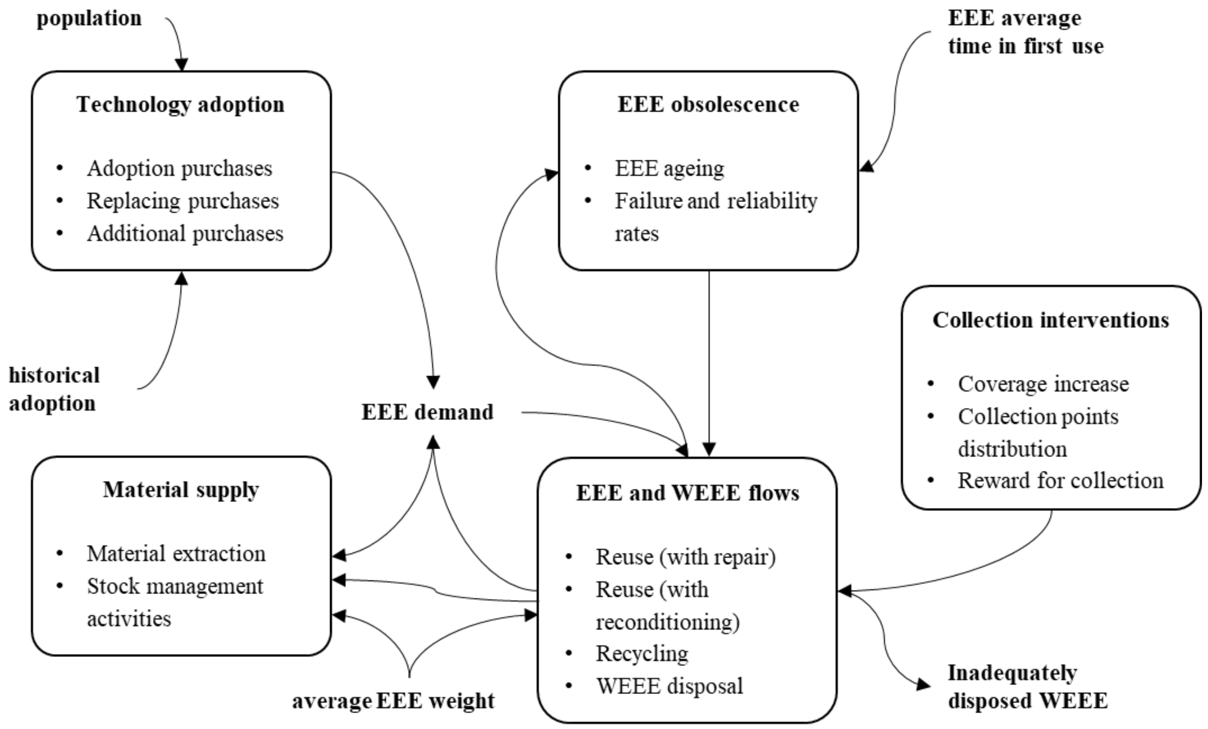

**Figure 5-1 –** Composition of the model used in the BIAEEE investigation

The **(2) EEE and WEEE flows** (detailed in Figure 5-2), 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”*.

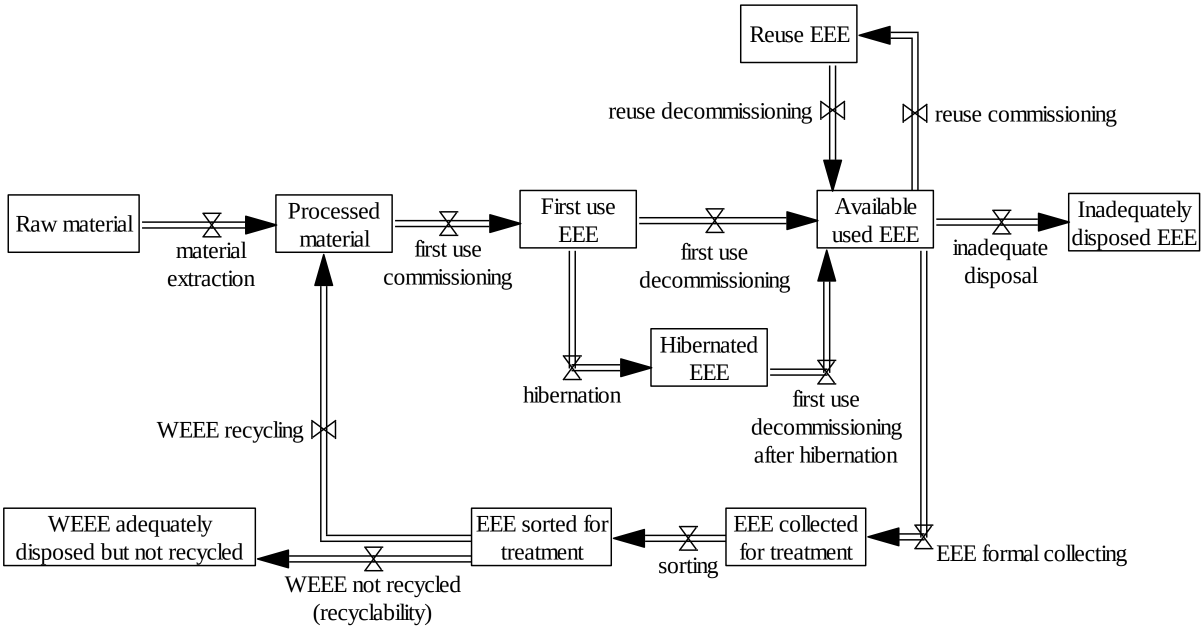

**Figure 5-2 –** A simplified representation of the stocks and flows of the EEE and WEEE flows submodel

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.

### *5.3.2 Model calibration and use*

#### *5.3.2.1 Setting the baseline scenario*

Table 5-2 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).

**Table 5-2 –** Input data and sources used for the baseline scenario

| **Variable** | **Value** | **Unit** | **Source** |
|---|---|---|---|
| Population | f(t) | People | United Nations (2019) – see Figure 5-7.a (Appendix) |
| potential adoption fraction | f(t) | Dimensionless | Pew Research Center (2016; 2019) – see appendix – see Figure 5-7.b (Appendix) |
| historic annual EEE put on market | f(t) | Unit/year | IDC (2019) – see Figure 5-8 (Appendix) |
| 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 and colleagues (2020) |
| fraction fit for second use | Lookup | Dimensionless | Makov and colleagues (2019) – see Figure 5-9 (Appendix) |
| 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 |

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 Figure 5-9 (Appendix). 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.

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.

#### *5.3.2.2 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 5-3 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.

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.

**Table 5-3 –** 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 |

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 5-10 (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 5-11 (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.

#### *5.3.2.3 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 5-4 (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 5-12 (Appendix) and Table 5-5 (Appendix).

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, since EEEs hold different lifetime patterns and that it would be impractical to examine only products from a specific year for actual verifications of the system. Also, considering the all-time material could lead to too much inertia to demonstrate any change in the collection system.

## 5.4 Simulation results

### *5.4.1 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 5-3.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.

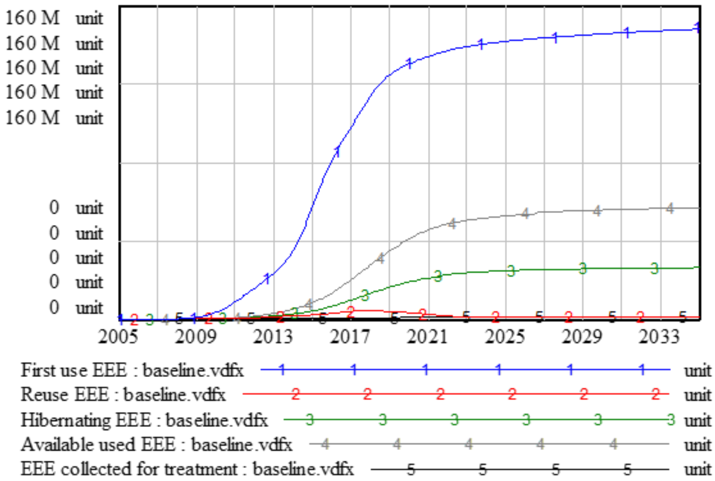

**Figure 5-3.a** – EEE stocks in the baseline scenario in unit

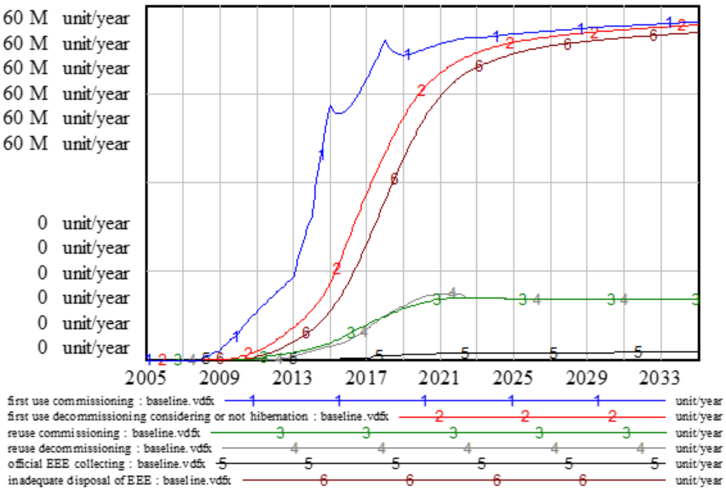

**Figure 5-3.b** – EEE flows in the baseline scenario in unit/year

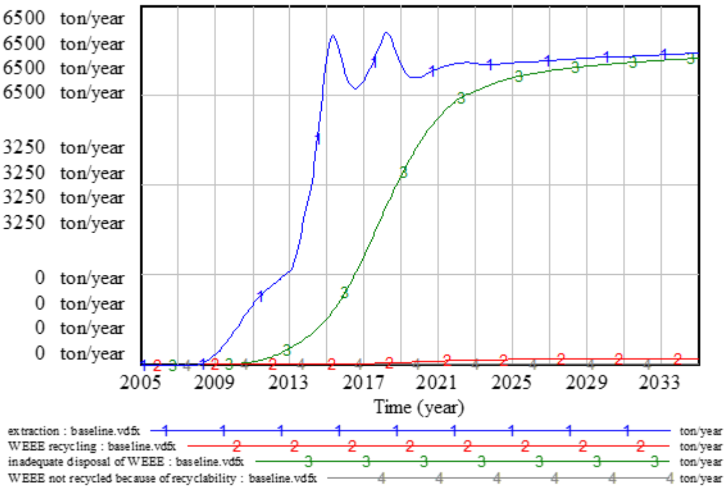

**Figure 5-3.c** – Material flows in the baseline scenario in ton/year

**Figure 5-3 –** The material and EEE stocks and flows of smartphones in Brazil

Figure 5-3.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)[19], 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 5-3.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 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.

### ***5.4.2 The effects of EEE collection interventions***

Figure 5-4 shows critical flows that demonstrate the effects of the twelve scenarios. Official EEE collection (Figure 5-4.b) enables decreased material extraction (Figure 5-4.a) and decreased inadequate disposal of EEE (Figure 5-4.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

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[19] 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.

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.

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 5-6 (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.

### *5.4.3 Reaching the BIAEEE targets*

Figure 5-5 shows that only scenario 12 (C) reached the BIAEEE targets on time (see Figure 5-5.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.

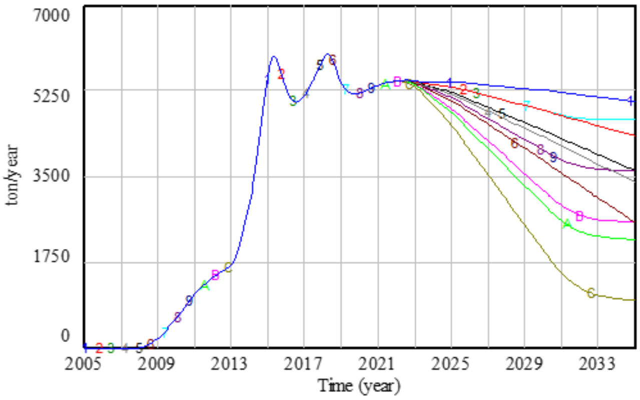

**Figure 5-4.a** – Material extraction (in ton/year)

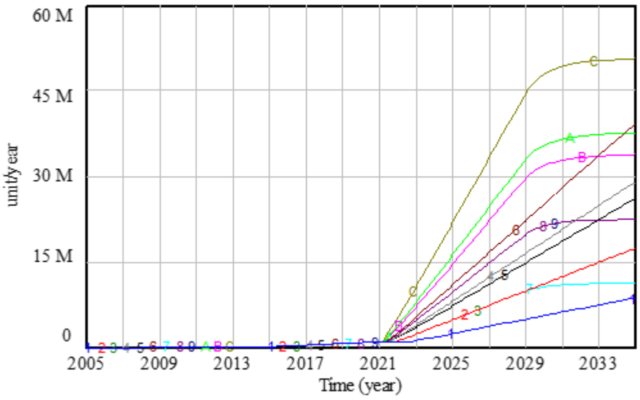

**Figure 5-4.b** – Official EEE collecting (in ton/year)

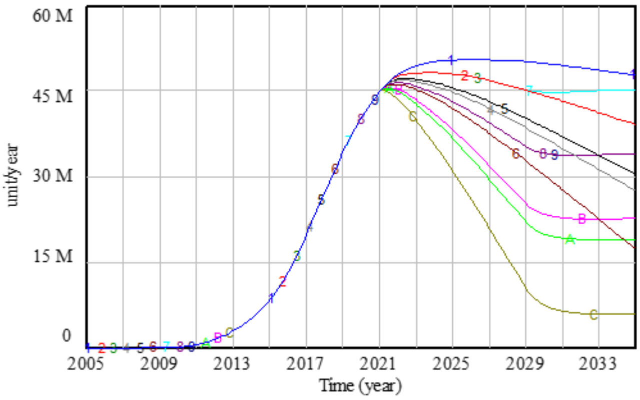

**Figure 5-4.c** – inadequate disposal of EEE (in unit/year)

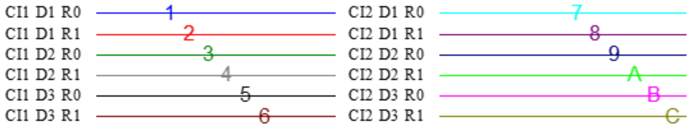

**Figure 5-4** – Critical flows demonstrating the effects of CE implementation in the baseline scenario and in scenarios 1, 2 and 3

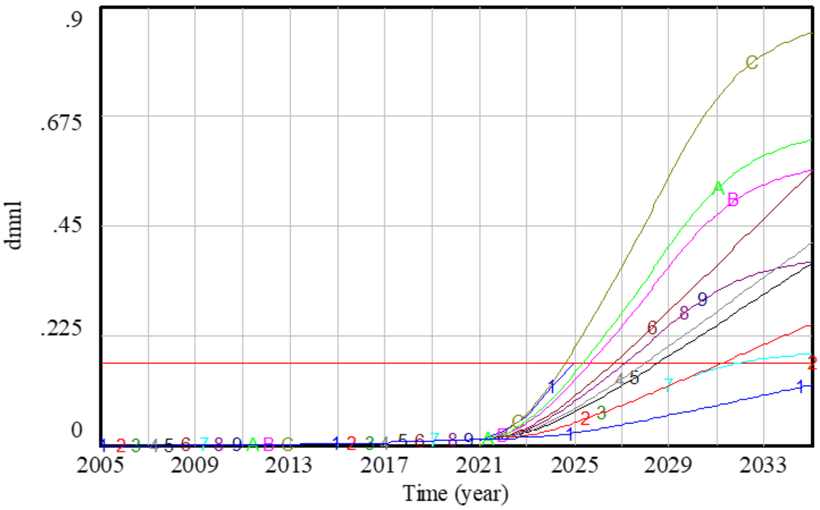

**Figure 5-5.a** – Ratio of material treated considering the last 2.6 years (dimensionless)

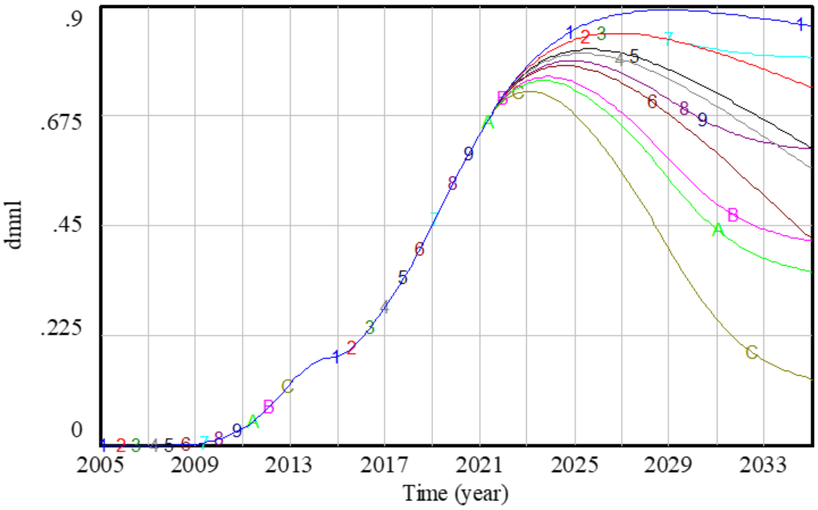

**Figure 5-5.b** – Ratio of material lost considering last 2.6 years (dimensionless)

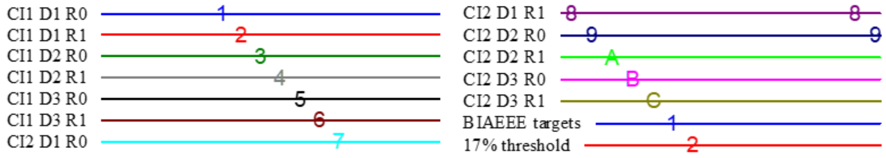

**Figure 5-5 –** Ratio of material treated and lost considering the last 2.6 years for the baseline, the three policy implementation scenarios, and an exploratory analysis

## 5.5 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.

### *5.5.1 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.

### *5.5.2 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.

### *5.5.3 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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# Appendix

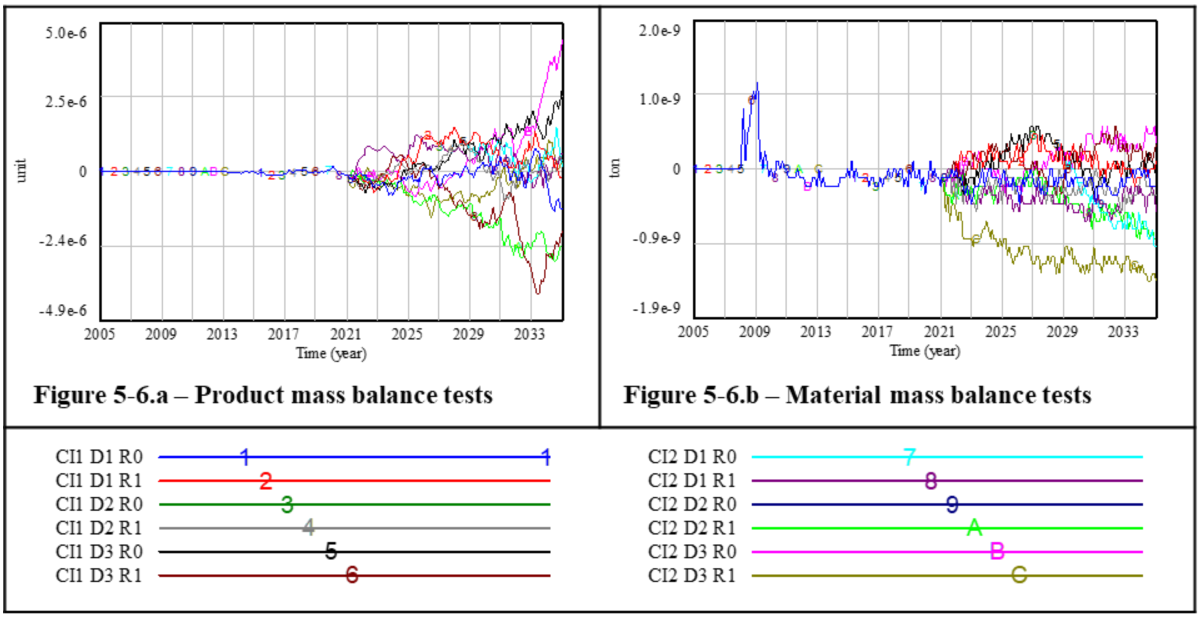


**Figure 5-6.a – Product mass balance tests**

**Figure 5-6.b – Material mass balance tests**

**Figure 5-6 –** 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.

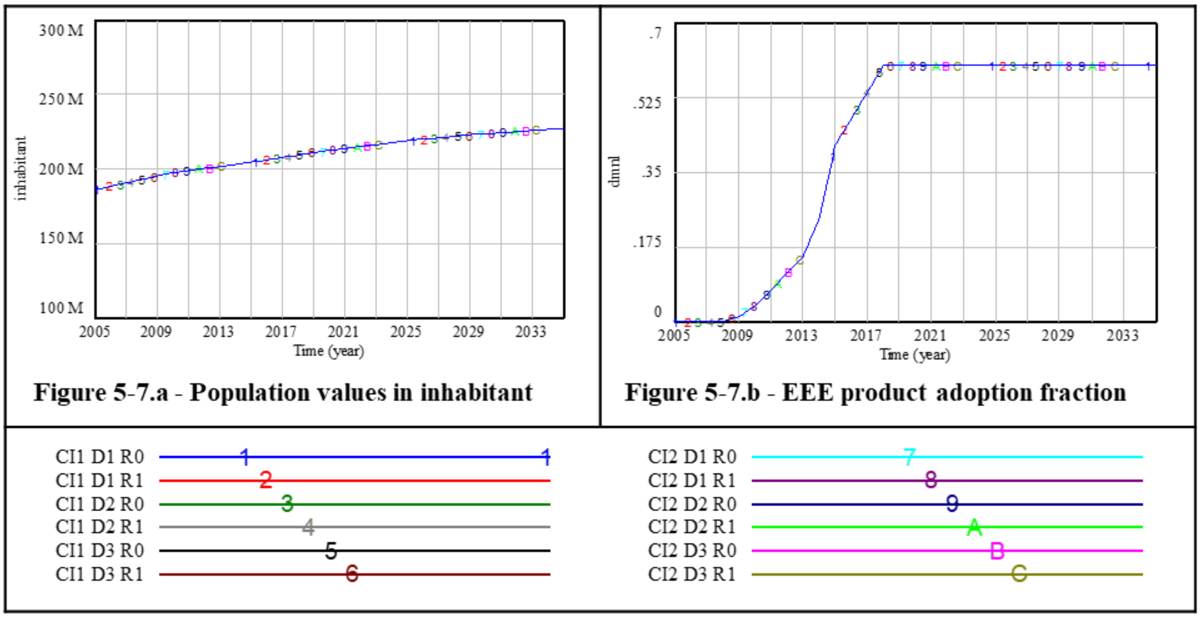


**Figure 5-7.a - Population values in inhabitant**

**Figure 5-7.b - EEE product adoption fraction**

**Figure 5-7 –** Population and technology adoption time series used as input data in the model

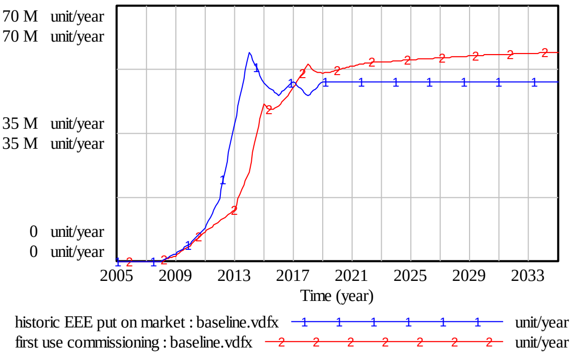


**Figure 5-8 –** Calibration results of first use commissioning and historical data from IDC (2019). The similar behaviour and order of magnitude from the two curves demonstrate the calibration from calculated to real data.

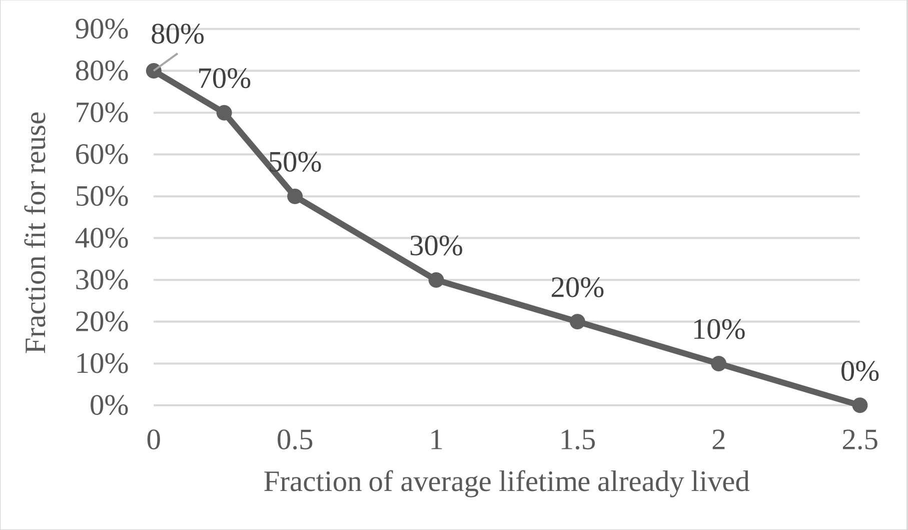


**Figure 5-9 –** Values adopted for reuse commissioning. Adapted from Makov et al. (2019)

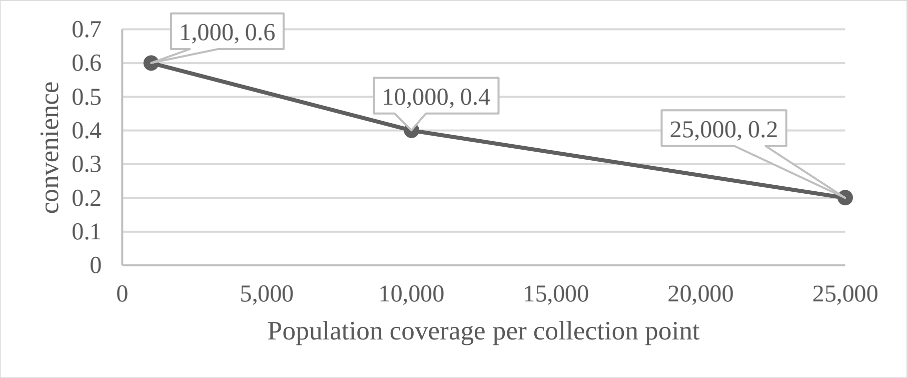


**Figure 5-10 –** Convenience of EEE reverse logistics system considering the population coverage per collection points with no rewards

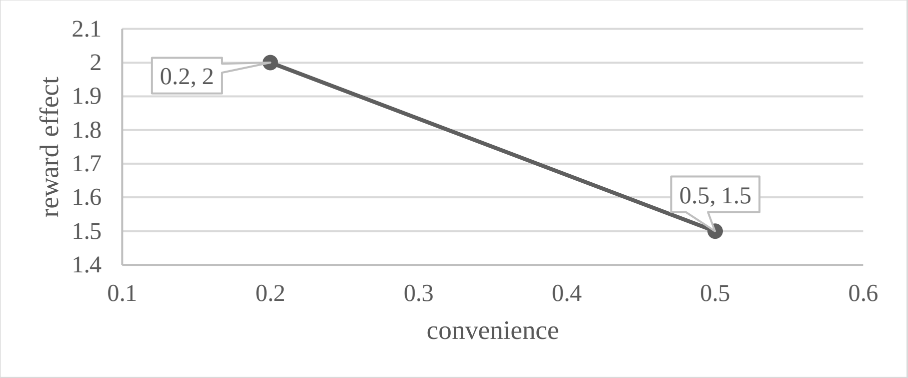


**Figure 5-11 –** Reward effect considering the EEE reverse logistics system convenience

**Table 5-4 –** 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% |

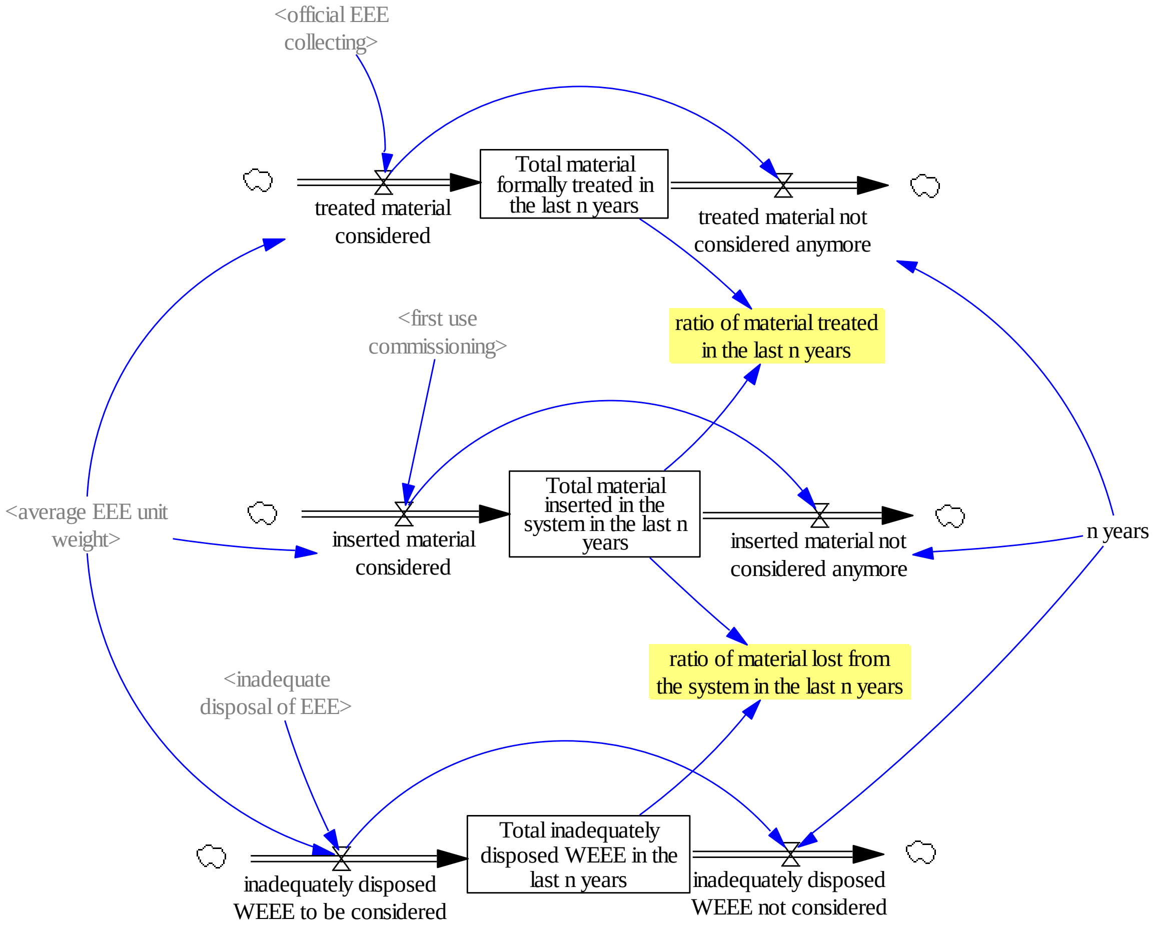


**Figure 5-12 –** Test bench created to examine the BIAEEE targets

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

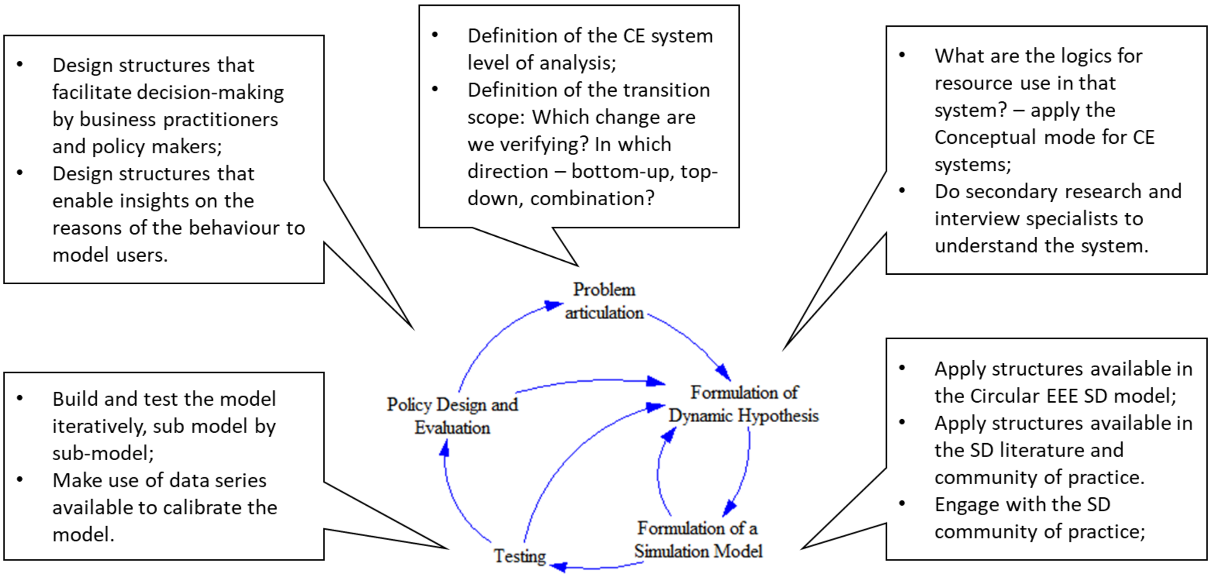
| **Variable** | **Equation** | **Unit** |
|---|---|---|
| ratio of material treated in the last n years | ZIDZ (Total material formally treated in the last n years, Total material inserted in the system in the last n years) | dmnl |
| ratio of material lost from the system in the last n years | ZIDZ (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 5-6 –** 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 |

# 6 GUIDELINES FOR EXAMINING CIRCULAR ECONOMY TRANSITIONS

Figure 6-1 represents guidelines for examining CE transitions using System Dynamics modelling and simulation as an attempt to organize the accumulated knowledge from the three studies to help future investigations. The guidelines address critical decisions and activities relevant to each of the five iterative stages proposed by Sterman (2000). Such decisions and activities help to frame the problem in examining CE transitions, conceptually determine the system under investigation, and formulate, calibrate and use simulation models towards insights for deceleration of the flows of resources in a given system. Specific activities, questions, and good practices are proposed for each of the five stages.



- Definition of the CE system level of analysis;
- Definition of the transition scope: Which change are we verifying? In which direction – bottom-up, top-down, combination?

- What are the logics for resource use in that system? – apply the Conceptual mode for CE systems;
- Do secondary research and interview specialists to understand the system.

- Apply structures available in the Circular EEE SD model;
- Apply structures available in the SD literature and community of practice.
- Engage with the SD community of practice;

- Build and test the model iteratively, sub model by sub-model;
- Make use of data series available to calibrate the model.

- Design structures that facilitate decision-making by business practitioners and policy makers;
- Design structures that enable insights on the reasons of the behaviour of model users.

**Figure 6-1** – Guidelines for modelling and simulating Circular Economy systems using the steps provided by Sterman (2000)

In the **(i)** Problem articulation stage, it is critical to define the CE system level of analysis. First, the three levels of CE System and relevant aspects for system understanding represented in Figure 1-1 can help with this definition. The definition of the CE system level helps determining the level of detail of the modelling effort. For micro-level systems, SD can be used to examine the reasons for change in an organization, household or individual. For macro-level systems, SD can be used to examine the stocks and flows of resources in industries, regions, and nations. Models developed aiming to represent the micro-level can be used as building blocks for higher levels. Connecting micro-, meso-, and macro-levels models can bring greater confidence in the models and greater explanatory capacity to system behaviour.

Second, defining the transition direction perspective – whether bottom-up, top-down or combinations – helps to determine the approach to CE transition in the case and, therefore, the modelling objectives. The direction of change helps to determine the stakeholders to be involved in the investigation and the instruments for collecting and organizing information. In the case of a bottom-up transition investigation emerging from the implementation of new business models, the companies proposing and delivering the CE solution, clientes and users must be involved in the investigation. The dynamic business modelling for sustainability approach (Cosenz, Rodrigues, & Rosati, 2019) is applicable as a conceptual model for the investigation. In a top-down approach, it is necessary to involve proponents and enablers of public policies as members of the government, industry associations and members of civil society. The building blocks of the extended policy mix introduced by Rogge and Reichardt (2016) can help to define the scope of the investigation in top-down change investigations.

In the **(ii.)** Formulation of Dynamic Hypothesis stage the focus should be on portraying the logics for resource use in that system. The scope of the investigation must encompass the appropriate life-cycle phases of the products involved in the system under study to enable examining the potential strategies for decelerating the flows of resources. The conceptual model for CE systems available in article 2 can help in this task by helping to position circular strategies in the value chain and identify the appropriate modelling structure, whether by deaccelerating inflows or outflows or by using the outflow of a given resource as an inflow for previous activity. At this point, it is essential to do extensive secondary research and interview specialists to gain knowledge about the system under investigation. For example, it is essential to thoroughly investigate the forms of circularity that make sense for the sector and understand what determines obsolescence in the case under study towards a sound conceptual understanding of the system.

In the **(iii.)** Formulation of a Simulation model stage, it is essential to develop the simulation models by building on top of existing models and structures. Adaptations or parts of the Circular EEE SD Model can assist in formulating simulation models in the context of CE transitions. Also, there are plenty of structures available in the SD literature and community of practice. The *Business Dynamics* reference book (Sterman, 2000), the *Small System Dynamics Models for Big Issues* reference book (Pruyt, 2013), and the *Molecules of Structure* (Hines, 1996) provide examples of recurrent structures, their uses and the rationale sustaining them. The *MetaSD* website[20] is also a useful reference on model structures.

It is also essential to engage with the SD community of practice and the community around the modelling tool chosen for the simulation effort. The System Dynamics Society provides plenty of resources for learning about SD modelling and simulation, and empowers regional chapters and special interest groups (SIGs) in specific topics such as assets dynamics, business and environment. Engaging with the community of practice can help with sharing modelling and simulation challenges as well as getting early feedback on the research. From the perspective of the modelling tools, there are several available for SD modelling and simulation, such as Vensim and Ventity developed by Ventana Systems, Stella Architect, developed by isee systems, Powersim, anylogic, among others. Each tool has its capabilities and peculiarities. Challenges will emerge from the use of the tool, and the communities of

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[20] The MetaSD website is maintained by Tom Fiddaman, that works at Ventana Systems and moderates the community of practice around Ventana Systems' applications Vensim and Ventity. Access at: https://metasd.com/

practice around these tools share the challenges and solutions for formulating models. Much can be found and learned there.

In the **(iv.)** Test stage, building and testing the model must occur iteratively, in small steps, and constantly checking the behaviour of the sub-systems against the expectations of the modellers, users and available data (Pruyt, 2013, p. 87). Model testing guidelines for contextual, structural and behavioural validity are available in *The Business Dynamics* reference book (Sterman, 2000, Chapter 21) and prescribed by Schwaninger and Groesser's (2016). Tests as the mass-balance check (Dangerfield, 2014; Schwaninger & Groesser, 2016) are critical in CE transitions studies because they ensure that no material or product is "lost" in the system because of a poorly formulated relationship between variables. Calibrating and testing the model is challenging since we are dealing with technology and behaviour transitions. Often data or even evidence of behaviour is scarce for the systems in question.

Following a data-rich strategy to create simulation models brings the need to obtain quantitative information and data-series about the phenomenon, and this can be a rather time-consuming activity. Two types of studies are quite relevant in this sense: surveys and grey literature. Quantitative studies and surveys in the literature covering the sector under study are potential sources to determine values and relationships between variables in the most exogenous portions of the model. In turn, reports from associations and consultancies can help by providing essential data and time-series to calibrate the models. Balancing the use of data with the potential for insights from the use of the model is a vital aspect of the modelling effort.

In the (**v.**) Policy design and evaluation stage, some heuristics are essential. It is central to balance the trade-off among model adequacy and the cost for model improvement in comparison to the actual model being used to make decisions (Forrester, 1994). At all times, attention must be paid to the conceptual model, the formulation for simulation, and the performance of tests to enhance model validity. Sometimes, however, greater adequacy of the model brings limited additional potential for help business practitioners and policymakers in their decision making. Therefore, care must be taken not to focus on the model as an end, but to generate enough insight for decision making from the users' point of view.

As mentioned, the guidelines presented here are an initial prescriptive study, which has not yet been validated in practice. However, the guidelines are based on the knowledge accumulated in the three studies and can help future applications of SD modelling and simulation to examine CE transitions.

# 7 FINAL CONSIDERATIONS

This thesis aimed at resolving the general research question of *How can a systems approach help to understand and facilitate CE transitions?* The term ‘understand’ calls for the theoretical goal of interpreting CE transitions through a systems perspective, while ‘facilitate’ requires the generation of tools to help decision-making. The general question was unfolded into work packages that allowed the development of descriptive and prescriptive knowledge useful for the theory and practice. Modelling and simulation using SD was the guiding thread that enabled connecting descriptive and prescriptive efforts in this thesis.

The content of sections 2, 3, 4, 5 and 6 resolve the general research question, as well as the theoretical and practical goals defined. The sources of dynamic complexity in CE transitions (section 2), the requirements for an SD-based tool (section 2), the depiction of the sub-systems structure determining the use of resources (section 3.4.3) and the conceptual model for CE systems (section 4.2.2) constitute the primary grounding knowledge for understanding CE transitions and enabling the development of the tools. The Circular EEE SD model (section 4.4), its adaptation to examine the BIAEEE (section 5.3) and the guidelines for modelling and simulating CE systems using SD (section 6) constitute the primary prescriptive knowledge contained in the thesis, which allows for the reproduction and further development of simulation models to investigate CE systems and transitions. The discussions about the use of SD modelling and simulation in CE transitions (section 4.5.1) and the recommendations for the BIAEEE based on scenarios obtained (section 5.5.1) constitute the initial descriptive knowledge generated from the use of the models. The insights obtained in the three Studies demonstrate a few manners SD modelling and simulation can facilitate decision-making in CE transitions.

The results presented in the thesis allowed necessary investigations, results, and discussions for the urgent deceleration of resource flows in the consumption and production systems. The contributions contained in the thesis to the field of CE transitions and to decision-makers participating in CE transitions are following summarised. Finally, further avenues of investigation that can help to continue developing a systems view on CE transitions are presented.

## 7.1 Contributions to the field of CE transitions

The content and articles contained in this thesis make three significant contributions to the field of CE transitions. The first contribution is to **characterise and connect the concepts of CE systems and CE transitions** clarifying the systems view adopted in the thesis to understand the phenomena. A systems view allowed to create the foundation to facilitate CE transitions and address several of the sources of the dynamic complexity that emerge from the characteristics of CE systems and transitions presented in section 2.1.

The consumption and production systems need to meet human needs while decelerating the flow of resources in a Circular regime. The results obtained from the simulation model in articles 1, 2 and 3 evidence that understanding CE transitions constitutes a process of change between a socio-technical linear regime to a Circular one. This shift between regimes culminates in the need to compare prospecting systems enabled by the simulation models. The ability to compare prospecting systems allowed investigating whether the implementation of specific CE strategies in the systems lead to more effective use of resource and help to find routes for the desired future situation. For instance, the evaluation of the BIAEEE clearly shows that specific choices for developing the reverse logistics system for post-use EEE will determine the effectiveness in resource use.

As previously mentioned, the sustainability transitions literature contributes to the definition of studies and ground discussions of results with concepts that are still under development in the CE literature. Thus, acknowledging that CE systems occur in different levels: micro, meso, and macro also contributes to a systems view. The acknowledgement of the different levels can work as a rule of thumb to set the appropriate aggregation of change to aim for when examining the system, and the appropriate level of detail one should delve into at each investigation. Also, the different levels can hint the potential for impacts in each system. It is not true, however, that investigating micro-level change is less critical than macro-level change because a CE transition will only happen if it does at the multiple levels at once (Coenen, Benneworth, & Truffer, 2012). The need for change in the multiple levels is precisely the reason for understanding and discussing change at the different levels to help with CE transitions. The simulation models in the three articles show the possibilities for varying degrees of stock optimisation in systems of different levels.

Along with the different CE systems levels appears the directions in which the transition occurs: bottom-up, top-down, or combinations thereof. It is widely argued that CE transitions require the coordination of top-down and bottom-up initiatives. However, understating the direction of change likely to influence a given system makes it easier to identify what types of decisions to make, the appropriate forms of investigation and who should be involved in the process of understanding the system. The levels and directions of change within the three articles allowed to discuss modelling and simulation options available.

The **proposition and verification of a conceptual model for CE systems** constitute the second contribution of this thesis to academia. The conceptual model for CE systems presented in article 2 is the cornerstone for interpreting Circular Economy systems through the System Dynamics lenses. It represents the stock optimization principle in SD notation, allowing to conceptualise the deceleration of resource flows. The conceptual model contributes to clarifying the meaning of terms related to SD such as stocks, flows, and delays for understanding CE systems and transitions. Besides, managing the inflows and outflows of stocks is precisely the capability of stock and flow diagrams, that sustain the conceptual model.

The connection with industrial ecology and adjacent concepts underpins the efforts for stock optimisation. The closed system concept derived from industrial ecology, the application of Material Flow Analysis principles, the knowledge from closed-loop supply chains, and the thorough consideration of the ageing and obsolescence processes enabled by the Weibull reliability functions enhance model validity, i.e. trust of modellers and users in the model's mechanics and results. The use of modelling allows formalizing the connection between these fields using stocks, flows, auxiliaries, and formalization in equations. The formal application of knowledge from these fields enabled to rely on the robustness of the model concerning the counterintuitive characteristics of CE transitions while enriching the debate.

Although the conceptual model for CE systems is only articulated in article 2, a closer look at the structure of the simulation model to investigate the adoption of a sharing platform in healthcare reveals that the foundations for the conceptual model for CE systems were already in place in the first study. In article 1, the effects of adopting the sharing platform (which denotes a circular strategy) are investigated considering functional products, underutilized products, and obsolete products. The sharing platform permits underutilised products to become functional, closing the loop of products. In the article 2, the conceptual model for CE systems expands the foundation of that mechanism to the whole value chain of durable goods to resolve the gap of the absence of a conceptual model capable of representing and investigating the strategies that can slow, narrow or close the resource flows.

The conceptual model for CE systems is an enabler for implementing closed-loop thinking when investigating transitions. Closed-loop thinking is a necessary condition for making decisions towards more effective systems because it enables to acknowledge that consumption and production systems are not decoupled from Earth systems and that the balance between them can only be detrimental for both. The conceptual model permits considering causal relationships between consumption and production systems and adjacent systems at all stages of the life cycle of products. It also enables hypothesizing and examining the structures needed to decelerate the flow of resources.

The difference in scope among the three studies contained in this thesis only enriches the discussions about the application of a systems approach to understanding CE transitions. For example, the concepts of sustainability transitions were incorporated from this opening of the scope as it was necessary to understand more deeply the levels for CE systems and the directions for the occurrence of CE transitions to make sense of this change. However, the definition of the scope of investigation by modelling and simulation incurs in some decisions. The third contribution to academia contained in this thesis is the **clarification of opportunities and trade-offs of applying a systems approach in examining systems with different scopes**.

In article 1, reaching the tipping point for users’ adoption to the sharing platform is necessary to enable improved use of resources. The study shows a clear need to satisfy multiple types of stakeholders to allow the CE system to last. The sharing platform case considers the medical staff that uses the platform, patients that receive treatment, the hospital that will capture the benefit of needing fewer products, and the environment. Positive value is found for all stakeholders when the sharing platform is adopted since the demand continues to be met with less need for goods and consumables in the long run. Article 1 also allows examining the differences among the impacts of sharing durables and consumables, which hold different lifecycle patterns, constituting an essential source of dynamic complexity in CE transitions.

In article 2, the shift to a macro-level perspective enables examining the impacts of consumption and production systems in the whole lifecycle of products, which bring opportunities and trade-offs. An opportunity is to allow the discussion about the prioritization and combination of CE strategies towards the best results in terms of nationwide use of resources. Also, the wealth of data available for the EEE sector contributes to model calibration and the consequent increase in confidence in the simulations. A clear trade-off is the need to define assumptions regarding the behaviours at the meso and micro-level when many strategies are under investigation. In the study, the variation in the implementation of CE strategies happens at a high level of abstraction. For example, an index ranging from 0 to 4 represents the remanufacturing infrastructure level and determine the remanufacturing coverage and effectiveness to determine the fraction of products reintroduced in that market. In this way, the logic for determining the effects of remanufacturing occurs relatively exogenously, and it could be detailed to bring deeper insights to model users.

The collection mechanisms were further explored in article 3 since they are closely linked to the objective of the modelling effort – examining the instruments contained in the BIAEEE. Despite using the bases established in article 2, the mechanisms for collection implementation are much more detailed and consider the capillarity of the system and customer engagement, which enables informed discussions on the applicability of the targets in comparison to the initiatives under consideration. The prescriptive character in article 3 is much more profound as the scope of strategies is narrower than in article 2, allowing greater confidence in the results of the model if those strategies are followed. Besides, the adoption of a top-down perspective in article 3 enabled discussing the potential of a specific policy in enabling the achievement of a CE transition in a specific nation. The scenarios provide quantitative evidence of the potential implications of public policies in the use of resources.

The characterisation and connection among the concepts of CE systems and CE transitions, the proposition and verification of a conceptual model for CE systems, and the clarification of opportunities and trade-offs of applying a systems approach in examining systems with different scopes constitute the three contributions to the field of CE transitions of this thesis. The next section outlines the contributions to decision-makers participating in CE transitions.

## 7.2 Contributions to decision-makers participating in CE transitions

This research provides a few practical contributions. The explicit structuring of knowledge into requirements for an SD-based tool, the availability of the Circular EEE SD model, and the rationale for developing the models used in the studies should allow other researchers and practitioners to replicate the studies presented in this thesis as well as to adapt the models and use their structures. The guidelines for examining CE transitions presented in section 6 emerged from the accumulated knowledge of the three applications. They can be used as good practices for activities and decisions necessary to develop SD-based tools to examine and facilitate CE transitions.

This research aimed to contribute to the practice by generating tools to facilitate decision-making. The three studies present characteristics of applied and theoretical research (de Gooyert & Größler, 2018, fig. 577), addressing relevant practical problems. The problem in article 1 is practical as it involves the adoption of a new manner of managing medical equipment in a hospital via a platform proposed by a company through fee-based access. The problem in article 2 is practical as the use of electronics, and the generation of WEEE, is one of the relevant current global challenges concerning the use of resources. Article 3 is also clearly practical, as it seeks to contribute to the discussions of the Brazilian industrial agreement for electrical and electronic equipment (BIAEEE) in the context of the Brazilian solid waste policy (BSWP).

Simulation models were developed in all the studies to allow investigating and creating scenarios for the cases. In all studies, therefore, tools were created according to the objective of the study and the investigation scope. Articles 1 and 3 contain tools useful for those particular cases: the adoption of a sharing platform for a small hospital in article 1 and the implementation of public policies within the scope of BIAEEE in article 3. Despite the specificity, the models created can be used for investigations in similar contexts and therefore can serve as tools for verification of results obtained and complementary studies based on adaptations in the model. In both cases, the models are available upon request.

The tool presented in article 2 is the most generic of the three studies and perhaps the one that can contribute to the broadest range of future investigations. The Circular EEE SD model follows practical applications that demonstrate some of its capabilities. The model is made available for use in an accessible repository with guidelines for calibration, featuring a considerable contribution from the prescriptive point of view, as it allows others to use it as a basis to develop their models. Some boundary conditions delimit its application with little need for adaptation: it suits well the investigation of nationwide use of durable goods considering second-use with repair, remanufacturing, recycling, and enhanced lifetime strategies. The calibration process requires careful research of technology adoption time-series, information on product obsolescence, and information from the country's CE structure.

The requirements for an SD-based tool to investigate CE transitions guided the development of the three simulation models. Table 7-1 contains evidence of the fulfilment of those requirements from elements of the three studies. In the table, each of the requirements presented in section 2.2 is revisited and discussed.

**Table 7-1** – Evidence of fulfilment of requirements set for an SD-based tool in the three studies

| Requirement for an SD-based tool | Evidence of fulfilment in the three studies |
|---|---|
| Enable users examining the behaviour of resources – products, components, materials, and energy – within a system through time | In the three studies, the central sub-model contains the structures that allow investigating a possible deceleration in the flow of resources from CE interventions. Article 1 contemplates only stocks of resources of the MOL and EOL stages of equipment and consumables, which matches the scope of the investigation. On the other hand, the investigation of products with very different lifetime patterns - medical equipment and consumable supplies - enrich the discussion about the use of the sharing platform.<br>Articles 2 and 3 contemplate stocks of resources belonging to the BOL, MOL and EOL steps. In both studies, a specific product represents the class of EEE products, which are durable goods. In article 2, the product investigated is flat display panel TVs. In article 3, smartphones.<br>All three studies do not directly investigate the use of energy in the systems, but the addition of structures connected to the stocks and flows of products, components and materials may allow this function. |
| Enable users examining the effects of CE strategies adoption considering concurrent implementation and eventual rebound effects | All studies contain the implementation of known circular strategies. Sharing is the investigated strategy in article 1. It is, in fact, a type of circular strategy that requires further investigation since there is controversy regarding its contribution to the deceleration of resources. Article 1 indicates that the sharing of durable goods in a hospital can contribute to improved use of resources.<br>Article 2 presents the most extensive range of circular strategies examined: second-use with repair, remanufacturing, recycling, and enhanced lifetime strategies. The strategies are applied concurrently, enabling the discussion of their potential contribution to a CE transition.<br>Article 3 contemplates strategies for the collection of post-use products. Three factors determine the scenarios for collection of EEE: the coverage increase per year, the distribution of collection points and the possibility of reward for customers. The convenience allowed by the distribution of collection points along with the existence of a reward determines customers’ adoption. |
| Enable users defining and comparing scenarios for different consumption and production system configurations (as-is vs could-be) | For all studies, modelling and simulation objectives were defined in line with current discussions in the literature and the systems in question, aiming at generating insights for decision making.<br>The ability to compare scenarios allowed by SD modelling and simulation enabled to examine different configurations of CE strategies implementation in the systems under investigation. The calibration of the models for an accurate representation of the current state of resource use occurred in all studies to allow comparisons with could-be configurations. |
| Enable users investigating systems under a time range adequate to the scale of change, covering the transition to a new equilibrium | The first step when starting the formulation of a simulation model is defining the time range of that model. The scale of the system under investigation, the frequencies of flows in that system and the duration of the interventions determines the time scope of simulations.<br>The time boundary of the model in article 1 is of 120 months, following the lifetime of medical equipment considered in the investigation. This time range was sufficient to examine the pattern of behaviour from adopting the sharing platform.<br>The time boundary of the model in article 2 is of 50 years to demonstrate the effects of implementing CE strategies considering the adoption of flat display panel TVs technology until reaching a dynamic equilibrium behaviour. The adoption of flat display panel TVs in the Netherlands went from 0 to 90% in 12 years, and the product has an average lifespan of 8.33 years.<br>The time boundary of the model in Study 3 is of 30 years to demonstrate the process of adopting smartphones in Brazil (from 0 to 65% in 12 years). The smartphone is a product with a shorter lifetime, 2.6 years. However, the implementation of collection policies occurs after the adoption process has stabilized and takes five years to occur. |

| Requirement for an SD-based tool | Evidence of fulfilment in the three studies |
|---|---|
| Enable users examining the possibility of eco-economic decoupling to assist determining ideal states | In article 1, the fact that the hospital requires fewer products over time while serving even more patients makes us believe that the use of the sharing platform can contribute to a potential eco-economic decoupling.<br>In articles 2 and 3, in all cases, the national demand for EEE products is met. This way, value is being delivered to end-users in all cases. From the perspective of job creation, the circular flows activated in the investigations in both studies represent opportunities to operate these circular value chains, which may even positively influence the creation of value. However, the lower demand for material extraction may have negative impacts on the economy that would influence a potential eco-economic decoupling scenario. |
| Enable users examining the positive and negative effects of system change from the perspective of different stakeholders, including the environment and society | In article 1, the effects of adopting the sharing platform allow discussing the benefits and challenges for the medical staff, patients, the hospital, the platform provider, and the environment. The most significant adjustment required is from the medical staff behaviour, which must pass to use the platform and manage the downtime of the products or supplies near expiration. The potential benefit is clear from the point of view of patients, hospital and the environment.<br>Articles 2 and 3 bring the perspective of the EEE industry, retailers, service providers, users, society and the environment. Adaptations are necessary from the point of view of the industry, retailers, service providers, and user behaviour. Both studies consider the social expectation of adopting new technologies that will continue to contribute to resolving the needs of human beings. For the environment, reducing the need for resource extraction and diminishing losses of resources from the consumption and production system to the natural system should direct further discussions. |
| Facilitate decision-making for top-down and bottom-up transitions | The use of models to examine possible scenarios for implementing CE strategies can help in the decision making of policymakers and business practitioners in the three studies.<br>Study 1 shows the decision-making focused on the perspective of business practitioners. Model use can help both the platform providers to direct the design of the solution, as well as hospitals, to investigate the value proposition of a sharing platform.<br>Study 2 can facilitate communicating the circularity challenge to an entire industry. The use of the results can both help to direct the proposition of public policies that provide an adequate CE transition, as well as help businesses to direct the implementation of CE strategies and disseminate good practices to players in the sector.<br>Study 3 can help align expectations among policymaking efforts to the roles of businesses and individuals in the implementation of a national public policy. |

The three simulation models and its applications are a stepping stone for future research. The following section presents the avenues for future investigations.

## 7.3 Further avenues of investigation

From the results presented in this thesis, some avenues of investigation are visible. There is room to investigate further both bottom-up CE transitions connecting micro- to meso-level CE systems, and top-down CE transitions connecting macro- to meso and micro-levels CE systems. Besides, the studies presented here can help guide the identification of fundamental behaviours of CE systems and transitions. There are also other systemic approaches within the scope of System Dynamics or complementary modelling approaches that can contribute to facilitating CE transitions. These avenues are presented below connected to the results of articles 1, 2 and 3 to exemplify them.

From the perspective of bottom-up CE transitions, starting at the micro-level is a good strategy if the intention is to investigate the effects of adopting a circular innovation via business model adoption. The investigation of circular business model innovation at the micro-level allows investigating the solution's value proposition from the point of view of the effects of adopting innovation by one element – organization, household or individual – and its effects on use of resources. From this, it is possible to expand to the other levels in a structured way. For example, the adoption of a sharing platform can be expanded from a single hospital to multiple hospitals in a region and investigate the effects of shared use of resources at the meso-level. This meso-level view can, in turn, contribute to the discussion of the effects of potential macro-level adoption of that business model in a whole country. This path delimits the investigation of a bottom-up transition with an increasing aggregation of scope, holding the potential to clarify the role of innovation adoption in region-wide CE transitions, and identify leverages to boost the adoption of bottom-up circular innovation.

In the other hand, starting at the macro-level is a good strategy for examining the impact of public policies. From an aggregated investigation of change starting at the national level, it is possible to expand the analysis of public policy adoption to the meso- and micro-levels. Article 3 discusses that to make a national policy feasible, the city-level implementations and individual consumer adoption must be aligned with the targets and means set by the policy. Further detailing the mechanisms at the meso and micro levels can therefore contribute to discussions regarding the design of the actions to be taken to make a national policy feasible. At the meso level, it can be worthy to detail the dynamics in a city to help clarify the need for infrastructure and ways to monitor the results of the transition at a more detailed level than that presented in article 3. At the micro-level, for example, it is possible to endogenize the motivations of individuals to engage with the selective collection system. A multi-level investigation of top-down transitions can make it possible to align the implementation of measures that meet the needs of national levels down to individual levels.

The three studies and discussions held in this thesis reinforce the finding that the CE transition happens at multiple levels. Thus, it is essential to connect the levels of CE systems in the investigation of CE transitions when using modelling and simulation. In the SD literature, Schwanninger and Grösser (2016) recommend developing models in different degrees of resolution and suggests considering models composed of building blocks to connect these degrees of resolution. The building block structure prescribed by them can connect the investigation of the dynamics occurring in the multiple levels of CE systems. For example, the model presented in article 1 could serve as a building block to investigate the adoption of sharing platforms by a group of hospitals, which would support an investigation of adoption across an entire region. If well designed and disseminated, the building block structure for connecting CE systems can guide the efforts of the community interested in investigating CE transitions using SD modelling and simulation.

SFD-based simulations can also be used for more conceptual discussions to investigate concepts such as obsolescence or general behaviour of CE systems. For example, as discussed in article 2, multiple reasons for EEE obsolescence exist: material, functional, psychological, economic (Prakash, Dehoust, Gsell, & Schleicher, 2015; Proske, Winzer, Marwede, Nissen, & Lang, 2016; Wilson et al., 2017) and the co-flow structure determining obsolescence in the Circular EEE SD model can be expanded to investigate strategies to cope with different reasons for obsolescence. Besides, the comparison of inputs used in studies 2 and 3 and the patterns and magnitudes of behaviour obtained highlights the existence of fundamental behaviours in CE systems. The velocity and level of technology adoption, the average lifetime of products and the level of adoption of CE strategies determine a relevant portion of the behaviour of stocks and flows. In this way, sensitivity analysis and formal analysis of models can help to identify these fundamental behaviours and allow for more generalizable descriptions. The conceptual model for CE systems, as well as specific structures used in the Circular EEE SD Model can help in this research avenue.

This research was very focused on the stock optimization principle and on the use of the ability of simulation models to investigate the dynamics of inflows and outflows of stocks. The objective of developing a tool using SD modelling and simulation may explain part of the reason. However, the transition from a socio-technical system is certainly much more than a stock optimisation problem. In this way, it is possible to explore further the qualitative perspective of CE transitions based on the use of Causal Loop Diagrams (CLDs) and identify leverage points that may not be clear when thinking only of stock and flows structures (cf. Luna-Reyes & Andersen, 2003). Besides, agent-based modelling, a modelling and simulation approach that can be combined with SD in hybrid simulation models (Lättilä, Hilletofth, & Lin, 2010), is a candidate for additional investigations as it can examine patterns of behaviour emerging from agents (Borshchev & Filippov, 2004).

Finally, there is plenty of space to investigate what insights the use of models generates for decision-makers and the potential for continued use of models to enhance CE transitions. The application of a group model building approach to involve potential users already in the investigation process (Vennix, 1999) and the creation of learning laboratories to speed up users' learning about the system (Senge & Sterman, 1992) must be considered to explore potential trajectories for more effective consumption and production systems.

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