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A system dynamics-based framework for examining Circular Economy transitions

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ABSTRACT

Decision-makers in the public policy and business arenas need tools to deal with multiple sources of complexity in Circular Economy (CE) transitions. System Dynamics (SD) facilitates coping with increased complexity by enabling closed-loop thinking via identifying the causal structures underlying behaviour and permitting to proactively experiment with the system through simulation. This research aims to propose and test an SD-based framework for examining CE transitions to supporting decision-making at the micro-, meso-, and macro-levels. Two inductive model-based cases studies led to formalising the framework, finally tested in a third deductive model-based case study. The framework is built upon the well-known stages for building SD simulation models and complemented with domain-specific activities, guiding questions, and expected outcomes when examining CE transitions. The SD-based framework is the first modelling-oriented prescriptive approach to help researchers and practitioners examining CE transitions on their journeys to understand and facilitate changes through SD simulation models.

1. Introduction

Circular Economy (CE) aims to decouple economic growth from resource extraction and waste (Kalmykova et al., 2018; Murray and Skene, 2015). In contrast with the linear economy, CE is seen as a promising production and consumption model to achieve a future scenario of prosperity (Blomsma and Brennan, 2017), which can break the mass-value-carbon nexus (de Wit et al., 2019) and serve as a path towards sustainable development (Kirchherr et al., 2017).

Adopting a systems perspective (Ellen MacArthur Foundation, 2012; Kirchherr et al., 2017) is at the core of CE, which calls for the design and implementation of structural changes that appreciate the causal loops between socio-economic and natural systems. Decision-makers involved in CE transitions need tools to reduce uncertainties (Linder and Williander, 2015; Velte and Steinhilper, 2016), manage complex system dynamics and anticipate future scenarios (Hopkinson et al., 2018). The CE concept must be operationalised (Geisendorf and Pietrulla, 2018) to enable informed decisions that transcend disciplinary boundaries (Iacovidou et al., 2020).

Nevertheless, the majority of circular innovation tools still provide a static view, limited to representing a system's image at a given moment in time (Pieroni et al., 2019) without addressing dynamic characteristics of resource use, such as value loss and material scarcity (Merli et al., 2018). The deceleration of physical resource flows demands considering the "interests and preferences affecting and affected by the physical fluxes" (Korhonen et al., 2018b), reinforcing the need to capture and understand the dynamic aspects of social and behavioural change. The complexity of decision-making in CE transitions increases due to: (1) the insufficient capacity of tools to represent a system's dynamic behaviour; and (2) the lack of process-based approaches and guidelines to manage the transitions.

System Dynamics (SD) is a simulation modelling approach that represents the structure of complex systems through material and information feedback loops formed around stocks, flows and auxiliary variables (Forrester, 1961, 2016). Such structures enable exploring the causes and consequences of dynamic trends of concern and the design of high-leverage policies to improve systems' performance (Forrester, 1961, 2016). Scholars have started to explore SD for dealing with the complexity of CE transitions. Examples include SD-based simulations to

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Acronyms

ABM	Agent-based modelling
BAU	Business-as-usual
BIAEEE	Brazilian industry agreement for electrical and electronic equipment
CE	Circular Economy
CLD	Causal Loop Diagram
DES	Discrete-event simulation
DoI	Diffusion of innovation
EEE	Electrical and electronic equipment
KPI	Key performance indicator
LCA	Life-cycle assessment
MFA	Material flow analysis
SD	System Dynamics
WEEE	Waste of electrical and electronic equipment

investigate firm-level effects of the combination of CE strategies (Franco, 2019), combination with agent-based modelling (ABM) to examine the interplays of behavioural changes and solution performance in circular innovation (Asif et al., 2016; Lieder et al., 2017), the influence of products' lifetime and hibernation in European consumer electronics' demand (Glöser-Chahoud et al., 2019), and the effects of supply chain integration strategies in the European steel industry in iron ore consumption (Pinto and Diemer, 2020). These studies expose the potential of SD to facilitate decision-making in a single firm to national and supra-national circumstances for CE transitions.

Decision-making in CE transitions is immersed in complexity, jeopardising the abdication of linear practices towards more effective use of resources. Meanwhile, the growing interest in using simulation models to investigate CE systems and transitions opens up an opportunity to deal with the sources of complexity. A fundamental research gap lies in the unavailability of guidance to enable decision-making in CE transitions supported by SD simulation models. This gap leads to the following research question: *"What are adequate SD modelling practices to* support *decision-making in CE transitions?*". This research proposes and tests an SD-based framework for examining CE transitions built upon the five iterative stages for building SD simulation models (Sterman, 2000) and complemented with domain-specific activities, guiding questions and expected outcomes of CE transitions examinations. The framework was developed based on two inductive case studies of CE transitions (Guzzo et al., 2019a, 2022) and tested in a third case study (Guzzo et al., 2022).

The SD-based framework is a critical asset to enhance systems thinking when examining CE transitions. Systems are interconnected and coherently organised elements set to achieve a function or purpose, where that same structure determines the system behaviour revealed by a series of events over time (Meadows, 2009). Under a linear economy paradigm, production systems exist to meet consumption demands, and the structure of those systems cause the dependence on resource extraction and waste generation. Systems thinking allows exploring the system structure to make "what-if" questions about potential behaviours, thus enhancing the understanding of the reasons for once surprising patterns of behaviour (Meadows, 2009; Sterman, 2000), as the mass-value-carbon nexus. In this work, systems thinking is enabled by SD simulation models that can help achieve closed-loop thinking via experimentation, allowing decision-makers to deal with inherent dynamic complexities and favour the paradigm shifts required for CE transitions.

In addition to SD, other simulation modelling approaches such as ABM, and discrete-event simulation (DES) could be useful for examining CE transitions. DES emphasises on detail complexity (i.e., complexity emerging from the number of combinations for decision-making optimisation), making it prone to operational or tactical issues (Borshchev and Filippov, 2004; Sterman, 2000; Tako and Robinson, 2009). ABM holds high potential for investigating CE transitions as it can represent complexity arising from emergent and decentralised behaviour of individual agents, based on defined behavioural rules and nonlinear interactions among them (Anderson et al., 2018; Borshchev and Filippov, 2004; Siebers et al., 2010). While applying ABM or even coupling SD with ABM or DES are interesting possibilities for investigating CE transitions, SD was the featured approach in this study as the stocks, flows, and feedback loop structures sufficiently tackled the identified dynamic complexities that emerge in CE transitions decision-making.

The paper is organised as follows: section 2 describes the theoretical background within CE systems and transitions, the foundations for applying SD modelling and simulation to investigating CE transitions, and a review of SD-based simulation research in the field. Section 3 outlines the research methodology employed. Section 4 describes the process for developing and testing the framework, alongside the framework itself. Section 5 contains relevant discussions and contributions. Finally, section 6 delineates the concluding remarks and emerging research avenues.

2. Theoretical background

2.1. On Circular Economy systems and transitions

CE systems rely on applying strategies that slow, close, and narrow the flows of resources, leading to sustainability (Bocken et al., 2016; Geissdoerfer et al., 2017). Sharing, servitisation, maintenance provision, designing for optimal lifespan, industrial symbiosis, recycling, and use of renewable resources are among such strategies (Guzzo et al., 2019b). The systematic use of CE strategies aims to harmonise the technical and biological cycles (Ellen MacArthur Foundation, 2012) and maximise the value of resources in use at all stages of the value chain (Stahel, 2016) following a stock management principle (Kalmykova et al., 2018).

CE systems occur at three different levels determining specific characteristics and patterns of change (Ghisellini et al., 2015; Kirchherr et al., 2017; Su et al., 2013):

- Micro-level CE systems – change happens within a single organisation, household or individual. The focus is on product, firm and consumers (Kirchherr et al., 2017). For individuals, labelling systems can influence consumption and disposal behaviour (Ghisellini et al., 2015). Considering products and firms, eco-design and cleaner production techniques improve the design and manufacturing of products towards reduced environmental footprint (Ghisellini et al., 2015; Sauvé et al., 2016; Su et al., 2013).
- Meso-level CE systems – change happens due to symbiotic associations among system actors in geographic proximity for sharing resources (Kalmykova et al., 2018; Sauvé et al., 2016). Examples include the development of eco-industrial parks and eco-agricultural systems (Su et al., 2013); and urban symbiosis and eco-cities, which rely on geographic proximity opportunities for waste management and sharing of resources (Ghisellini et al., 2015; Su et al., 2013). Material, water, energy, and available infrastructure are among the resources shared (Ghisellini et al., 2015; Su et al., 2013).
- Macro-level CE systems – change happens in whole industries, regions or nations. The focus is on global or national areas, considering entire production and consumption systems (Kirchherr et al., 2017). Housing, mobility, nutrition, clothing, electronics are some of the value chains playing a crucial role in the transition to a CE since they represent essential societal needs while incurring large footprints globally (de Wit et al., 2019; Winans et al., 2017). The integrated representation of consumption and production encompasses the participation and interests of complex actors networks (Sauvé et al., 2016; Su et al., 2013).

Based on the previous characterisation, the definition for CE systems

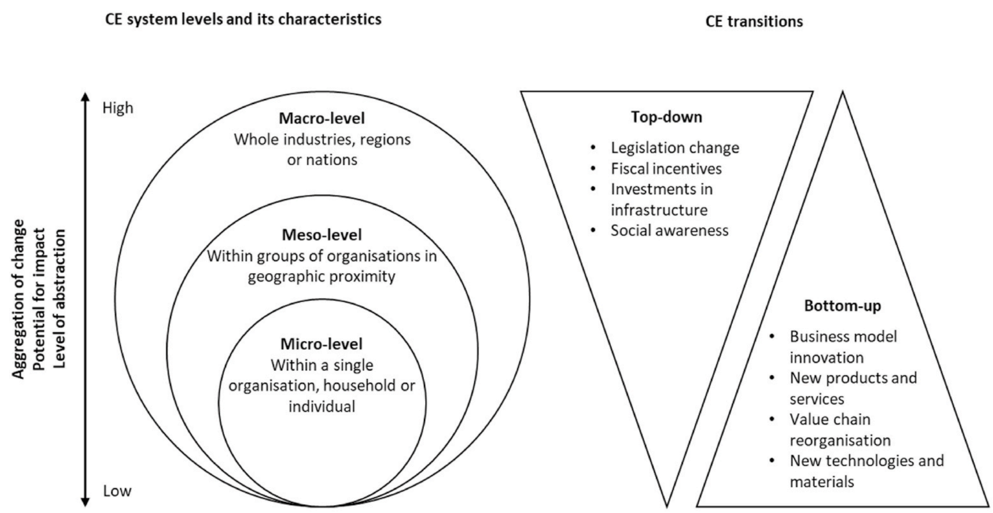


Fig. 1. CE system levels and their characteristics concerning CE transitions.

adopted follows.

CE systems are consumption and production systems occurring in multiple levels: micro-, meso-, and macro-, that permits enhanced positive effects on nature, society, and the economy via the deceleration of resources' flows.

Shifting from linear to circular systems unfolds three facets of transitions: the changing, comparative, and directional facets, as following described. The *changing facet* encompasses the necessary shifts to achieve improved modes of consumption and production. 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. Thus, CE transitions' *changing facet* positions linear systems ('as-is') to be replaced by CE system ('as could-be'). The very existence of 'could-be' CE systems demonstrates different options for better use of resources.

The *comparative facet* of CE transitions indicates that decision-makers often face challenging choices among different paths towards circularity, as prioritising among remanufacturing or recycling strategies, for instance. Specific circular system compositions can lead to preferable options for using resources and minimising negative sustainability impacts, on the basis of the same functional unit to allow for comparisons. Full-decoupling ideal states of consumption and production systems are often envisioned (Kjaer et al., 2019) as worth pursuing visions that permit identifying synergies for long-term collaboration (Brown et al., 2019). They can direct short- and medium-term action towards fundamental shifts in the consumption and production systems (Gorissen et al., 2016). The *comparative facet* enables prospecting change within the system under investigation and thinking of options to bridge the gap between the future vision and the current regime.

The *direction of change* is the third facet of CE transitions, which may happen through top-down, bottom-up initiatives or combinations of both (Lieder and Rashid, 2016; Merli et al., 2018). Top-down initiatives change the social and economic dynamics through legislation, fiscal incentives, investments in supporting infrastructure, and social awareness to create an atmosphere conducive to the implementation of CE systems (Ellen MacArthur Foundation, 2015; Geisendorf and Pietrulla, 2018; Hobson, 2015; Lieder and Rashid, 2016; Merli et al., 2018). Public policies should consider the total consumption and production over the life cycle to avoid short-sighted interventions (Zhu et al., 2019). Also, policies must effectively align CE initiatives locally, regionally and internationally (Milios, 2018). Thus, top-down interventions should consider the effects of incentives in the micro- and meso-levels to empower the transition in macro-level systems. Bottom-up initiatives implement and sustain the CE system driven by opportunities of creating, delivering and capturing value through technologies, products and services, and value chain innovations (Ellen MacArthur Foundation, 2015; Lieder and Rashid, 2016; Moreno et al., 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; Pieroni et al., 2020). In bottom-up change, companies play a crucial role in innovating and scaling business models that sustain enhanced consumption and production modes – 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 CE transitions. Innovations might combine new technologies, rules and legislation, and value arrangements (Geels, 2011; Gorissen et al., 2016). Thus, the adequate definition of top-down initiatives should align the roles and expectations of the 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, enable market formation, and achieve the necessary leverage to reach CE regimes. Either way, CE transitions might require small-scale testing in protected environments (niches) before full adoption by the regime.

Based on the above-detailed facets, the definition for CE transitions adopted in this study follows.

CE transitions constitute the change process from linear economy systems (as-is) to (could-be) CE systems, which comparatively make more effective use of resources and are ultimately characterised by absolute decoupling. Change happens through multiple directions: top-down initiatives, bottom-up initiatives, or combinations thereof.

Fig. 1 shows that bottom-up and top-down change enable CE transitions at the micro-, meso-, and macro-levels. Model-based investigations on the three levels might lead to a varying potential for impact, aggregation of change, and level of abstraction, establishing a rule of thumb to address CE systems. Change reaching higher system levels holds more significant potential for positive impact (Ceschin and Gaziulusoy, 2016) as they also contain the changes happening in the lower level. Meanwhile, higher level changes require higher aggregation to simultaneously deal with several aspects of change (Borshchev and Filippov, 2004). Therefore, system elements and relationships might disclose a higher level of abstraction (Borshchev and Filippov, 2004), leading to a clear trade-off among assessing potential impacts and detailing of specific system aspects. When dealing with micro-level systems, these characteristics will most likely be at the rulers' opposite limit.

Facing CE from the systems and transitions perspective helps to understand structures that might decelerate the flow of resources and consider the corresponding activation switches to activate long-lasting changes towards circularity.

2.2. Employing SD modelling and simulation to investigate CE transitions

Webster (2013) presents a "systems language", i.e., the definition of critical concepts such as feedback, resilience, effectiveness, metabolism, and inflexion point to understand CE through a systems perspective. Velte and Steinhilper (2016) present a list of complexity factors that emerge from CE 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 life cycle stages: from extraction to consumption and back through repair, remanufacturing and recycling. Although stocks, flows, feedback loops and leverage points are frequent terms in the CE literature, still few studies strive to clarify the meaning of systems thinking in the CE literature.

CE transitions entail system configurations of increased complexity. *Dynamic complexities*, or the counterintuitive behaviour of complex systems, stem from the multiple causal relationships among elements, accumulation processes, and delays and non-linearities in system behaviour over time (Sterman, 2000). A characteristic of CE systems that leads to potential counterintuitive behaviour is that these systems frequently rely on CE strategies' combined implementation, leading to essential trade-offs (Blomsma et al., 2018; Brennan et al., 2015; Reike et al., 2018; Zink and Geyer, 2017). Trade-offs indicate changes taking place in different parts of the system and at different scales that often interact (Sterman, 2000) or tensions between short-term gains and long-term opportunities (Hopkinson et al., 2018). Table A-1 presents the *dynamic complexities* found in CE systems and transitions.

A *paradigm shift* is needed to enable CE transitions, i.e., a change in shared social agreements of reality, purposes, the understanding of feedback and system structures (Meadows, 1999). Paradigm shifts hold high leverage that can completely transform systems. Besides, 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 sufficiently address the linear economy effects.

Closed-loop thinking allows identifying causal feedback in systems structures to understand how dominance among variables might alter system behaviour over time (Sterman, 2000). SD modelling favours CE transitions because it allows seeing the world as collections of stock-and-flow structures and enables determining policies to influence stocks' inflows and outflows (Videira and Rouwette, 2020). Simulation models can help achieve *closed-loop thinking* via experimentation, allowing decision-makers to deal with inherent *dynamic complexities* and favour the *paradigm shifts* required for CE transitions.

2.3. SD-based simulation research investigating CE systems and transitions

There is a growing body of studies using SD-based simulation models to investigate CE systems and transitions. Table 1 presents and characterizes twelve of these studies, classified according to: (i) position in the different CE system levels (micro-, meso-, and macro-); (ii) direction of change (bottom-up, top-down, combined, and conceptual); (iii) industry; (iv) modelling approaches; and (v) modelled features.

A considerable variety of research purposes emerge from the studies. It includes investigating the effects of the combined implementation of CE strategies (Franco, 2019; Guzzo et al., 2021), the effects of supply chain integration strategies (Pinto and Diemer, 2020), the co-evolutionary dynamics between the industry sector and public policy implementation (Kliem et al., 2021), and combined efforts of product design, business model innovation and supply chain alterations (Alamerew and Brissaud, 2020; Asif et al., 2016; Franco, 2019).

The approach used for SD modelling also varies widely between studies. Some studies use purely the SD language, taking advantage of the capabilities of SFDs and CLDs in different ways. For example, Kazancoglu et al. (2020) use pure SFD to organize forward and reverse logistics activities into value-adding and non-value-adding activities to investigate the environmental impacts under different scenarios. Glöser-Chahoud et al. (2019) created detailed ageing chains using SFD to examine measures to extend service lifetime and reduce hibernation time.

For the combined use of CLDs and SFDs, some studies employ simple CLDs and small SFDs in their investigations. For example, da Silva (2018) uses a simple CLD to demonstrate the impact of recycling on the cost of waste disposal and then through a small SFD model shows the impact of investing in public environmental education on the rate of collection and the total costs of final disposal. In turn, Okorie et al. (2018) use a simple CLD further deployed into a two-stock SFD to examine the effects of component information availability in the remanufacturing process. Alamerew and Brissaud (2020) follow a different strategy to combine CLDs and SFDs: they start with an SFD simulation model to examine scenarios for remanufactured electric vehicles batteries and then discuss the dynamics of decision factors based on four CLDs built from the literature and interviews.

Some studies transcend the SD modelling barriers. In total, five multi-method studies were identified. On the one hand, some studies combine established ways of examining life cycle flows and impacts to SD models. For example, Guzzo et al. (2021) built the simulation model logic using concepts from the material flow analysis (MFA) domain to increase the conceptual validity of the structures. In turn, Gao et al. (2020) integrate intensity efficiency indexes of the MFA domain into the SD model to evaluate the implementation of regional CE strategies. Pinto and Diemer (2020) build an extensive SFD following the LCA methodology to compare ore and iron consumption, steel output and scrap consumption from the different strategies to close the material loop in different parts of the value chain. Both Guzzo et al. (2021) and Pinto and Diemer (2020) use mass balance tests for enhanced model validity.

In other multi-method studies, SD approaches are combined with simulation methods such as ABM and DES. For example, Asif et al. (2016) combine the customer's decision-making process ABM-based sub-model to the supply chain behaviour and the economic and environmental performance SD-based sub-models to examine the performance of circular product systems. Finally, Charnley et al. (2019) examine the effects of certainty of product quality (CPQ) on remanufacturing processes using parallel DES and SFD models.

There are also studies that apply the SD approach to investigate CE without focusing on simulation that, although out of the scope of this research, are worth mentioning. For example, Mies and Gold (2021) use pure CLD to map the social dimension of the CE phenomena. Also, Gnoni et al. (2017) represent the effects of introducing an use-based business model on the supply chain configuration from a CE perspective. Finally, pure ABM models also help investigate CE systems and transitions. For example, Lieder et al. (2017) develop a purchase decision model on ABM to examine customer behaviour due to the introduction of buy-back and pay-per-use offers in the washing machines market. This study deploys the ABM sub-model used in Asif et al. (2016).

Measuring the performance of CE systems beforehand (Asif et al., 2016; Franco, 2019), exploring the viability of targets (Franco, 2019), exposing the cost of non-action (da Silva, 2018), sustaining the discussions of top-down and bottom-up measures (Glöser-Chahoud et al., 2019), and identifying the existing barriers to CE transitions (Kliem et al., 2021) are some of the claimed benefits of SD-based simulation research to investigate CE systems and transitions. The body of studies identified show different strategies might be followed in the investigations. Nevertheless, no clear guidance for less experienced modellers and researchers to enable decision-making in CE transitions supported by SD simulation models is available. Thus, a clear opportunity lies in providing a more prescriptive approach to help researchers

Table 1
Characterisation of identified SD-based simulation research investigating CE systems and transitions. *BM stands for business model, Pr. For product, VC for value chain, and Pol for policy.

Title	Authors and Year	CE system level	Direction of change	Industry	Modelling approach	Modelled features*			
						BM	Pr	VC	Pol
Multi-method simulation-based tool to evaluate economic and environmental performance of circular product systems	Asif et al. (2016)	Micro-level (one company)	Bottom-up	Generic (durable goods)	SD and ABM applied in the same model	X	X	X	
Simulation to Enable a Data-Driven Circular Economy	Charnley et al. (2019)	Micro-level (a hypothetical remanufacturing facility in the UK)	Bottom-up	Automotive	DES and SD applied in different models			X	
A system dynamics approach to product design and business model strategies for the circular economy	Franco (2019)	Micro-level (one manufacturer)	Bottom-up	Varied (short-life and long-life products)	SD (CLD and SFD simulation model)	X	X	X	
Performance evaluation of reverse logistics in food supply chains in a circular economy using system dynamics	Kazancoglu et al. (2020)	Micro-level (milk and dairy company in Turkey)	Bottom-up	Food	SD (SFD simulation model)	X		X	
A Systems Dynamics Enabled Real-Time Efficiency for Fuel Cell Data-Driven Remanufacturing	Okorie et al. (2018)	Micro-level (a hypothetical remanufacturing facility in the UK)	Bottom-up	Automotive	SD (CLD and SFD simulation model)			X	
Proposal of a dynamic model to evaluate public policies for the circular economy: Scenarios applied to the municipality of Curitiba	da Silva (2018)	Meso-level (City of Curitiba)	Top-down	Municipal waste	SD (CLD and SFD simulation model)			X	X
Closing the mineral construction material cycle – An endogenous perspective on barriers in transition	Kliem et al. (2021)	Meso-level (settlement development in Switzerland)	Combined	Built environment	SD (CLD and SFD simulation model)	X		X	X
Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries	Alamerew and Brissaud (2020)	Macro-level (France)	Combined	Automotive	SD (SFD simulation model and CLD)	X	X	X	X
Circular economy model of gold recovery from cell phones using system dynamics approach: a case study of India	Chaudhary and Vrat (2020)	Macro-level (India)	Top-down	Electronics	SD (CLD and SFD simulation model)			X	X
Pathways towards regional circular economy evaluated using material flow analysis and system dynamics	Gao et al. (2020)	Macro-level (Guangdong region)	Top-down	Municipal resource use and waste	SD (CLD and SFD simulation model) following a MFA approach				X
Simulating the service lifetimes and storage phases of consumer electronics in Europe with a cascade stock and flow model	Glöser-Chahoud et al. (2019)	Macro-level (Europe continent)	N/A	Electronics	SD (SFD simulation model)		X	X	
Supply chain integration strategies and circularity in the European steel industry	Pinto and Diemer (2020)	Macro-level (Europe continent)	Bottom-up	Steel	SD combined with LCA	X		X	

and practitioners on their journeys to understand and facilitate change towards CE through SD simulation models.

3. Research methodology

Case studies contribute to the inductive construction of new theories based on empirical evidence, followed by a deductive theory-testing process (Eisenhardt and Graebner, 2007). Multiple model-based studies (Kopainsky and Luna-Reyes, 2008) were used to propose and test the framework to examine CE transitions using SD simulation models (Fig. 2).

The accumulated knowledge from two inductive case studies enabled identifying a set of activities, guiding questions and outcomes when examining CE transitions that were positioned within the five-stage approach for SD modelling and simulation (Sterman, 2000). A third case study deductively tested the proposed framework. The three model-based case studies followed an iterative approach for SD modelling and simulation, based on the five iterative stages of Sterman (2000):

1. **Problem Articulation** determines the modelling purpose.
2. **Formulation of the Dynamic Hypothesis** leads to a conceptual representation of the complex system.
3. **Formulation of a Simulation Model** translates the conceptual representation into a simulation model with equations determining the relationships among variables.
4. **Model Testing** calibrates the partial and full-model simulation stocks and flows' behaviour to available data and model users' expectations.
5. **Policy Design and Evaluation** builds on scenarios enabled by altering parameters or structures to learn about the effects of change.

Two requirements set cases selection: (i) if they represented a CE system, i.e., a case of resource flows deceleration via the application of one or more CE strategies; and (ii) if there were evident CE transition options.

Each case study uncovered CE transitions occurring at different CE system levels, taking different perspectives of change:

- Case 1 (C1): effects of adopting a sharing platform in one healthcare institution – a micro-level CE system. C1 comprised bottom-up

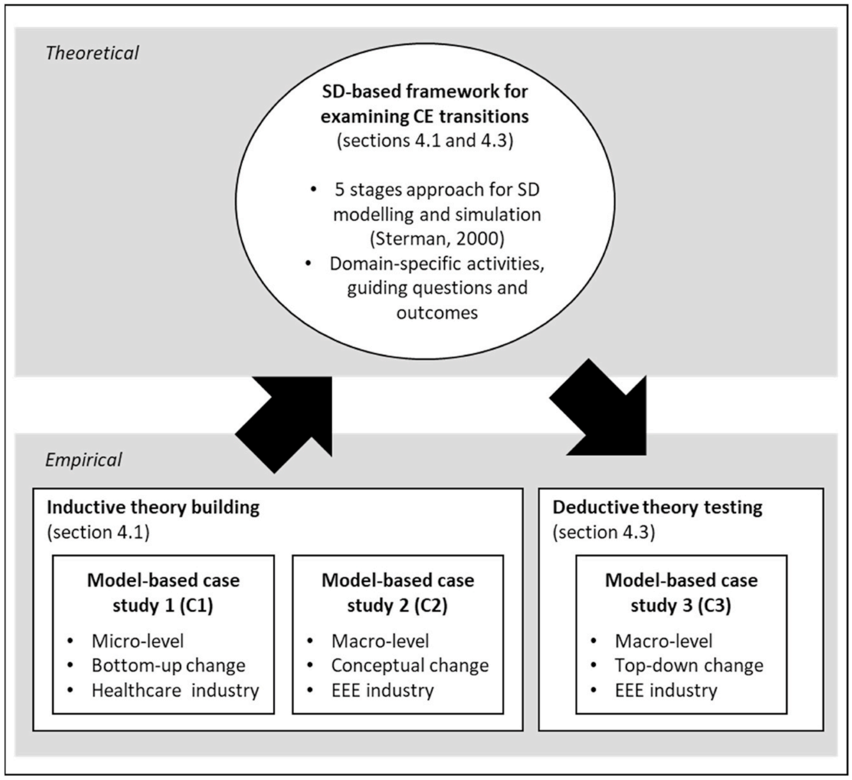


Fig. 2. Multiple model-based case studies to developing a framework for examining CE transitions using SD.

change as it investigates a transition led by adopting a circular business model in the healthcare industry. In C1, the CE transition option involved the potential full adoption of the platform and the effects in consumption of consumable and durable goods.

- Case 2 (C2): effects of a nationwide adoption of CE strategies for Electrical and Electronic Equipment (EEE) products in the Netherlands. C2 comprehended a conceptual transition at a macro-level CE system, contributing to the continuous debate of the nationwide use of electronics. In C2, the CE transition options involved the possibilities for the adoption of different strategies (e.g. second-use, remanufacturing, recycling, and longer lifetime design).
- Case 3 (C3): effects of interventions for collecting end-of-life EEE products following the Brazilian industry agreement for EEE (BIAEEE). C3 comprehended top-down change through public policy adoption. In C3, the CE transitions options involved the possibilities for setting up collection infrastructures for EEEs.

Separate publications detail model-specific results and insights for each case study (Guzzo et al., 2019a, 2021, 2022). In this manuscript, we detail the development and testing of the SD-based framework for examining CE transitions.

4. Results

4.1. Towards a conceptual framework for examining CE transitions using SD modelling

The initial conceptual representation of the framework for examining CE transitions using SD modelling and simulation (Fig. 3) stems from the five iterative stages for SD modelling (Sterman, 2000).

The inductive process described in cases 1 and 2 (C1 and C2) culminated in setting:

- Domain-specific activities denoting prescriptions of critical tasks in each modelling stage.

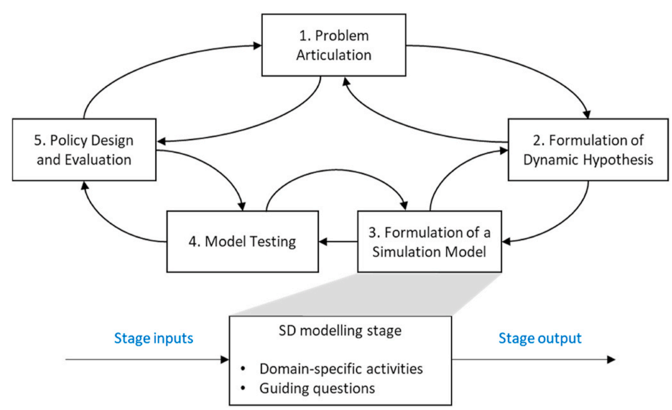


Fig. 3. Conceptual representation of the SD-based framework for examining CE transitions.

- Guiding questions indicating essential considerations for designing and assessing the modelling initiative.
- Expected inputs and outputs, exemplifying typical feedbacks among the process stages.

4.1.1. Problem articulation

Determining the modelling purpose is challenging, as there are multiple perspectives to examining a CE transition. A latent issue was to clarify how model use could accelerate a CE transition at the outset. In C1, the effects of sharing in resource usage by one hospital were prioritised as the service provider needed to understand further the dynamics of sharing and identify levers to their service. C2 aimed to represent EEE stocks and flows' long-term dynamics under specific CE strategies as CE transitions' potential regional effects were unknown. To ensure contribution to a CE transition, the first guiding question in

"Problem Articulation" emerges:

- **Q1.1.:** How can the modelling effort contribute to a CE transition in that system?

With a first version of the modelling purpose, the level of analysis and the perspectives of change contributed to sharp the problem articulation (Fig. 1). C1 deals with a micro-level CE system, investigating resource dynamics in one organisation. It investigated business model adoption by one hospital (i.e., bottom-up change). C2 comprehends a macro-level CE system, as the scope of change is a whole country. C2 represents a conceptual transition, as interventions do not represent specific business or public policy initiatives. The cases were positioned within an industry (healthcare and EEE, respectively) to connect to those value chains' current debates. While C1 leads to a lower abstraction level in adopting a single CE strategy, change in C2 happens in a higher degree of aggregation and represents a more significant potential for impact. The second guiding question helps to detail key CE system and transition characteristics:

- **Q1.2.:** Are the CE system level of analysis, the transition direction and the industry clearly stated in the modelling purpose?

In both cases, research protocols shed light on the dynamics within the systems and potential levers. In C1, interviews with the sharing platform co-founder and secondary research in the healthcare field determined the resources and socio-economic dynamics. C2 followed an extensive literature review focused on durable goods and EEE. The need for a thorough investigation to support the modelling initiative leads to the last guiding question in this stage:

- **Q1.3.:** Is the research protocol adequate to investigate a shift in that system?

4.1.2. Formulation of Dynamic Hypothesis

With the CE transition problem defined, narrowing both studies helped dealing with the several dynamics of interest. When looking at the business model dimensions, several mechanisms were potentially relevant. The same applied to studying an entire EEE production chain. Fig. 4 conceptually depicts the product life cycle phases considered for both cases. C1 focuses on examining the influence of sharing on demand for new healthcare products. C2 considers durable goods' entire life cycle. Both cases considered the mechanisms that pull products in the linear economy and the mechanisms that allow circularity. Thus, the logic for product demand, the product obsolescence and how this triggers more resource extraction were investigated alongside the logics for slowing, closing, or narrowing resources' flows. C2 broadened scope allowed to examine alternative CE strategies that influenced obsolescence, reuse (via second use and remanufacturing), and recycling. The recycling, remanufacturing, repairing and second use levels define the coverage and capacity of such processes. Lifetime design influences products lifetime length, through design decisions (e.g modular design). Inadequate disposal happens whenever no other end-of-life option is available. Positioning the potential deceleration of resources along the product life cycle phases leads to the first question to guide the "Formulation of Dynamic Hypothesis":

- **Q2.1.:** Are the logics for product demand, resource usage, and circularity comprehensively understood for the system under investigation? Are the relevant life cycle stages considered?

It is critical to define endogenous behaviour (values determined by the model's structure), exogenous behaviour (values determined outside the model and imposed on it), and excluded behaviour (mechanisms deliberately disregarded to limit model complexity). In C1, the model *endogenously* captures the dynamics of product acquisition, under-utilisation and obsolescence. These were critical structures to examine the effects of sharing in overall resources' dynamics over time induced by hospital employees' adoption of the new consumption behaviour. A few *exogenous* mechanisms run the model allowing simplicity when no significant feedback elements existed. The demand for healthcare services, the hospital's size, the lifetime characteristics of the products, and

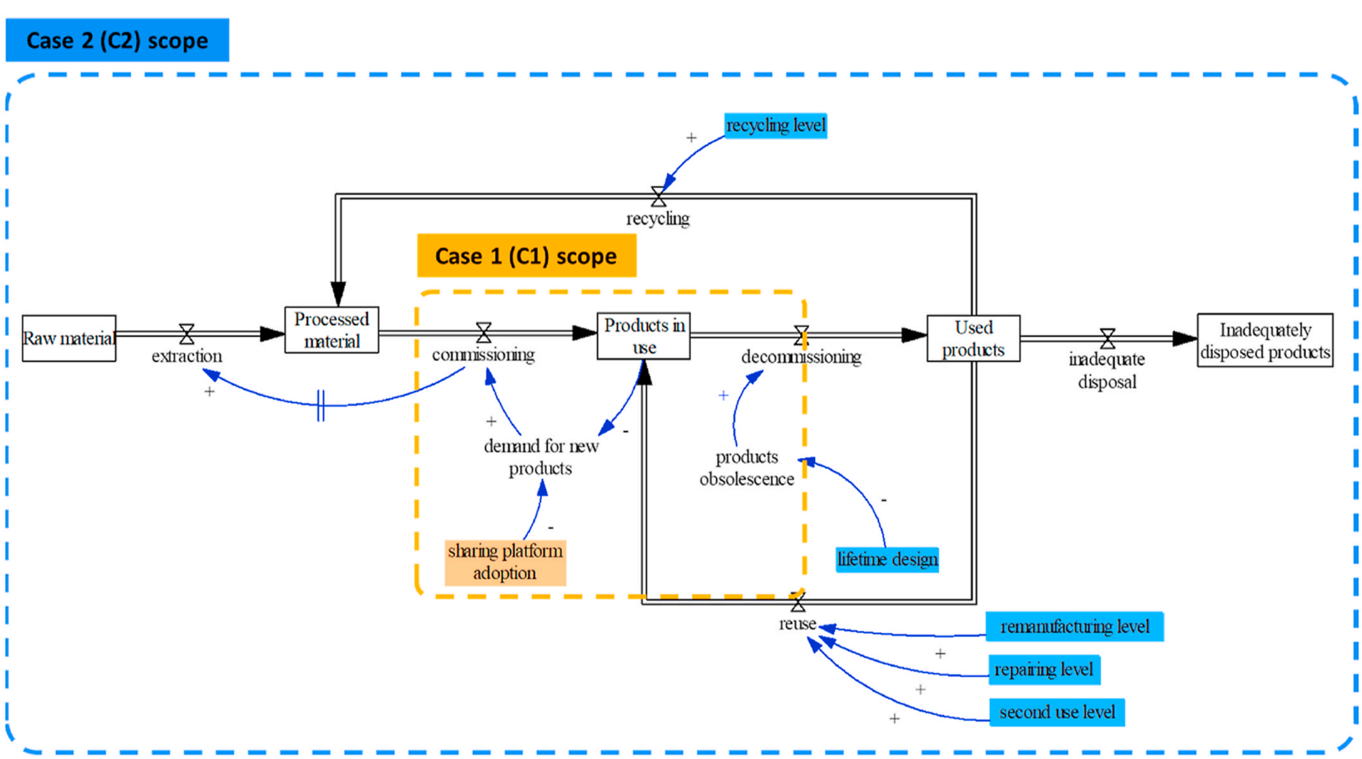


Fig. 4. Scope of analysis of simulation models in cases 1 and 2.

Table 2
Structures employed in simulation models for C1 and C2.

Case \ System structure	Products demand	Resource usage	Circularity
Case 1 (C1)	Demand for healthcare services in one hospital: - use of random time series to determine actual demand. - use of information delay to determine projected demand.	Dynamics of functional, underused and obsolete products determine resource usage: - Constants determine the underutilisation and obsolescence rates.	Adoption of hospital employees to the sharing platform and engagement in sharing activities: - diffusion of innovation structure determines adoption. - users may abandon the platform due to a bad experience, and they may forget that bad experience as well.
Case 2 (C2)	Technology adoption of a EEE product in one country: - diffusion of innovation structure determines adoption. - socio-economic variables as PPP per capita, EEE price and population set adoption values. - demand is composed by adoption, replacing and additional purchases.	Dynamics of first use, reuse, remanufacturing, recycling, inadequate disposal and material extraction determine resource usage: - Weibull distribution functions set obsolescence and additional lives of products. - co-flow structures determine the ageing process, which restoration processes can reverse. - a stock management structure determines the extraction of raw material.	Adoption of second-use, remanufacturing, recycling, and lifetime design strategies: - infrastructure levels determine second-use, remanufacturing, and recycling capabilities. - constant ratios determine variations in the lifetime of products. - constants determine remanufacturability and recyclability.

the users' attributes were model inputs. Further assumptions *excluded* the dynamics of items sharing, considering that registering items on the platform is enough to make the product useful. Also, item degradation due to underuse and careless sharing were ignored because they significantly increased the model's complexity. Both assumptions constitute clear opportunities for future inquiries.

In C2, dynamic MFA, reliability engineering, closed-loop supply chains, and the CE bodies of knowledge conceptually determine resources dynamics. The model *endogenously* represents the technology adoption process, which determines the demand for a type of EEE. Technology adoption was essential to investigate the macro-level transition since any change on a national scale in products' life-cycle influences the resources market. The EEE and WEEE (waste of EEE) flows represent the many statuses and paths one electronic product can follow. An obsolescence process is endogenous to the model, as capturing the ageing process of products is critical to understand the flow of materials at the macro-level (Müller et al., 2014; Murakami et al., 2010; Oguchi et al., 2010). Material supply responds to the additional need for extraction. Relevant socio-economic dynamics *exogenously* determine the demand for products and life-cycle characteristics, linking the resource flows to the socio-economic systems' dynamics. Population, purchasing power parity, and historical values for EEE put on market, price, weight and obsolescence parameters are exogenous parameters determining model behaviour. Despite recognising that systemic changes can modify EEE price and obsolescence rationale, the feedback was considered weaker and *excluded* in this modelling initiative. These are opportunities for future investigations.

The model scoping sets the second question at this stage:

- **Q2.2.:** What are the model boundaries? What behaviour is endogenous, exogenous, and excluded? Is the scope adequate to holistically understand the flow of resources?

4.1.3. Formulation of a simulation model

The next step is to create a simulation model based on the rationale and scope for resource use. C1 and C2 use different time units considering different time horizons to represent transitions happening at different levels. The C1 time horizon was 120 months, aiming for the appropriate representation for healthcare services demand, employees' interaction, and assets' behaviour in one organisation. The time horizon was adequate to consider a whole lifetime of durables and present clear patterns of behaviour. The time horizon used for C2 was 70 years, following the available data for historical consumption for different EEE types starting in 1980 (Forti et al., 2018; van Straalen et al., 2016) and aimed to represent the long-term resource flows dynamics. The results specific to flat-panel TVs in the Netherlands used a time horizon of 35 years, enough to represent the full adoption of the technology and the patterns of behaviour emerging from CE strategies implementation. The first guiding question for the "Formulation of a Simulation Model" is, thus:

- **Q3.1.:** Is the time scale adequate to investigate that CE transition? Is there available data and evidence to sustain assumptions for the selected time horizon? Is it enough to show patterns of behaviour?

Subsequently, assembling stock and flow structures departed from the system's conceptual understanding. Table 2 shows the structures for operationalising products' demand, resource usage, and circularity in both cases. The model building process made use of existing structures in the literature and the community of practice.

In C1, a random time series compute a seasonalised demand for healthcare services. A delayed response to services demand determines the demand for products (Cote and Tucker, 2001). Non-parametric lifespan distribution using constants (Oguchi et al., 2010) sets the underutilisation and obsolescence rates, allowing simple mechanisms to establish products outflows. A diffusion of innovation (DoI) structure operationalises the sharing platform adoption, representing a new social behaviour (Rogers, 2003; Sterman, 2000). The DoI structure sets the process of users' activation, idling, and forgetting an unsatisfactory experience. Active users register products in the platform, enabling underutilised products to become functional.

In C2, a DoI structure driven by socio-economic variables determines the technology adoption of a EEE product in one country, defining three reasons for demand: adoption, replacing and additional purchases (Rogers, 2003; Sterman, 2000) and setting a reliable behaviour for EEE commissioning. EEEs might follow multiple paths as first use, reuse, remanufacturing, recycling, inadequate disposal and material extraction. Products' obsolescence complies with a parametric approach, which assumes a statistical distribution for products' obsolescence (Oguchi et al., 2010). Weibull distribution functions consider the non-uniform obsolescence of products, and their parameter values are widely available for different types of EEE in several countries (Forti et al., 2018; van Straalen et al., 2016). Co-flow structures determined the product's ageing process (Hines, 1996; Sterman, 2000) that allowed capturing the average age of the product fleet in their multiple states and deal with the countless possibilities for a product's destiny. Constant values operationalise CE adoption for the level of infrastructure, factors for the Weibull parameters, and the ability to restore products. The option for a wide breadth of CE strategies brought a clear trade-off regarding each strategy's depth of investigation in this modelling initiative. A supply chain structure activated whenever additional material extraction was necessary (Hines, 1996; Sterman, 2000), as expected demand for consumption of new products in a region will start the extraction of materials in some part of the globe.

The process of building the model structures lead to the following question:

- **Q3.2.:** Which are stock and flow structures capable of operationalising the logics of the resources' flows? Could you adapt available SD models and structures?

While C1 uses one widely known structure in the SD literature and community of practice (DoI), in C2, more of them were used (DoI, co-flow, and stock management). In C1, the DoI sets the adoption of a CE strategy based on the platform and users' characteristics. In C2, it allows generalisable behaviour for products demand and, consequently, for resource usage. The co-flow determining products' ageing process was crucial in the second case, where resources exist under different states. In C1, this structure could help comprehend the effects of underuse and sharing in products' obsolescence. The known structures do not have a specific function when examining CE transitions. The construction of a model is, thus, not an assembling process from existing building blocks. It is up to the modellers to recognise, adapt and create additional ones according to their needs. The value of mastering the functions and features and leaning on the SD body of knowledge and community of practice repertoire is undeniable to build suitable models, leading to the final question in the third stage:

- **Q3.3.:** Are you taking advantage of (and contributing to) the communities of practice? What modelling skills and features you still need to master?

4.1.4. *Model Testing*

C1 and C2 followed an iterative process by separately building portions of the models, testing, and finally connecting them into a complete model capable of representing systems' full dynamics of interest. Independent and iterative building restricts the complexity of the multiple possible effects of changing variables relationship, fostering a deeper understanding of models' structures and further confidence in simulated behaviour. Moreover, calibration against reference modes of behaviour led to a BAU (business-as-usual) scenario. For C1, due to lack of historical data, theoretical calibration of the adoption behaviour and demand behaviour resonating healthcare demand forecasting literature permitted reasonable confidence in conclusions taken from the results. An explicit Causal Loop Diagram (CLD) was presented alongside the simulation results to the case study informant, seeking to enrich the understanding of sharing dynamics and clarify the conclusions.

In C2, calibration to historical EEE consumption (Forti et al., 2018; van Straalen et al., 2016) permitted obtaining a BAU scenario for comparison based on reliable projections of EEE products in use, their conditions, and age while considering the country's expected restoring capabilities. Calibrating EEE demand posed a significant challenge as it connected the technology adoption and the EEE and WEEE flows sub-models. Two complementary model files allowed continuous behaviour from 1980 to 2050. The first model enabled the calibration of resource flows to historical data, allowing the socio-economic variables time-series to prospect for future demand for products. Descriptive statistics (Oliva, 1995; Sterman, 2000) is applied in combination to measure calibration among retrospective and prospective behaviour.

The first guiding questions in the "Model testing" stage is:

- **Q4.1:** Can you define a reference mode to calibrate the model? Is it a reliable BAU, linear economy scenario?

The building and testing process required setting a few assumptions. In C1, two assumptions scoped model results. First, the simulation model addresses only two types of goods – consumables and durables. Simplifying for two life-cycle patterns permitted showing sharing effects' patterns. Second, items become useful when registered into the platform. Product registration worked as a proxy for sharing since two dimensions of adopters' behaviour were already under investigation –platform adoption and product registration. Another dimension would require further calibration to allow for confidence in the results.

In C2, Model testing activities addressed contextual, structural and behavioural validity (Schwaninger and Groesser, 2016; Sterman, 2000). Alongside the conceptual implementation of MFA principles in the model structure, the mass-balance check (Dangerfield, 2014; Schwaninger and Groesser, 2016) helped ensure the system does not lose or gain products or materials due to structural and formulation errors. Both features enhance confidence in the resource flows, decisive when investigating CE transitions. Family member tests demonstrated that the country and EEE type choice were essential to achieve the model purpose and helped to choose an ideal case. After testing the model to fridges, flat-panel TVs became the investigation subject. They represented the expected behaviour of full regional technology adoption, providing further insights into nationwide CE transitions. Finally, dealing with the discontinuity from retrospective to prospective simulation led to further behaviour validity.

The second guiding question at this stage is:

- **Q4.2:** Can you ensure model fitness to purpose? Which are the contextual, structural, and behavioural validity tests performed?
  - What are the assumptions about boundaries, structures, and parameters?
  - Does the model structure conform to basic physical laws?
  - Do the simulated behaviours match available evidence and 'real-world' behaviour?

Apart from using case-specific data and presenting more systematic validation, the C2 model is available online for verification. The model, guidelines for application, and its documentation obtained using the SDM-Doc (Martinez-Moyano, 2012) are freely available (https://github.com/danguzzo/circularEEE_SDmodel). This practice allows tool dissemination and enhances model transparency. Such feature leads to the final question in the fourth stage:

- **Q4.3:** Is the model widely available for verification by other modellers/users?

4.1.5. *Policy Design and Evaluation*

With a validated SD model, simulation runs should support policy analysis and decision-making in CE transitions. Fig. 5 shows the control panels created for model use on both cases to help develop scenarios consistent with the possible decision mechanisms at hand. In C1, three KPIs (Key Performance Indicators) show the CE strategies implementation effects over time. Simulations compared four different scenarios—the combination of platform availability (on or off) and durables or consumables (Guzzo et al., 2019a). The results indicate that adopting the sharing platform allows for lower amounts of *total acquired products* and higher values for *total useful products* over time. The analysis also shows lower *total unmet demand* by the available products, indicating the possibility of positive impacts for a client hospital and healthcare accessibility. These potential positive economic, social, and environmental effects are more prominent for durables than for consumables, pointing to greater effectiveness in sharing longer life span goods.

C2 simulations show different compositions for product lifetime length and restoration infrastructure. Model users might guide their policies by investigating the effects of CE strategies implementation in the model's critical flows as the *material extraction*, *EEE demand* and the *EEE decommissioning rate*. They should prioritize strategies that create the dynamics for general resource flows deceleration. Results compare eight different scenarios — the result of varying levels of implementation of CE strategies compared with the BAU scenario (Guzzo et al., 2021). When applied alone, the deceleration effects are more prominent for increased product lifetime, and advanced remanufacturing—combining the strategies led to a best-case CE transition scenario.

Critical flows and KPIs enable obtaining insights from model use, leading to the single question in this stage:

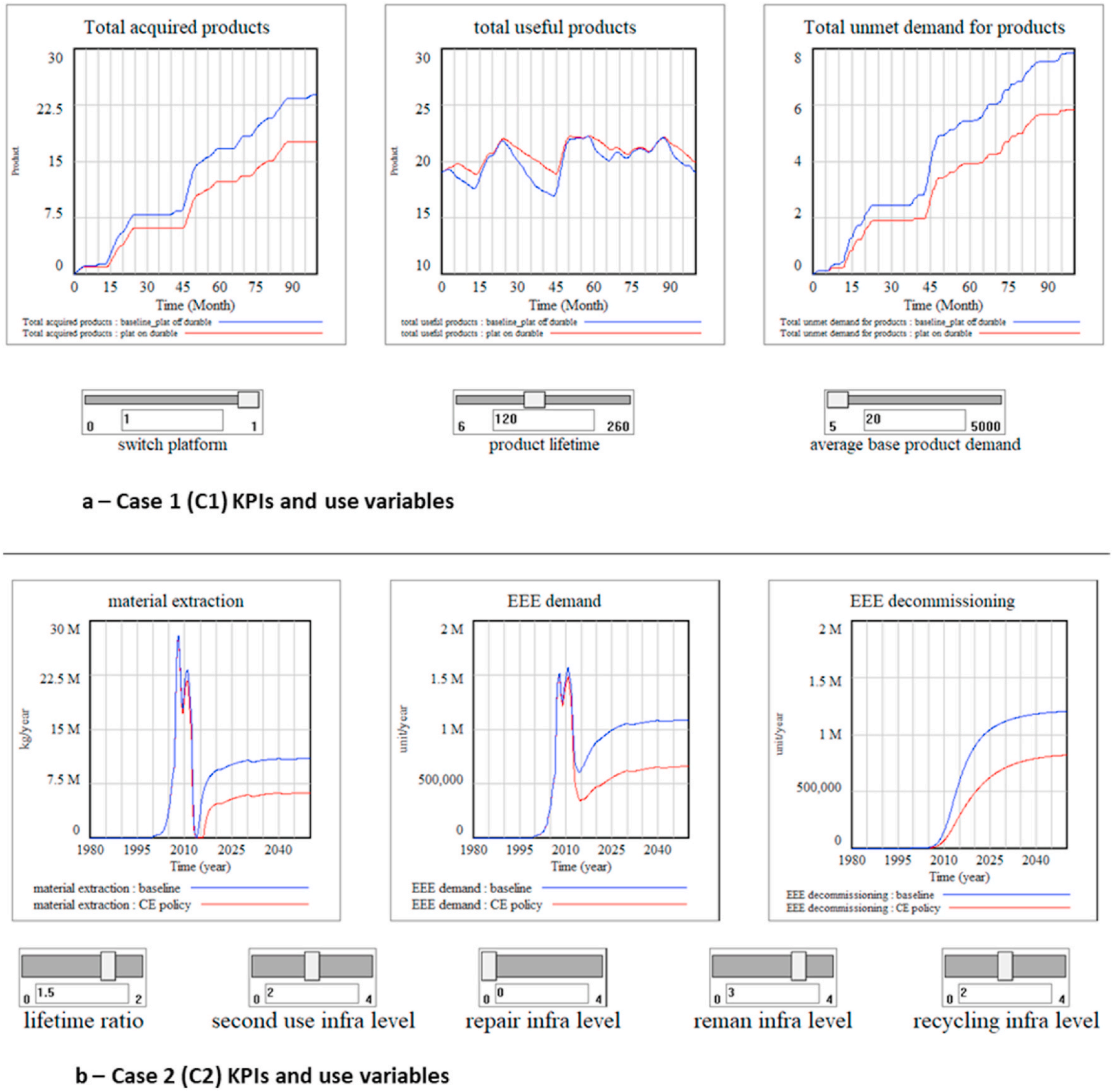


Fig. 5. Control panels for model use in C1 and C2.

- **Q.5.1:** What insights the defined CE transition scenarios provide? What are the circularity and sustainability KPIs? How does monitoring them facilitate decision-making?

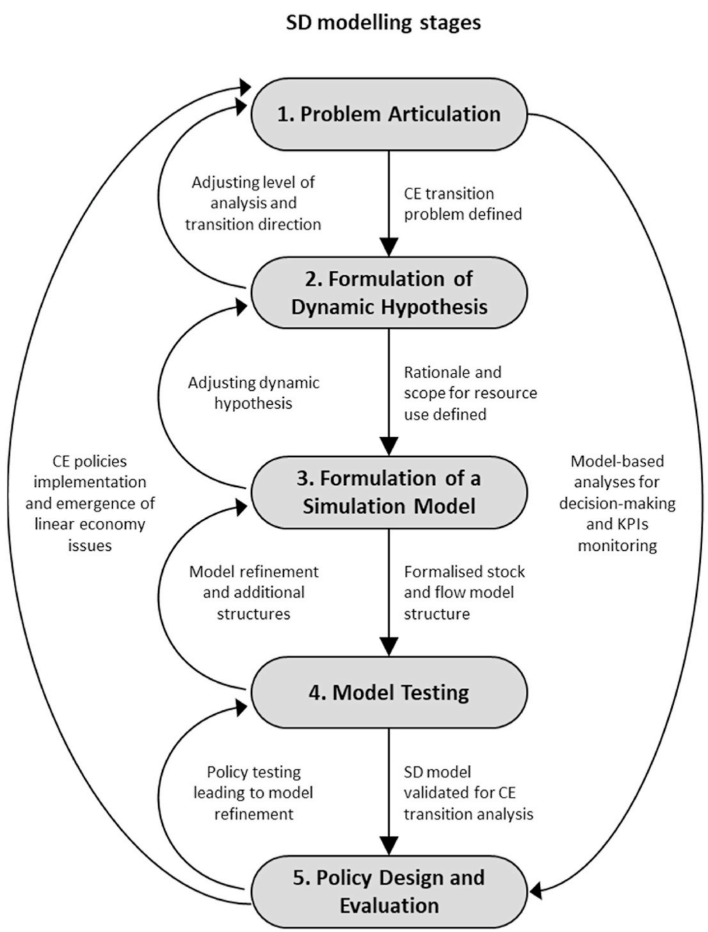
In the next section, the resulting SD-based framework for examining CE transitions is detailed.

4.2. SD-based framework for examining CE transitions

Fig. 6 shows the SD-based framework for examining CE transitions uncovering the critical activities, guiding questions, inputs and outputs relevant to each of the five iterative stages provided by Sterman (2000).

The **Problem Articulation (Stage 1)** connects the model purpose to the CE system level of analysis and the transition direction (Fig. 1). The system levels improve understanding by supporting the definition of the: (i) aggregation of change; (ii) potential for impact; and (iii) level of abstraction in the modelling effort. The transition direction (whether bottom-up, top-down, combination or conceptual) supports the definition of the modelling purpose, the stakeholders involved in the investigation, and the instruments for collecting and organising information. Finally, setting the industry helps to identify the synergies with ongoing initiatives and debates. The study of new CE business models should consider the involved companies, clients and users. The dynamic business modelling for sustainability (Cosenz et al., 2019) might guide the investigation. In a top-down transition study, it is desirable to involve proponents and enablers of public policies as government, industry association, and civil society. The analytical policy mix framework introduced by Rogge and Reichardt (2016) can help such investigations.

The **Formulation of Dynamic Hypothesis (Stage 2)** portrays the rationale and scope for resource use in system. A sound conceptual understanding of the system relies on the logics for product demand, resource usage, and circularity strategies for resources types of interest. The conceptual model for CE systems (Guzzo et al., 2021) enables positioning the circular strategies in the value chain to encompass the appropriate product life-cycle phases and examine system-wide effects. The principles methodologies as MFA (Müller et al., 2014), input-output analysis (Munksgaard et al., 2005), and LCA (Finnveden et al., 2009) can guide the mapping of resource flows and identification of impacts. Extensive secondary research and interviews with specialists are helpful to acquire knowledge about the system. Carefully setting and communicating the model boundaries helps distinguish endogenous structures, exogenous variables, and the dynamics not considered in the model to support communication. It also avoids a narrow view of the system, leaving decisions based on model use resistant to rebound effects. On the flipside, parsimony is vital as additional endogenous mechanisms add



Activities	Guiding questions
A1.1. Define CE system level of analysis **A1.2.** Determine transition direction: top-down, bottom-up, combination, conceptual **A1.3.** Define industry of interest **A1.4.** Consider primary and secondary sources for investigation	**Q1.1.** How can the modelling effort contribute to a CE transition in that system? **Q1.2.** Are the CE system level of analysis, the transition direction and the industry clearly stated in the modelling purpose? **Q1.3.** Is the research protocol adequate to investigate a shift in that system?
A2.1. Define rationale for resources use **A2.2.** Connect to existing methodologies **A2.3.** Set model boundaries	**Q2.1.** Are the logics for product demand, resource usage, and circularity comprehensively understood for the system under investigation? Are the relevant life cycle stages considered? **Q2.2.** What are the model boundaries? What behaviour is endogenous, exogenous, and excluded? Is the scope adequate to holistically understand the flow of resources?
A3.1. Define the time scale **A3.2.** Apply structures available: in the Circular EEE SD Model and in the SD literature **A3.3.** Engage with the SD community	**Q3.1.** Is the time scale adequate to investigate that CE transition? Is there available data and evidence to sustain assumptions for the selected time horizon? Is it enough to show patterns of behaviour? **Q3.2.** Which are stock and flow structures capable of operationalising the logics of the resources' flows? Could you adapt available SD models and structures? **Q3.3.** Are you taking advantage of (and contributing to) the communities of practice? What modelling skills and features you still need to master?
A4.1. Iterative modelling and testing **A4.2.** Build a testing control panel **A4.3.** Set reference modes to business-as-usual scenarios **A4.4.** Ensure contextual, structure and behavioural validity	**Q4.1.** Can you define a reference mode to calibrate the model? Is it a reliable BAU, linear economy scenario? **Q4.2.** Can you ensure model fitness to purpose? Which were the contextual, structural, and behavioural validity tests performed? ○ What are the assumptions for boundaries, structures, and parameters? ○ Does the model structure conform to basic physical laws? ○ Does the simulated behaviour match available evidence and 'real-world' behaviour? **Q4.3.** Is the model widely available for verification by other modelers/users?
A5.1. Set-up decision-making scenarios **A5.2.** Determine circularity and sustainability KPIs	**Q.5.1.** What insights the defined CE transition scenarios provide? What are the circularity and sustainability KPIs? How does monitoring them facilitate decision-making?

Fig. 6. The SD-based framework for examining CE transitions.

complexity to the modelling exercise. Using sub-system diagrams, model boundary charts, CLDs, and simplified stock and flow maps (Rahmandad and Sterman, 2012; Sterman, 2000) is helpful to communicate the model structure and boundaries.

The **Formulation of a Simulation Model (Stage 3)** should combine novel stock and flow structures to the ones available on existing models and literature. The modeller may choose to adopt the Circular EEE SD Model to other cases or use the standalone sub-models. Furthermore, 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), the *Molecules of Structure* (Hines, 1996), and the *MetaSD* website (https://metasd.com) provide examples of recurrent structures, their uses and rationales. It is wise to engage with the SD community of practice. The SD Society provides plenty of learning resources and empowers regional chapters and special interest groups (SIGs) in assets dynamics, business and environment. The community of practice supports modelling challenges and provides early feedback on research. Finally, challenges will emerge from the tool's use (e.g., Vensim and Ventity, Stella Architect, Powersim, and anylogic). Each tool holds its capabilities and peculiarities. Software documentation and forums support the model formulation process.

Model **Testing (Stage 4)** must occur iteratively to enhance model validity. Reference modes help guide the conceptualisation and the calibration of the model by setting a BAU scenario for subsequent comparison. Assembling a testing control panel and using descriptive statistics (Oliva, 1995; Sterman, 2000) help in the calibration process. A data-rich strategy in simulation models requires obtaining quantitative information, a rather time-consuming activity. Academic quantitative studies as surveys and reports from associations and consultancies provide time series and values for the most exogenous portions of the model. Modellers should continually check the sub-systems' behaviour against expectations and available data (Pruyt, 2013, p. 87). Model testing guidelines for contextual, structural and behavioural validity may guide testing (Schwaninger and Groesser, 2016; Sterman, 2000). Tests as the mass-balance check (Dangerfield, 2014; Schwaninger and 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. Finally, adequate documentation for publishing research papers (Rahmandad and Sterman, 2012) is critical for increased validation. The model, data to run it, and its documentation – obtained through, e.g., the SDM-Doc tool (Martinez-Moyano, 2012) – should be made available in the journal's supplementary material or in a repository with version control as GitHub or any other dedicated SD model library.

For **Policy Design and Evaluation (Stage 5),** simulations should aim to grasp the effects of system change in circularity and sustainability through a meaningful set of scenarios and time graphs clarifying behaviour reasons. Additional structures connected to the system represent the model KPIs. The CE literature's quantitative indicators (Pauliuk, 2018; Saidani et al., 2019) can help design the assessment structures. Modellers should be parsimonious as it is central to balance the trade-off between the cost for model improvement compared to the adequacy of the actual model being used to make decisions (Forrester, 1994). The model itself is not an end, but a means to generate insight for decision making from the users' point of view.

4.3. Testing the SD-based framework for examining CE transitions in case 3

Table 3 presents the technical sheet for the SD modelling and simulation process following the proposed SD-based framework in C3, which adapts the Circular EEE SD Model to a different purpose—investigation of a specific policy initiative. Five central model adaptations enable achieving the new purpose:

- Technology adoption extrapolates historical data, eliminating the need for two models for calibration and use.
- An average value now sets products lifetimes—a non-parametric approach for lifespan distribution (Oguchi et al., 2010), facilitating experimentation.
- Products can hibernate before they become available, an essential aspect for small ICTs.
- Further detailed logic for available products destiny into reuse, recycling or inadequate disposal.
- Detailed collection mechanisms for recycling, allowing to discuss essential aspects of the collection policies.

Extensive model calibration employed country-specific information available in academic and grey literature, maintaining the mass-balance checks and descriptive statistics inherited from the Circular EEE SD Model. The model, its documentation, and step-by-step guide for use are also available online. The CE strategy considers three factors for post-use EEE collection that decision-makers can influence through policies: (i) coverage increase for EEE collection, (ii) distribution of collection points and (iii) the existence of a reward. The results show the effects of EEE collection interventions in *official EEE collecting* and *inadequate disposal of EEE*, demonstrating the expected magnitude and behaviours from the implementation of policies. The *ratio of material treated in the last 2.6 years* is the proposed circularity KPI to show the effectiveness of policy initiatives considering the average lifetime of smartphones in Brazil: 2.6 years. Such an indicator is adaptable to other EEE products with different lifetimes.

5. Discussion and contributions

This research proposed and tested a framework to investigate CE transitions using SD simulation models. Inductive and deductive model-based case studies permitted proposing and testing the framework. The framework elicits critical decisions and activities to carry out when examining the effects of implementing CE strategies in a given system through time using SD modelling and simulation. The framework is based on extensive empirical knowledge accumulated in the three studies and can help future SD modelling and CE transitions examinations.

5.1. Theoretical contributions

The model-based case studies provide several **insights to the CE body of knowledge.** C1 (Guzzo et al., 2019a) contributes to the need to further investigate service-oriented strategies (Kirchherr and van Santen, 2019) and the use of strategies that slow resources use instead of closing them (Merli et al., 2018). It uncovers the potential of sharing in leading to better use of resources, which is more prominent to durable goods than to consumable goods. C2 (Guzzo et al., 2021) shows a path to handling the options for configurations of CE systems (Blomsma and Brennan, 2017), allowing decision-makers to prioritize the combinations of strategies that lead to better aggregate impact among several alternatives. C3 (Guzzo et al., 2022) contributes to tackling the need for clear regulations to help CE transitions in supply chains (Kazancoglu and Kazancoglu, 2020) focusing on an under investigated developing economy (Kirchherr and van Santen, 2019). It demonstrates the possibilities for a collection infrastructure for EEEs that might achieve the targets of the BIAEEE. Additional insights might be available on the three publications that thoroughly describe each case.

Furthermore, several insights emerge to the CE body of knowledge when considering the three cases altogether. All three cases show the deceleration of resource flows mostly conceptualised in the literature (Geisendorf and Pietrulla, 2018) operationalised to micro- and macro-level CE systems under different types of transitions. In all three cases, plausible changes in the system occur to investigate the decreased need for resources in the long-term. The differences among potential

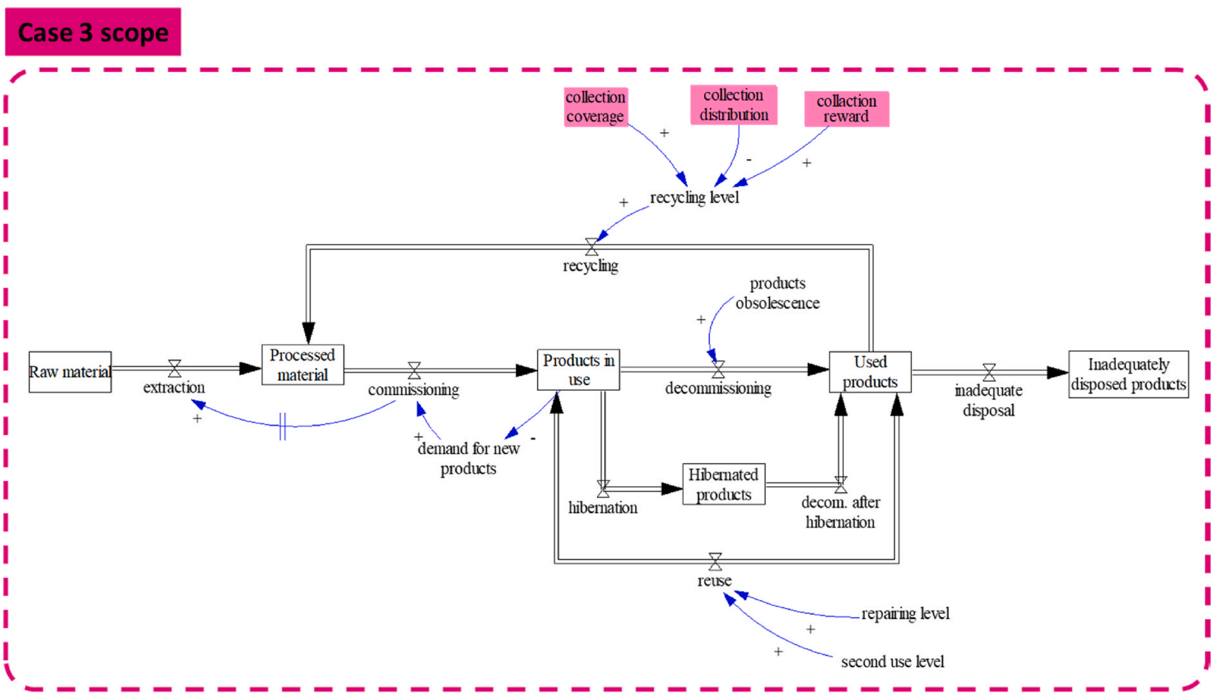
Table 3
Canvas for CE transition examination using SD modelling and simulation of Case 3 (C3).

1. Problem Articulation

Modelling purpose: Examine the effects of interventions for the collection of end-of-life EEE smartphones following the BIAEEE
CE system level: Macro-level CE System
Direction of change: Top-down
Industry: EEE

2. Formulation of Dynamic Hypothesis

Resource use scope



Model boundaries

Excluded	**Exogenous**	**Endogenous**
- Refurbishing and remanufacturing markets for EEE, recycling infrastructure development.	- Historical technology adoption, population, average EEE weight, EEE lifetime values, EEE collection interventions.	- Technology adoption, EEE and WEEE flows, EEE obsolescence, Material supply.

3. Formulation of a Simulation Model

Time Horizon: 30 years (2005-2035), with historical values available for calibration and appropriate to represent the adoption of smartphones and the effects of collection interventions

Model structure

Products demand	**Resource usage**	**Circularity**
- Technology adoption of a EEE product in one country - Diffusion of innovation structure determines technology adoption (Rogers, 2003; Sterman, 2000) - Historical adoption (Pew Research Center, 2016 and 2019) and population (United Nations, 2019) set adoption values. - Demand is composed by adoption, replacing and additional purchases (Sterman, 2000).	- Dynamics of first use, hibernation, reuse, recycling, inadequate disposal and material extraction determine resource usage: - Co-flow structures determine the ageing process (Hines, 1996; Sterman, 2000), which can be reversed by restoration processes. - Constants determine obsolescence – non-parametric approach (Oguchi et al., 2010). - Depreciation curve determines additional lives of products (Makov et al., 2019). - A stock management structure determines extraction of raw material (Hines, 1996; Sterman, 2000).	- Adoption of collection interventions for recycling: - Lookup functions determine interaction among collection coverage increase, distribution of collection points and reward for collection (Bai et al., 2018; MMA et al., 2019; Qu et al., 2019; Tan et al., 2018). - Constant determines recyclability (Buchert et al., 2012).

4. Model Testing

Contextual validation	**Structural validation**	**Behavioural validation**
- Model purpose and audience are clearly set, use of SD simulation model is sustained.	- Model conceptualisation following dynamic MFA concept.	- Behaviour reproduction to a baseline scenario: fitting model obtained first use commissioning to historical data of EEE put on market (IDC, 2019).

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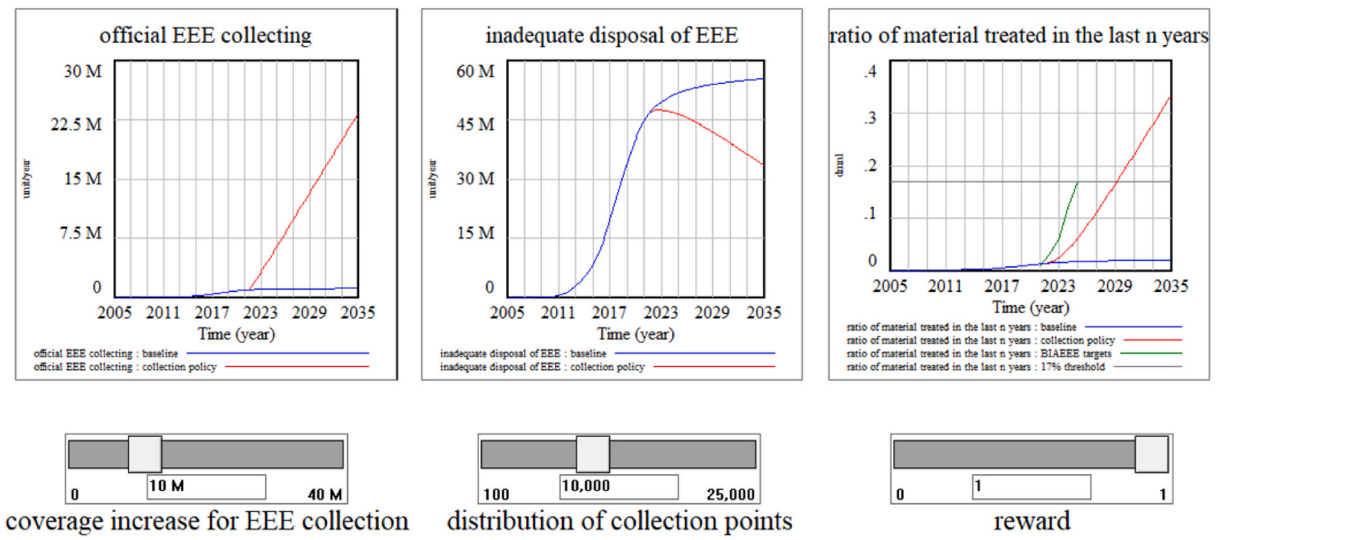
Table 3 (*continued*)

- Sub-system diagram, simplified stock and flow maps, and model boundary chart are developed. - Collection mechanisms are detailed to enhance the potential for insights.	- Development and testing relevant sub-model parts in isolation. Application of the mass-balance check (Dangerfield, 2014; Schwaninger and Groesser, 2016) to products and materials. - Bounding auxiliaries and flows with potential extreme behaviour. - Orienting the use of the model by lookups for CE mechanisms.	- Application of descriptive statistics tools to calibrate the model – Theil inequality statistics (Oliva, 1995; Sterman, 2000). - Applying the model to different country, EEE product, and purpose constitutes a family member test to the Circular EEE SD Model compared to the results presented in Guzzo et al. (2021).

5. Policy Design and Evaluation



impacts of C1 in relation to C2 and C3 draw attention. While C1 shows the behaviour of dozens of products such as MRI machines, C2 and C3 show the effect of CE strategies implementation in millions of products such as flat-panel TVs and smartphones. This reinforces the hypothesis that changes in higher-level systems may lead to higher aggregate impact. This is not to say that investigating systems at lower levels is not important, since, in practice, macro-level change relies on aggregate changes in the micro- and meso-levels. In addition, critical insights for enacting change might be concealed in the micro- and meso-levels as to the levers to coordinate action and to avoid resistance that might be hidden when facing highly aggregate systems. Another interesting aspect in the model-based case studies, is that C1 and C3 deepen analysis of behavioural dynamics to enabling CE strategies implementation. It includes the adoption of the sharing platform by potential users in the hospital (C1), and the influence of the distribution of collection points and reward schemes in the user adoption of EEE appropriate disposal. Both cases showcase the potential of SD simulation models to further understand the reasons for behaviour change that might lead to CE transitions.

The SD-based framework for examining CE transitions is the first prescriptive approach to help researchers and practitioners on their journeys to understand and facilitate changes through SD simulation models. The framework is grounded on empirical studies and organises the learnings for use by others, demonstrating a common rationale for investigating CE transitions. The simulation models enable closed-loop thinking by showing the possibilities for solutions to managing stocks under specific CE strategies over time. Using the models help to address several sources of complexity that emerge, for instance, by assisting in the trade-offs between CE strategies and foreseeing conditions for "win-win-win" scenarios. The difference in scope among the three cases enriches the framework development and its applicability, paving the way to further enhancing the body of SD-based simulation research investigating CE systems and transitions.

Using the framework from the onset benefited C3 in several ways: (i) by providing assertiveness in defining the modelling purpose, drawing upon the CE system level of analysis, the direction of change and the industry under investigation; (ii) further clarity to delimit the scope of the investigation and conceptual framing of the system; (iii) enabling the adoption of an existing simulation model with calibration guidelines for a more specific case. C3 scope undoubtedly helped to obtain meaningful insights in collection interventions within the public policy under investigation. The knowledge gained from building and testing the framework in the three cases made it possible to explicit important aspects that might be neglected by SD modelers when examining a CE transition. The framework provides congruence in face of the multiple perspective to examining such phenomena by assisting to frame the problem under investigation in connection to the widely discussed system levels and directions of change, prominent in the CE literature. Additionally, it guides researchers in applying SD modelling conceptualisation, simulation, and testing practices to enhance validity towards model use.

This research also contributes by **integrating the concepts of CE systems and CE transitions in SD-based investigations**. Acknowledging that CE systems occur in different levels: micro, meso, and macro can work as a rule of thumb to set the appropriate level of detail one should delve into at each investigation. The different levels can hint at the potential for impacts in each system. However, it is not true that investigating micro-level change is less critical than macro-level change because sustainability transitions will only happen at multiple levels at once (Coenen et al., 2012). CE transitions also require the coordination of top-down and bottom-up initiatives. The direction of change helps identify the types of decisions to be made, the appropriate forms of investigation, and who could help to understand the system.

This research **further connects the CE and sustainability transitions fields**. The possibility of top-down, bottom-up, and combinations underpin central discussions in the sustainability transitions field (Geels, 2011; Verbong and Geels, 2010). Understanding the dynamics of systems (Loorbach, 2007) and the multiple interactions within systems (Hekkert et al., 2007) are determinant in the shift to more sustainable production modes. 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 SD (Papachristos, 2019; Raven and Walrave, 2020). In this way, the framework accommodates essential aspects of both concepts.

5.2. Practical contributions

The proposed framework's pragmatic character, via the domain-specific activities, guiding questions, and expected stages inputs and outputs, allow other researchers and practitioners to perform model-based CE transitions investigations. The cases used for building and testing the framework demonstrate its usefulness, serving as front-running guides. All three cases address relevant practical issues and show situations modellers may encounter. The framework is flexible, enabling users to adapt it to circumstances and add recommendations as knowledge builds up.

There are six key benefits of using SD modelling and simulation to investigate CE transitions with the proposed framework:

1. Enable users to examine resources behaviour-over-time in a system, including products, components, materials, and energy. It is up to the modeller to include the relevant life-cycle stages and flows. It is possible to experiment with products with varying lifetime patterns by making structure or parameter adjustments. MFA and LCA principles and mass-balance checks enhance the models' robustness.
2. Enable users to examine the effects of adopting different CE strategies concomitantly. With a robust understanding of resource flows in place, it is possible to explore CE strategies' consequences through mechanisms with varying levels of detail and endogeneity.
3. Enable users to define and compare scenarios for different consumption and production system configurations ('as-is' vs 'as could-be'). Calibrations for an accurate representation of resource use's state in a BAU scenario allow comparisons with different configurations according to modelling purpose. From a sustainability perspective, ideal scenarios should seek ecological-economic absolute decoupling. The structures and variables must correspond to the information and levers that decision-makers have at hand.
4. Enable users to investigate systems under a time horizon adequate to the scale of change and covering the transition to a new equilibrium. The system's scale, flows' frequencies, and interventions' duration help set the time scope. A good time boundary expounds the patterns of behaviour from adopting the CE strategies.
5. Enable users to examine the positive and negative effects of system change from the perspective of different stakeholders, including individuals, organisations, the environment, and society. Structures connecting the effects of resource flows deceleration to actors' mental models hold a high potential for leverage. Additional benefits for stakeholders can act as arguments for change. The identification of detrimental effects allows a proactive attitude to circumvent them.
6. Facilitate decision-making for top-down and bottom-up transitions. The framework is adequate to help policymakers and business practitioners' decision-making by gaining knowledge about the potential outcomes of public and business policies for implementing CE strategies. Model use may align expectations in the implementation of interventions and facilitate consensus about adequate paths.

6. Concluding remarks and research avenues

This research started with the question: "What are adequate SD modelling practices to support decision-making in CE transitions?". In this paper, the development and test of a framework that aims to support the investigation of CE transition cases through SD modelling was described. The proposed framework further connects and expands the growing body of SD-based research to investigate CE systems and transitions, complying with **the multiple levels of CE systems and the direction of change in CE transitions**. Adequately framing studies related to CE systems and transitions can enhance clarity in the modelling purpose, confidence in results, and the explanatory capacity of system behaviour.

The multitude of modelling strategies implies plentiful research opportunities available. **From the perspective of bottom-up CE transitions**, most studies focus on the micro-level, investigating the dynamics of one manufacturer, one client organisation, and a few individuals. This approach can be rather insightful to investigate the interplay of the value proposition, value creation and delivery activities, and resource usage effects. Framing the other levels can expand investigations to the business eco-system in the meso-level (c.f. Kliem et al., 2021) towards macro-level adoption in whole regions (c.f. Pinto and Diemer, 2020). A multi-level study holds the potential to investigate a bottom-up transition from value proposition to scale. For example, the adoption of a sharing platform can be expanded from a single hospital to multiple hospitals in a metropolitan region to a country. Including the meso- and macro-levels dynamics can help identify leverages and potential effects of that expansion.

A similar rationale applies to **top-down CE transitions**, where most studies aim at the macro-level, following an aggregated investigation of public policies. At the meso-level, policy makers can benefit from using the framework to detail the dynamics in a city (c.f. da Silva, 2018) and clarify the need for infrastructure and ways to monitor the transition results at a more detailed level than that presented in C3. Such investigation can assist in cascading attainable policies into regions and cities, making them less susceptible to unintended consequences and resistance. At the micro-level, it is possible to further endogenize individuals' motivations to engage with the selective collection system. Micro-level examinations might shed light on the reasons for the intention-behaviour gap towards more sustainable actions (Echegaray and Hansstein, 2017). A multi-level investigation taking the city and individual perspectives can contribute to designing policy measures that meet national to individual needs.

Future versions of the framework could include guidelines for multi-level investigations, helping to **further connect the multiple CE system levels in SD simulation models.** Schwaninger and Groesser (2016) suggest SD simulation models as building blocks with varying resolution degrees. The building block structure can connect the dynamics occurring in the multiple levels and empower the community interested in investigating CE transitions using SD modelling and simulation. Researchers and practitioners should use the existing body of SD-based simulation models investigating CE systems and transitions. For example, the Circular EEE SD Model is a building block to be used, adapted, and connected to other SD models.

Finally, there is plenty of space to expand the methodological approaches to examine CE transitions through simulation models and integrate them into the framework. **Hybrid modelling combining SD with ABM and DES might lead to additional insights** and should be considered in cases in which gains of understanding from disaggregation to heterogeneous agents or entities surpass the concomitant challenges for model formulation and cognitive load for model understanding and use (Borshchev and Filippov, 2004; Rahmandad and Sterman, 2008). **More conceptual investigations can shed light on socio-technical aspects of CE transitions**, as demonstrated by works in CE literature (See Bassi et al., 2021; Laurenti et al., 2016). It is possible to explore further the qualitative perspective of CE transitions based on CLDs and identify leverage points that may not be clear when prioritising stock and flow structures (cf. Luna-Reyes and Andersen, 2003). The framework could help choose when employing qualitative approaches and simulation models. There is also **space to help involve decision-makers throughout the process**. Applying a group model building approach to involving stakeholders through the process (Vennix, 1999) and creating learning laboratories to speed up users' learning about the system (Senge and Sterman, 1992) can enable participatory CE transitions.

CRediT authorship contribution statement

D. Guzzo: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **D.C.A. Pigosso:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **N. Videira:** Conceptualization, Methodology, Visualization, Writing – review & editing. **J. Mascarenhas:** Conceptualization, Methodology, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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A. APPENDIX.

Table A
The sources of dynamic complexity in CE transitions.

Characteristics of complex systems	Definition following Sterman (2000)	Occurrence in CE transitions	Selected References
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)
		CE systems involve implementing combinations of CE strategies, and there are potential synergies and trade-offs among the options.	(Blomsma et al., 2018; Brennan et al., 2015; Reike et al., 2018; Zink and Geyer, 2017)
Tightly coupled	The actors in the system actively interact with one another and with the natural world.	The CE concept considers the relations of the consumption and production system with the adjacent systems, seeking to enhance environmental quality, economic prosperity, and social equity. CE 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 and 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 and Rashid, 2016)
Non-linear	The effect is rarely proportional to cause.	The need for a CE 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.	(de Wit et al., 2019; Rockström et al., 2009)
		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.	(Ellen MacArthur Foundation, 2012; Webster, 2013)

(*continued on next page*)

Table A (*continued*)

Characteristics of complex systems	Definition following Sterman (2000)	Occurrence in CE transitions	Selected References
		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 et al., 2018a; Lüdeke-Freund et al., 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 CE 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 and Williander, 2015; Planing, 2015)
		People and organisations develop intrinsic motivation (energising behaviour that comes from within the individual or organisation) and extrinsic motivation (behaviour that comes to earn an external reward or avoid punishment) to engage in CE innovations.	(Brown et al., 2019, Fig. 2)
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 life-cycle 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 life-cycles 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 et al., 2017; Linder and 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 et al., 2018a; 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 et al., 2018a; 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)

References

Alamerew, Y.A., Brissaud, D., 2020. Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: a case study on electric vehicle batteries. J. Clean. Prod. 254, 120025. https://doi.org/10.1016/j.jclepro.2020.120025.

Anderson, E.G., Lewis, K., Ozer, G.T., 2018. Combining stock-and-flow, agent-based, and social network methods to model team performance. Syst. Dynam. Rev. 34, 527–574. https://doi.org/10.1002/sdr.1613.

Antikainen, M., Valkokari, K., 2016. A framework for sustainable circular business model innovation. Technol. Innov. Manag. Rev. 6, 5–12. https://doi.org/10.22215/timreview/1000.

Asif, F.M.A., Lieder, M., Rashid, A., 2016. Multi-method simulation based tool to evaluate economic and environmental performance of circular product systems. J. Clean. Prod. 139, 1261–1281. https://doi.org/10.1016/j.jclepro.2016.08.122.

Bai, H., Wang, J., Zeng, A.Z., 2018. Exploring Chinese consumers' attitude and behavior toward smartphone recycling. J. Clean. Prod. 188, 227–236. https://doi.org/10.1016/j.jclepro.2018.03.253.

Bassi, A.M., Bianchi, M., Guzzetti, M., Pallaske, G., Tapia, C., 2021. Improving the understanding of circular economy potential at territorial level using systems thinking. Sustain. Prod. Consum. 27, 128–140. https://doi.org/10.1016/j.spc.2020.10.028.

Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. J. Ind. Ecol. 21 https://doi.org/10.1111/jiec.12603.

Blomsma, F., Kjaer, L.L., Pigosso, D.C.A., McAloone, T.C., Lloyd, S., 2018. Exploring circular strategy combinations - towards understanding the role of PSS exploring circular strategy combinations - towards understanding the role of PSS. Procedia CIRP 69, 752–757. https://doi.org/10.1016/j.procir.2017.11.129.

Bocken, N.M.P., de Pauw, I., Bakker, C.A., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Borshchev, A., Filippov, A., 2004. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools.

Braungart, M., Mcdonough, W., Bollinger, A., 2006. Cradle-to-cradle design: creating healthy emissions e a strategy for eco-effective product and system design 1–12. https://doi.org/10.1016/j.jclepro.2006.08.003.

Brennan, G., Tennant, M., Blomsma, F., 2015. Business and production solutions: closing loops and the circular economy. In: Sustainability: Key Issues, pp. 219–239.

Brown, P., Bocken, N., Balkenende, R., 2019. Why do companies pursue collaborative circular oriented innovation? Sustain. Times 11, 1–23. https://doi.org/10.3390/su11030635.

Buchert, M., Manhart, A., Bleher, D., Pingel, D., 2012. Recycling critical raw materials from waste electronic equipment commissioned by the north rhine- Westphalia state agency for nature. Environment and Consumer Protection Authors 49, 30–40.

Ceschin, F., Gaziulusoy, I., 2016. Evolution of design for sustainability: from product design to design for system innovations and transitions. Des. Stud. 47, 118–163. https://doi.org/10.1016/j.destud.2016.09.002.

Charnley, F., Tiwari, D., Hutabarat, W., Moreno, M., Okorie, O., Tiwari, A., 2019. Simulation to enable a data-driven circular economy. Sustain. Times 11, 1–16. https://doi.org/10.3390/su10023379.

Chaudhary, K., Vrat, P., 2020. Circular economy model of gold recovery from cell phones using system dynamics approach: a case study of India. Environ. Dev. Sustain. 22, 173–200. https://doi.org/10.1007/s10668-018-0189-9.

Coenen, L., Benneworth, P., Truffer, B., 2012. Toward a spatial perspective on sustainability transitions. Res. Pol. 41, 968–979. https://doi.org/10.1016/j.respol.2012.02.014.

Cosenz, F., Rodrigues, V.P., Rosati, F., 2019. Dynamic business modeling for sustainability: exploring a system dynamics perspective to develop sustainable business models. Bus. Strat. Environ. 1–14. https://doi.org/10.1002/bse.2395.

Cote, M.J., Tucker, S.L., 2001. Four methodologies to improve healthcare demand forecasting. Healthc. Financ. Manag. 54–58.

da Silva, C.L., 2018. Proposal of a dynamic model to evaluate public policies for the circular economy: scenarios applied to the municipality of Curitiba. Waste Manag. 78, 456–466. https://doi.org/10.1016/j.wasman.2018.06.007.

Dangerfield, B., 2014. Systems thinking and system dynamics: a primer. Discret. Simul. Syst. Dyn. Manag. Decis. Mak. 26–51. https://doi.org/10.1002/9781118762745.ch03, 9781118349.

de Wit, M., Verstraeten-Jochemsen, J., Hoogzaad, J., Kubbinga, B., 2019. The circularity gap report: closing the circularity gap in a 9% world. Circ. Econ. 56.

den Hollander, M.C., Bakker, C.A., Hultink, E.J., 2017. Product design in a circular economy: development of a typology of key concepts and terms. J. Ind. Ecol. 21 https://doi.org/10.1111/jiec.12610.

Echegaray, F., Hansstein, F.V., 2017. Assessing the intention-behavior gap in electronic waste recycling: the case of Brazil. J. Clean. Prod. 142, 180–190. https://doi.org/10.1016/j.jclepro.2016.05.064.

Eisenhardt, K.M., Graebner, M.E., 2007. Theory building from cases: opportunities and challenges. Acad. Manag. J. 50, 25–32. https://doi.org/10.5465/AMJ.2007.24160888.

Ellen MacArthur Foundation, 2015. Growth within: a Circular Economy Vision for a Competitive Europe.

Ellen MacArthur Foundation, 2012. Towards the Circular Economy: Economics and Business Rationale for an Accelerated Transition.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manag. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Forrester, J.W., 2016. Learning through system dynamics as preparation for the 21st century. Syst. Dynam. Rev. 32, 187–203. https://doi.org/10.1002/sdr.1571.

Forrester, J.W., 1961. Industrial Dynamics. MIT Press, Cambridge, Massachusetts.

Forrester, J.W., 1994. System dynamics, systems thinking, and soft OR. Syst. Dynam. Rev. 10, 1–14. https://doi.org/10.1002/sdr.4260100211.

Forti, V., Baldé, C.P., Kuehr, R., 2018. E-waste Statistics.

Franco, M.A., 2019. A system dynamics approach to product design and business model strategies for the circular economy. J. Clean. Prod. 241, 118327. https://doi.org/10.1016/j.jclepro.2019.118327.

Gao, Chengkang, Gao, Chengbo, Song, K., Fang, K., 2020. Pathways towards regional circular economy evaluated using material flow analysis and system dynamics. Resour. Conserv. Recycl. 154, 104527. https://doi.org/10.1016/j.resconrec.2019.104527.

Geels, F.W., 2011. The multi-level perspective on sustainability transitions: responses to seven criticisms. Environ. Innov. Soc. Transitions 1, 24–40. https://doi.org/10.1016/j.eist.2011.02.002.

Geisendorf, S., Pietrulla, F., 2018. The circular economy and circular economic concepts—a literature analysis and redefinition. Thunderbird Int. Bus. Rev. 60, 771–782. https://doi.org/10.1002/tie.21924.

Geissdoerfer, M., Naomi, S., Monteiro, M., Carvalho, D., Evans, S., 2018. Business Models and Supply Chains for the Circular Economy 190.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P.P., Hultink, E.J., 2017. The Circular Economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Ghisellini, P., Cialani, C., Ulgiati, S., 2015. A review on Circular economy: the expected transition to a balances interplay of environment and economic systems. J. Clean. Prod. 114, 2015–2018. https://doi.org/10.1016/j.jclepro.2015.09.007.

Glöser-Chahoud, S., Pfaff, M., Walz, R., Schultmann, F., 2019. Simulating the service lifetimes and storage phases of consumer electronics in Europe with a cascade stock and flow model. J. Clean. Prod. 213, 1313–1321. https://doi.org/10.1016/j.jclepro.2018.12.244.

Gnoni, M.G., Mossa, G., Mummolo, G., Tornese, F., Verriello, R., 2017. Supporting circular economy through use-based business models: the washing machines case. Procedia CIRP 64, 49–54. https://doi.org/10.1016/j.procir.2017.03.018.

Gorissen, L., Vrancken, K., Manshoven, S., 2016. Transition Thinking and Business Model Innovation — towards a Transformative Business Model and New Role for the Reuse Centers of Limburg. https://doi.org/10.3390/su8020112. Belgium, Sustainability.

Guzzo, D., Jamsin, E., Balkenende, R., Costa, J.M.H., 2019a. The use of System Dynamics to verify long-term behaviour and impacts of circular business models: a sharing platform in healthcare. 3rd PLATE 2019 Conf 18–20.

Guzzo, D., Rodrigues, V.P., Mascarenhas, J., 2021. A systems representation of the Circular Economy: transition scenarios in the electrical and electronic equipment (EEE) industry. Technol. Forecast. Soc. Change 163, 120414. https://doi.org/10.1016/j.techfore.2020.120414.

Guzzo, D., Rodrigues, V.P., Pigosso, D.C.A., Mascarenhas, J., 2022. Analysis of national policies for circular economy transitions: modelling and simulating the Brazilian industry agreement for electrical and electronic equipment. Waste Manag 138, 59–74. https://doi.org/10.1016/j.wasman.2021.11.017.

Guzzo, D., Trevisan, A.H., Echeveste, M., Costa, J.M.H., 2019b. Circular innovation framework: verifying conceptual to practical decisions in sustainability-oriented product-service system cases. Sustainability 11, 3248. https://doi.org/10.3390/su11123248.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Change 74, 413–432. https://doi.org/10.1016/j.techfore.2006.03.002.

Hines, J., 1996. Molecules of structure. Syst. Dyn. Group, Sloan Sch. 1–128.

Hobson, K., 2015. Closing the loop or squaring the circle? Locating generative spaces for the circular economy. Prog. Hum. Geogr. 40, 88–104. https://doi.org/10.1177/0309132514566342.

Holtz, G., Alkemade, F., De Haan, F., Köhler, J., Trutnevyte, E., Luthe, T., Halbe, J., Papachristos, G., Chappin, E., Kwakkel, J., Ruutu, S., 2015. Prospects of modelling societal transitions: position paper of an emerging community. Environ. Innov. Soc. Transitions 17, 41–58. https://doi.org/10.1016/j.eist.2015.05.006.

Homrich, A.S., Galvão, G., Abadia, L.G., Carvalho, M.M., 2018. The circular economy umbrella: trends and gaps on integrating pathways. J. Clean. Prod. 175, 525–543. https://doi.org/10.1016/j.jclepro.2017.11.064.

Hopkinson, P., Zils, M., Hawkins, P., Roper, S., 2018. Managing a complex global circular economy business model: opportunities and challenges. Calif. Manag. Rev. 60, 71–94. https://doi.org/10.1177/0008125618764692.

Iacovidou, E., Hahladakis, J.N., Purnell, P., 2020. A systems thinking approach to understanding the challenges of achieving the circular economy. Environ. Sci. Pollut. Res. 24785–24806. https://doi.org/10.1007/s11356-020-11725-9.

IDC, 2019. Mobile Phone Tracker [WWW Document].

Kalmykova, Y., Sadagopan, M., Rosado, L., 2018. Circular economy - from review of theories and practices to development of implementation tools. Resour. Conserv. Recycl. 135, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034.

Kazancoglu, I., Kazancoglu, Y., 2020. Circular economy and the policy: a framework for improving the corporate environmental management in supply chains. Bus. Strat. Environ. 1–19. https://doi.org/10.1002/bse.2641.

Kazancoglu, Y., Ekinci, E., Mangla, S.K., Sezer, M.D., Kayikci, Y., 2020. Performance evaluation of reverse logistics in food supply chains in a circular economy using system dynamics. Bus. Strat. Environ. 1–21. https://doi.org/10.1002/bse.2610.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.
Kirchherr, J., van Santen, R., 2019. Research on the circular economy: a critique of the field. Resour. Conserv. Recycl. 151, 4–5. https://doi.org/10.1016/j.resconrec.2019.104480.
Kjaer, L.L., Pigosso, D.C.A., Niero, M., Bech, N.M., McAloone, T.C., 2019. Product/service-systems for a circular economy: the route to decoupling economic growth from resource consumption? J. Ind. Ecol. 23, 22–35. https://doi.org/10.1111/jiec.12747.
Kliem, D., Scheidegger, A., Kopainsky, B., 2021. Closing the mineral construction material cycle – an endogenous perspective on barriers in transition. Resour. Conserv. Recycl. 175, 105859. https://doi.org/10.1016/j.resconrec.2021.105859.
Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Transitions 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.
Kopainsky, B., Luna-Reyes, L.F., 2008. Closing the loop: promoting synergies with other theory building approaches to improve system dynamics practice. Syst. Res. Behav. Sci. 25, 471–486. https://doi.org/10.1002/sres.913.
Korhonen, J., Honkasalo, A., Seppälä, J., 2018a. Circular economy: the concept and its limitations. Ecol. Econ. 143, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041.
Korhonen, J., Nuur, C., Feldmann, A., Birkie, S.E., 2018b. Circular economy as an essentially contested concept. J. Clean. Prod. 175, 544–552. https://doi.org/10.1016/j.jclepro.2017.12.111.
Laurenti, R., Singh, J., Sinha, R., Potting, J., Frostell, B., 2016. Unintended environmental consequences of improvement actions: a qualitative analysis of systems' structure and behavior. Syst. Res. Behav. Sci. 33, 381–399. https://doi.org/10.1002/sres.2330.
Lieder, M., Asif, F.M.A., Rashid, A., 2017. Towards Circular Economy implementation: an agent-based simulation approach for business model changes. Auton. Agent. Multi. Agent. Syst. 31, 1377–1402. https://doi.org/10.1007/s10458-017-9365-9.
Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042.
Linder, M., Williander, M., 2015. Circular business model innovation: inherent uncertainties. Bus. Strat. Environ. 26, 182–196. https://doi.org/10.1002/bse.1906.
Loorbach, D., 2007. Transition Management: New Mode of Governance for Sustainable Development. International Books, Utrecht, the Netherlands.
Lüdeke-Freund, F., Gold, S., Bocken, N.M.P., 2018. A review and typology of circular economy business model patterns. J. Ind. Ecol. 1–26. https://doi.org/10.1111/jiec.12763, 00.
Luna-Reyes, L.F., Andersen, D.L., 2003. Collecting and analyzing qualitative data for system dynamics: methods and models. Syst. Dynam. Rev. 19, 271–296. https://doi.org/10.1002/sdr.280.
Makov, T., Fishman, T., Chertow, M.R., Blass, V., 2019. What affects the secondhand value of smartphones: evidence from eBay. J. Ind. Ecol. 23, 549–559. https://doi.org/10.1111/jiec.12806.
Martinez-Moyano, I.J., 2012. Documentation for model transparency. Syst. Dynam. Rev. 28, 199–208. https://doi.org/10.1002/sdr.1471.
Meadows, D., 1999. Leverage points: places to intervene in a system. World 91, 21. https://doi.org/10.1080/02604020600912897.
Meadows, D.H., 2009. Thinking in Systems. https://doi.org/10.1017/CBO9781107415324.004.
Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112.
Mies, A., Gold, S., 2021. Mapping the social dimension of the circular economy. J. Clean. Prod. 321, 128960. https://doi.org/10.1016/j.jclepro.2021.128960.
Milios, L., 2018. Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix. Sustain. Sci. 13, 861–878. https://doi.org/10.1007/s11625-017-0502-9.
Mma, Abinee, Abradisti, Assespro Nacional, Eletron, G., 2019. Acordo setorial para implantação de sistema de logística reversa de produtos eletroeletrônicos de uso doméstico e seus componentes.
Moreno, M., de los Rios, C., Rowe, Z., Charnley, F., 2016. A Conceptual Framework for Circular Design. https://doi.org/10.3390/su8090937. Sustainability.
Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ. Sci. Technol. 48, 2102–2113. https://doi.org/10.1021/es403506a.
Munksgaard, J., Wier, M., Lenzen, M., Dey, C., 2005. Using input-output analysis to measure the environmental pressure of consumption at different spatial levels. J. Ind. Ecol. 9, 169–185. https://doi.org/10.1162/1088198054084699.
Murakami, S., Oguchi, M., Tasaki, T., Daigo, I., Hashimoto, S., 2010. Lifespan of commodities, part I: the creation of a database and its review. J. Ind. Ecol. 14, 598–612. https://doi.org/10.1111/j.1530-9290.2010.00250.x.
Murray, A., Skene, K., 2015. The circular economy: an interdisciplinary exploration of the concept and application in a global context. J. Bus. Ethics 369–380. https://doi.org/10.1007/s10551-015-2693-2.
Oguchi, M., Murakami, S., Tasaki, T., Daigo, I., Hashimoto, S., 2010. Lifespan of commodities, part II: methodologies for estimating lifespan distribution of commodities. J. Ind. Ecol. 14, 613–626. https://doi.org/10.1111/j.1530-9290.2010.00251.x.
Okorie, O., Salonitis, K., Charnley, F., Turner, C., 2018. A Systems Dynamics Enabled Real-Time Efficiency for Fuel Cell Data-Driven Remanufacturing. https://doi.org/10.3390/jmmp2040077.
Oliva, R., 1995. A Vensim® module to calculate summary statistics for historical fit. Dyna 10, 51–56.
Papachristos, G., 2019. System dynamics modelling and simulation for sociotechnical transitions research. Environ. Innov. Soc. Transitions 31, 248–261. https://doi.org/10.1016/j.eist.2018.10.001.
Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129 (September 2017), 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019.
Peng, H., Shen, N., Liao, H., Xue, H., Wang, Q., 2020. Uncertainty factors, methods, and solutions of closed-loop supply chain — a review for current situation and future prospects. J. Clean. Prod. 254, 120032. https://doi.org/10.1016/j.jclepro.2020.120032.
Pew Research Center, 2019. Smartphone ownership is growing rapidly around the world, but not always equally. Pew Res. Cent 47.
Pew Research Center, 2016. Smartphone Ownership and Internet Usage Continues to Climb in Emerging Economies. Pew Research Center.
Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2020. From theory to practice: systematising and testing business model archetypes for circular economy. Resour. Conserv. Recycl. 162, 105029. https://doi.org/10.1016/j.resconrec.2020.105029.
Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2019. Business model innovation for circular economy and sustainability: a review of approaches. J. Clean. Prod. 215, 198–216. https://doi.org/10.1016/j.jclepro.2019.01.036.
Pinto, J.T.M., Diemer, A., 2020. Supply chain integration strategies and circularity in the European steel industry. Resour. Conserv. Recycl. 153, 104517. https://doi.org/10.1016/j.resconrec.2019.104517.
Planing, D.P., 2015. Business Model Innovation in a Circular Economy - Reasons for Non-acceptance of Circular Business Models.
Preston, F., 2012. A Global Redesign? Shaping the Circular Economy.
Pruyt, E., 2013. Small System Dynamics Models for Big Issues: Triple Jump towards Real-World Dynamic Complexity. TU Delft Library, Delft.
Qu, Y., Wang, W., Liu, Y., Zhu, Q., 2019. Understanding residents' preferences for e-waste collection in China - a case study of waste mobile phones. J. Clean. Prod. 228, 52–62. https://doi.org/10.1016/j.jclepro.2019.04.216.
Rahmandad, H., Sterman, J., 2008. Heterogeneity and network structure in the dynamics of diffusion: comparing agent-based and differential equation models. Manag. Sci. 54, 998–1014. https://doi.org/10.1287/mnsc.1070.0787.
Rahmandad, H., Sterman, J.D., 2012. Reporting guidelines for simulation-based research in social sciences. Syst. Dynam. Rev. 28, 396–411. https://doi.org/10.1002/sdr.1481.
Raven, R., Walrave, B., 2020. Overcoming transformational failures through policy mixes in the dynamics of technological innovation systems. Technol. Forecast. Soc. Change 153, 119297. https://doi.org/10.1016/j.techfore.2018.05.008.
Reike, D., Vermeulen, W.J.V., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0? — exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour. Conserv. Recycl. 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027.
Rockström, J., Steffen, W.L., Noone, K., Persson, Å., Chapin III, F.S., 2009. Planetary Boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 https://doi.org/10.1007/s13398-014-0173-7.2.
Rogers, E.M., 2003. Diffusion of Innovations, fifth ed. New York.
Rogge, K.S., Reichardt, K., 2016. Policy mixes for sustainability transitions: an extended concept and framework for analysis. Res. Pol. 45, 1620–1635. https://doi.org/10.1016/j.respol.2016.04.004.
Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.
Sauvé, S., Bernard, S., Sloan, P., 2016. Environmental sciences, sustainable development and circular economy: alternative concepts for trans-disciplinary research. Environ. Dev. 17, 48–56. https://doi.org/10.1016/j.envdev.2015.09.002.
Schwaninger, M., Groesser, S., 2016. System dynamics modeling: validation for quality assurance. Encycl. Complex. Syst. Sci. 1–20. https://doi.org/10.1007/978-3-642-27737-5.
Senge, P.M., Sterman, J.D., 1992. Systems thinking and organizational learning: acting locally and thinking globally in the organization of the future. Eur. J. Oper. Res. 59, 137–150. https://doi.org/10.1016/0377-2217(92)90011-W.
Siebers, P.O., MacAl, C.M., Garnett, J., Buxton, D., Pidd, M., 2010. Discrete-event simulation is dead, long live agent-based simulation. J. Simulat. 4, 204–210. https://doi.org/10.1057/jos.2010.14.

Stahel, W.R., 2016. Circular economy. Nature 435–438. https://doi.org/10.1038/531435a.
Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. Management. https://doi.org/10.1057/palgrave.jors.2601336.
Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: moving from rhetoric to implementation. J. Clean. Prod. 42, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020.
Tako, A.A., Robinson, S., 2009. Comparing Discrete-Event Simulation and System Dynamics: Users' Perceptions 296–312. https://doi.org/10.1057/palgrave.jors.2602566.
Tan, Q., Duan, H., Liu, L., Yang, J., Li, J., 2018. Rethinking residential consumers' behavior in discarding obsolete mobile phones in China. J. Clean. Prod. 195, 1228–1236. https://doi.org/10.1016/j.jclepro.2018.05.244.
United Nations - Department of Economic and Social Affairs - Population Division, 2019. World Population Prospects 2019 [WWW Document].
van Straalen, V.M., Roskam, A.J., Baldé, C.P., 2016. Waste over Time.
Velte, C.J., Steinhilper, R., 2016. Complexity in a circular economy: a need for rethinking complexity management strategies. Proc. World Congr. Eng. 2224, 763–768, 2016.
Vennix, J.A.M., 1999. Group model-building: tackling messy problems. Syst. Dynam. Rev. 15, 379–401. https://doi.org/10.1002/(SICI)1099-1727(199924)15:4<379::AID-SDR179>3.0.CO;2-E.
Verbong, G.P.J., Geels, F.W., 2010. Exploring sustainability transitions in the electricity sector with socio-technical pathways. Technol. Forecast. Soc. Change 77, 1214–1221. https://doi.org/10.1016/j.techfore.2010.04.008.
Videira, N., Rouwette, E., 2020. Circular Economy – thinking in systems for sus- tainable production and consumption. In: System Dynamics & Sustainability: A Research Agenda for the Coming Decade. S), p. 89.
Webster, K., 2013. What might we say about a circular economy? Some temptations to avoid if possible. World Futures J. Gen. Evolut. 69, 542–554. https://doi.org/10.1080/02604027.2013.835977.
Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renew. Sustain. Energy Rev. 68, 825–833. https://doi.org/10.1016/j.rser.2016.09.123.
Zhu, J., Fan, C., Shi, H., Shi, L., 2019. Efforts for a circular economy in China: a comprehensive review of policies. J. Ind. Ecol. 23, 110–118. https://doi.org/10.1111/jiec.12754.
Zink, T., Geyer, R., 2017. Circular economy rebound. J. Ind. Ecol. 1–10. https://doi.org/10.1111/jiec.12545, 00.