Resources, Conservation & Recycling 199 (2023) 107216

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Agent-based model for assessment of multiple circular economy strategies: Quantifying product-service diffusion, circularity, and sustainability

Ryu Koide [a,b,c,*], Haruhisa Yamamoto [a], Keisuke Nansai [a], Shinsuke Murakami [b]

[a] Material Cycles Division, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
[b] Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[c] Institute for Global Environmental Strategies, 2108-11 Kamiyamaguchi, Hayama 240-0115, Japan

ARTICLE INFO

Keywords:
Product-service systems
Agent-based model
Consumer behavior
Consumer durables
Circularity assessment
Consequential life cycle assessment

ABSTRACT

Despite the increasing need for tools to support a circular economy, methods for assessing circularity and environmental consequences in a way that considers dynamic changes in heterogeneous consumer behavior are lacking. Here we propose an agent-based model for assessing seven explicitly-defined product-level circular economy strategies. The model endogenizes bounded rational consumer behavior and interactions related to product acquisition, obsolescence, repair, hibernation, and discharge. Simulation experiments with numerical examples were used to quantify the diffusion of product service systems (e.g., leasing of refurbished products and sharing/rental services), product circularity, and lifecycle greenhouse gas emissions over 30 years. As a result, synergies arising from promotion measures (e.g., pricing, advertisements, and service levels), bottlenecks (e.g., lack of collected products), and rebound effects (e.g., due to new production and transport) were identified. By employing "what-if" analyses, this model provides a means to identify effective interventions in the transition to a net-zero circular economy.

1. Introduction

The adoption of circular economy strategies such as reuse, refurbishing, repair, and maintenance (Salvador et al., 2021), can facilitate the transition to a circular economy (Ellen MacArthur Foundation, 2013). In particular, product-service systems, such as shifting to product use rather than ownership and providing maintenance services, are considered to be promising approaches for improving sustainability benefits (Tukker, 2004). In order to transition effectively to a circular economy, measuring circularity, i.e., the degree of circular use of resources, has been a critical issue among decision makers and has resulted in the development of more than 60 metrics (Parchomenko et al., 2019; Saidani et al., 2019), as well as the ongoing development of a standardized assessment framework under the ISO initiative (Mathur et al., 2023). Regardless of such efforts, micro-level assessment methodologies that are applicable to product and business models are still underdeveloped, especially beyond recycling and end-of-life management, such as product lifetime extension and reuse (Kristensen and Mosgaard, 2020). In addition, despite the potential synergies and competition among them, there is a shortage of methodologies that address multiple circular economy strategies, including comparison (e.g., competition between reuse and sharing services) and combination (e.g., leasing refurbished products) (Koide et al., 2022).

Further, assessments of the circular economy must not only consider material circularity, but also environmental, social, and economic sustainability (Corona et al., 2019; Kristensen and Mosgaard, 2020; Walzberg et al., 2021b). Given that improvements in circularity do not necessarily improve environmental sustainability, studies need to address both product circularity and environmental impacts (Harris et al., 2021; Van Loon et al., 2021). A systematic review study identified potential causes of rebound and backfire effects due to changes in product lifetime, imperfect substitutions between linear and circular products, transport due to shared uses, and behavioral heterogeneity in the use phase (Koide et al., 2022). As discussed in a previous study on the importance of consumer behavior in modeling the use phase (Polizzi di Sorrentino et al., 2016) and the complexity of product-service system assessments (Kjaer et al., 2016), rebound effects are closely related to both the heterogeneity of consumer behavior and changes in the use patterns associated with a circular economy. However, existing assessment methods do not consider the linkages between micro-level changes and macro-level consequences and mechanisms of rebound effects, due to underrepresentation of the use phase and stocks or the lack of

* Corresponding author.
E-mail address: koide.ryu@nies.go.jp (R. Koide).

https://doi.org/10.1016/j.resconrec.2023.107216
Received 8 December 2022; Received in revised form 25 July 2023; Accepted 14 September 2023
Available online 22 September 2023

consumer behavior models (Harris et al., 2021; Van Loon et al., 2021; Walzberg et al., 2021b).

Even if improvements in environmental sustainability are realized from the products and manufacturing system perspectives, the transition to a circular economy requires an improved understanding of human behavior and re-shaping of consumer behaviors (Planing, 2018; Sutherland et al., 2020). Despite the importance of consumers in diffusing the circular economy, other than supply-side-focused studies, relatively little research has been conducted on consumer behavior (Camacho-Otero et al., 2018; Elzinga et al., 2020; Ferasso et al., 2020). Most existing research on consumer acceptance has focused on identifying barriers and drivers; however, studies exploring effective interventions for fostering the adoption and diffusion of the circular economy on the system level have been limited (Camacho-Otero et al., 2018).

Although a variety of methods have been proposed for assessing circular economies, we currently lack the tools to fully consider the dynamic changes in consumer behavior and their interactions with product circularity. Life cycle assessment (LCA) faces challenges in evaluating product-service systems (Kjaer et al., 2018, 2016), in considering behavioral science and consumer segments (Polizzi di Sorrentino et al., 2016), and in reflecting imperfect substitutions and consequential changes in society at large (Koide et al., 2022). Instead of an attributional approach, consequential LCA has been proposed as a means of quantifying the consequences of a decision, such as through market dynamics (Zamagni et al., 2012). Material flow analysis (MFA) can account for the status of circularity in a system at aggregated levels (Graedel, 2019), but underrepresentation of dynamisms within in-use stocks has led to difficulties in assessing some circular economy strategies, such as repairing and sharing (Walzberg et al., 2021b). On the other hand, life cycle simulations that couple discrete event simulation and quantification of life cycle impacts add temporal and dynamic dimensions to the assessments (Fujimoto et al., 2003; Umeda et al., 2000). However, discrete event simulations do not fully consider heterogeneous consumer behaviors and their interactions, which are critical factors in assessing the environmental consequences of product-service systems (Borshchev and Filippov, 2004; Polizzi di Sorrentino et al., 2016; Walzberg et al., 2021b). Indeed, studies employing discrete event simulation have also recognized the importance of modeling consumer behavior, such as by considering market segmentation (Kumazawa and Kobayashi, 2006), and a framework for hybridizing discrete event simulation with agent-based modeling of consumer behavior have been proposed (Kobayashi et al., 2020).

In contrast, agent-based modeling can overcome such limitations. An agent-based model is a computational simulation method that is used to simulate and visualize spatio-temporal processes and dynamics as consequences of interventions, by representing a system as a set of agents (e.g., individuals and firms), interacting based on micro-level behavioral rules with macro-level constraints (e.g., market, social network, and urban space) (Bianchi and Squazzoni, 2015). This approach has been applied to a variety of fields, including social sciences, ecology, biology, engineering, operations research, and environmental studies (Niazi and Hussain, 2011). Agent-based modeling is particularly useful when the interactions among people and products are characterized by active dynamics (Borshchev and Filippov, 2004) and overall consequences emerge from individual decision-making and their interactions (Siebers et al., 2010), which is indeed applicable to consumer behavior and its interplay with product systems in a circular economy. Agent-based modeling is considered to be a promising approach for modeling the diffusion of products and services (Rand and Stummer, 2021), energy consumption (Rai and Henry, 2016), mobility sector (Onat et al., 2017; Vasconcelos et al., 2017), industrial symbiosis (Lange et al., 2021a, 2021b; Raimbault et al., 2020), and waste management and recycling (Farahbakhsh et al., 2023; Meng et al., 2018; Tong et al., 2023). Although some studies have combined agent-based modeling with LCA (Davis et al., 2009; Hicks, 2022; Micolier et al., 2019), the application of agent-based modeling to the life cycles of consumer durables is only just beginning to attract academic interest. For example, Hicks et al. (2015) and Raihanian Mashhadi and Behdad (2018) applied agent-based modeling to assess energy efficiency during the use phase of appliances, and Lieder et al. (2017b) combined discrete event simulation and agent-based modeling to examine remanufacturing focusing on the component reuse. In addition to these studies, Lieder et al. (2017a) investigated the adoption of pay-per-use of washing machines, Walzberg et al. (2021a) examined reuse and recycling of solar photovoltaic panels, and Bozdoğan et al. (2023) proposed a framework for reuse and refurbishment; however, these studies did not consider environmental impacts. Furthermore, in a study on the reuse and recycling of hard disk drives, Walzberg et al. (2022) quantified recovered materials and greenhouse gas emissions, but their study was applicable only to strategies in which ownership is retained by customers. Thus, existing agent-based model studies have limitations in terms of the coverage of life cycle phases, circular economy strategies, and/or assessment dimensions.

In the present study, an agent-based simulation model of consumer behavior and product circulation for the assessment of multiple circular economy strategies is developed. The model is applicable to any geographical context and can consider i) a comparison and combination of seven explicitly defined, product-level, circular economy strategies, including those that forego ownership by consumers; ii) a variety of promotion measures focusing on changing consumer behavior; iii) bounded rational consumer behavior through information searches, consideration, habituation, and social influence related to product-service system acquisition, obsolescence, repair, hibernation, and discharge; and iv) the consequential changes in product circularity and life cycle environmental impacts. After describing the model formulation, this study demonstrates the application of the model by simulation experiments using two numerical examples of home appliances over a 30-year period for a comparison and combination of multiple circular economy strategies.

The remainder of the manuscript examines existing literature related to consumer decision-making processes, product-service systems, and product obsolescence as a foundation for modeling circular economy (Section 2), followed by descriptions of the processes and sub-models of the proposed agent-based model (Section 3). After introducing scenario settings (Section 4), the results and discussion of numerical examples are presented (Section 5). Finally, the manuscript concludes with research contributions and future prospects (Section 6). In Supplementary Information 1 (SI 1), additional details of the model are provided following the widely used and standardized model description format, Overview, Design concepts, Details (ODD) protocol for describing individual- and agent-based models (Grimm et al., 2020).

2. Literature review

2.1. Consumer decision-making process

The consumer decision-making process has been a major research topic in marketing and management studies. The widely cited Engel-Blackwell-Miniard model considers needs recognition, information search, pre-purchase evaluation of alternatives, purchase, consumption, post-consumption evaluation, and disposal processes (Blackwell et al., 2006). Diffusion has also been a key research topic in both aggregated models, such as the Bass Model (Bass, 1969), and agent-based models, in which social influences, opinion dynamics, and choice probabilities are often considered (Kiesling et al., 2012; Wakolbinger et al., 2013; Zhang and Vorobeychik, 2019). However, the predominant focus of marketing and diffusion studies has been on brand and channel choice, and in some cases, choices of green products (Kiesling et al., 2012; Mela et al., 2013); most of these studies assumed that brand-new products are sold and used in a linear economy.

In agent-based modeling, consumer adoption behavior can be modeled using utilitarian, social psychology, and opinion dynamics approaches (Kiesling et al., 2012). In utilitarian approaches, an evaluation process for alternatives is typically modeled using the random utility theory and is reflected in marketing and transport choices (McFadden, 1986, 1974). The model proposed in the present study adopts this approach in the context of a circular economy, because several empirical studies have shown that utilitarian approaches are applicable to product purchases and discharge choices, whereas price, year of manufacture, circularity status (e.g., reused or refurbished), ownership status (e.g., purchased or leased), and treatment methods are among the determinants that are employed in choosing reused, refurbished, and remanufactured products (Hunka et al., 2021; Koide et al., 2023; Kwarteng et al., 2018; Lieder et al., 2018; Wallner et al., 2022), repairing broken products (Pérez-Belis et al., 2017), and employing end-of-life product collection services (Mansuy et al., 2020; Qu et al., 2019). Conversely, the theory of planned behavior has been typically used in social psychological approaches (Kiesling et al., 2012). Originally proposed by Ajzen (1991), the theory of planned behavior has a number of applications in pro-environmental behavior, such as in the field of recycling, energy saving, and travelling and commuting (Yuriev et al., 2020).

As has been highlighted in the field of behavioral economics, in what is referred to as bounded rationality, consumers tend to seek satisfying alternatives rather than maximization and make decisions through heuristic choices rather than by deliberation (Kahneman, 2003; Simon, 2000). In marketing sciences, it is well known that consumers often narrow down alternatives when provided with a choice, and that they formulate awareness sets (alternatives known by a consumer) and consideration sets (alternatives considered in the last phase of choice) (Brisoux and Cheron, 1990). In this regard, integrative models that involve formulating consideration sets and then selecting an alternative after final alternative evaluation have been proposed (e.g., Manski, 1977; Roberts and Lattin, 1991). The formulation and composition of consideration sets has been studied extensively and empirically in the marketing sciences (Hauser, 2014; Roberts and Lattin, 1997). Consideration sets can also be applied to a circular economy; an in-depth questionnaire-based study concluded that a significant barrier to selecting circular products arises from the lack of entry to final consideration sets (Van Weelden et al., 2016).

Information searches and social networks are other important aspects of modeling diffusion. Searches for information by consumers can be either active (consumers actively seek out information) or passive (receiving information that happens to be relevant) (Wilson, 1997), typically through word-of-mouth and by advertisements (Allsop et al., 2007). Social influence, which refers to the behavioral changes of one individual induced by another individual, manifests either inadvertently or deliberately (Razaque et al., 2022) through compliance (direct response to communication) and/or conformity (behavior that matches the response of others) (Cialdini and Goldstein, 2004). Social network is a critical component of information diffusion in the structural, relational, and cognitive dimensions (Razaque et al., 2022), whereas small-world network topologies, which are characterized by local clusters and short connections, are often observed in society (Watts, 1999).

2.2. Product-service systems

Product-service systems are considered to be suitable for use as a tool for realizing the transition from a linear to a circular economy (Michelini et al., 2017). Product-service systems refer to "a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs" (Tukker and Tischner, 2006, page 1552). A widely cited framework for product-service systems distinguishes among product-, use-, and result-oriented product-service systems, depending on the level of changes in the access patterns of products and services (Tukker, 2004). Leasing, renting, sharing, and pooling all forego the ownership of products by consumers (use-oriented product-service systems) (Tukker, 2004). In these cases, the duration of use (time of exclusive access by a consumer) and use frequency are all important factors; in particular, short-term use can intensify utilization while increasing consumer-provider touchpoints (Tunn et al., 2021). Consumer-to-consumer (C2C) sharing has proliferated with the rise of the sharing economy, where direct transactions among consumers are facilitated through a platform (Puschmann and Alt, 2016). These models may induce additional processes, such as transport and preparation by service providers, changing the product lifetime and frequency of use (Koide et al., 2022). Conversely, maintenance and take-back systems can foster circularity while ownership status is retained by consumers (product-oriented product-service systems) (Tukker, 2004). A variety of circular economy strategies exist that retain product ownership; for example, repair, reuse, and refurbishing can enhance the circular use of products (Lüdeke-Freund et al., 2019). For these circular economy strategies, consumer preferences still play a central role in determining the overall performance of the systems, e.g., through repair and acquisition choices (Pérez-Belis et al., 2017) and through product obsolescence (Cooper, 2004). These approaches may extend service life and maintain the quality of stock, facilitating the utilization of stocks and reducing material intensity in the economy (Stahel and Clift, 2016).

2.3. Product obsolescence

Product obsolescence is typically classified into product failure (absolute obsolescence) and the replacement of functioning products due to consumer decisions for psychological, economic, and technological reasons (relative obsolescence) (Cooper, 2004). Obsolescence is a key process in determining product and resource flows, in which consumers play a key role as they typically own the resources when obsolescence occurs (Van der Laan and Aurisicchio, 2019). A product lifetime, such as total lifespan (i.e., from production to treatment) and possession span (i.e., from purchase to discharge by a single owner), is often modeled using a parametric approach with statistical distributions (Oguchi et al., 2010), such as Weibull's distribution (Weibull, 1951). In reliability engineering, product failure in a simple non-redundant system can be modeled as a system consisting of multiple parts, where a product operates until one of the components malfunctions (Mohamed et al., 1992). Although most empirical analyses do not consider the different reasons for obsolescence, a recent study distinguished between absolute and relative obsolescence, and concluded that both are important (Yamamoto and Murakami, 2021). Hibernation (dead storage) is another critical factor, as it generates a gap between the duration of use and possession (Murakami et al., 2010), which lowers the value of still-functioning products and benefits from reuse, upgrading and refurbishment (Sabbaghi et al., 2015).

2.4. Summary of the literature review

As described in this literature review, consumer decision-making processes, product-service systems, and product obsolescence are key elements in modeling a circular economy. In particular, the modeling of bounded-rational consumer behavior based on random utility theory with the formulation of awareness and considered sets and social interactions, including an information search through word-of-mouth and advertising on social networks, will determine consumer behavior in a circular economy. Furthermore, modeling the duration of product use requires distinguishing between relative and absolute obsolescence to better understand the role of consumer behavior in a circular economy. A comprehensive model based on these elements that is applicable to a variety of product-service systems could contribute to a better representation of consumer decision-making in circular economy modeling. We propose such a simulation model in this study.

3. The model

3.1. Model entities and process overview

The proposed agent-based model takes scenarios (circular economy strategies and promotion measures), simulates the dynamism and interactions among households, products, and circular supply chains, and then quantifies their consequences in product circularity and lifecycle environmental impacts (see Fig. 1(a) for an overview of the model). The model consists of multiple processes and sub-models related to two dimensions of the model: consumer decision-making, where bounded rational consumers seek information adaptively and make decisions about product-service acquisition, discharge, and repair (Fig. 1(b)), and product circulation, where products are acquired, used, made obsolete, hibernated, discharged, and processed for further circulation or disposed (Fig. 1(c); for more details, see process scheduling chart in Fig. S1-1 in SI 1). Although changes in the status of households and products are sequentially modeled with their mutual interactions in the same modeling space, for clarity, the processes and sub-models are described in two parts, consumer decision-making and product circulation, in the following sub-sections.[1]

The model includes the following entities: households, products, and circular supply chains (manufacturer, lease/rental provider, reuse shop, and recycler/landfill). Household agents are characterized by state variables, including awareness sets and word-of-mouth reception rate (see Fig. 1(b1–3) and Section 3.2.2), consideration costs (see Fig. 1(b4) and Section 3.2.4), and utility functions (see Fig. 1(b5) and Section 3.2.3), a relative obsolescence function (see Fig. 1(c4) and Section 3.3.1), and products in use, products on standby, products in hibernation, and possible sharing with other households (see Fig. 1(c2, 7, and 13) and Section 3.3.2). Product agents have state variables including circularity status (e.g., brand-new, reused, or refurbished), ownership status (e.g., owned, leased, or rented[2]) (see Fig. 1(c8–13) and Section 3.2.1 and 3.3.3), year of manufacture of the product and its parts, and the failure status of parts (see Fig. 1(c3) and Section 3.3.1). Circular supply chain agents update the information for leased, rented, stocked, and disposed products (see Fig. 1(c8–12) and Section 3.3.3). Households and circular supply chain agents are randomly located in a two-dimensional lattice, but spatial information has only an abstract meaning.

The temporal resolution of the model is monthly and the simulation period is decades, which is sufficient to cover several times the typical lifetimes of durable consumer products. The simulation model is implemented with Netlogo (Wilensky, 1999) version 6.1.1 and the simulation experiments are conducted using the nlrx package (Salecker et al., 2019) of the R software program. A full list of state variables, process scheduling, and the details of all processes and sub-models is included in SI 1.

3.2. Consumer decision-making

3.2.1. Choice of acquisition, repair, and discharge

The proposed model incorporates three key consumer decision-making processes in a circular economy: product repair, discharge, and acquisition (see Section 2.1 for literature review). For malfunctioning products owned by a household, a *repair choice* is made by the household (Fig. 1(c5)). If the household decides to repair the product, then any broken parts in the malfunctioning products are replaced with new parts, whenever this is technically feasible and considering the availability of spare parts.

For products flagged as being end-of-use due to failure or because they are obsolete, a *discharge choice* is made (Fig. 1(c6)). The discharged products are collected by formal or informal collectors, sold to reuse shops, or returned to service providers, depending on the availability of these services. In some cases, such products are stored at the house for some period (hibernation) (Fig. 1(c7)). Products not owned by a household (i.e., leased, rented, or shared products) always undergo a repair process when broken, and are returned to service providers when their use is terminated.

When households need to replace discharged products, an *acquisition choice* is made (Fig. 1(c1)). Households can purchase brand-new, reused, or refurbished (with/without functional upgrading) products, or they can lease, rent, or share products to use without owning them; these choices depend on their availability, awareness, and consideration sets. In the decision-making process for acquiring products, households typically screen potential alternatives before making their final selection. As described in Sections 3.2.2–3.2.4, this screening process typically involves a search of new product-service alternatives, and an evaluation of expected utilities with costs of consideration.

3.2.2. Passive and active searches

The search for information on products by households consists of passive and/or active searches. *Passive searches* are implemented by households at every time step, regardless of the timing of their decision-making (Fig. 1(b1)). Here, households receive information by word-of-mouth via their social network and through advertisements with a certain probability. Conversely, households that have decided to acquire a product go through *active search* for information through word-of-mouth (Fig. 1(b2)). The information exchanged in these searches includes an awareness set of acquisition alternatives (alternatives known by a consumer) (Fig. 1(b3)) and a perceived number of acquaintances who have selected the alternative (to account for conformity of social influence).

3.2.3. Evaluation of alternatives

In the *repair, discharge, and acquisition sub-models*, the evaluation of alternatives by households is determined by the random utility theory (Fig. 1(b5); see Section 2.1 for literature review). Here, the availability of product in stocks of circular supply chains (see Section 3.3.3) is reflected as alternatives. The probability that household h selects alternative k from a set of alternatives G can be represented by the (multinomial) logit model[3] given in Eq. (1),

$$P(k|G) = \frac{exp(W_{k,h})}{\sum_{j\in G} exp(W_{j,h})} \tag{1}$$

where the fixed-term of the utility $W_{k,h}$ is defined by the sum of the multiplication of weight and levels of attributes shown in Eq. (2),

[1] The belonging of sub-sections does not mean that each process is solely related to consumer decision-making or product circulation. For example, product obsolescence is described under product circulation, but it is determined through interaction between products and households. Similarly, choice of acquisition, repair, and discharge is described as part of a consumer decision-making, but they are affected by and determine product circularity.

[2] In the model, leasing refers to providing a product for a longer period of time without transferring ownership until the product is no longer used by the household. Renting refers to providing a product for a shorter period of time while the product is in operation and returning it to the service provider once the product is on standby.

[3] It should be noted that the multinomial logit model may suffer from limitations arising from the independence of irrelevant alternatives (IIA) property. In the acquisition choice, a nested logit model was used in this study to avoid overestimating the market share of products with the same ownership status (e.g., leasing) but different circularity statuses (e.g., reuse, refurbishment). Depending on the application, approaches other than the multinomial logit model, such as the mixed logit model or nested logit model, may be more appropriate, especially when two or more alternatives with similar characteristics (e.g., multiple suppliers of reused products and/or different brands of refurbished products) are assumed to be available in the market.

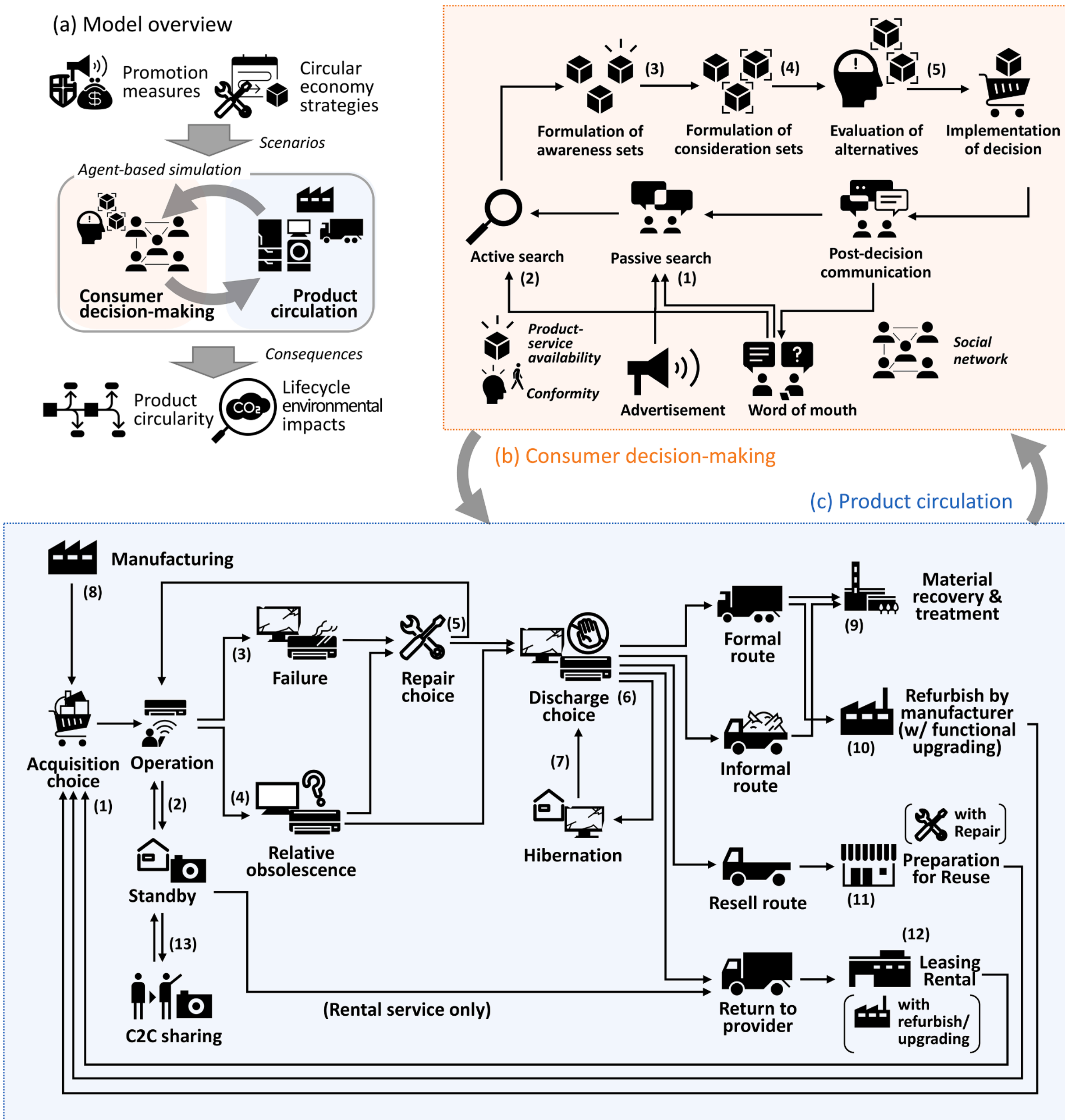

Fig. 1. Conceptual framework of the proposed agent-based simulation model. (a) Model overview; (b) Consumer decision-making; (c) Product circulation.

$$W_{k,h} = \sum_{l=1}^{L} \beta_{h,l} x_{k,l} \tag{2}$$

where $\beta_{h,l}$ and $x_{k,l}$ refer to weight and levels of alternative k and attribute l, such as price, year manufactured, circularity and ownership status of product, free-repair warranty, and perceived number of acquaintances using the same alternative. Here, social influence, or more specifically, conformity, is included in the utility function to consider the network externality by more acquaintances selecting the same alternative.

Among three sub-models, repair choice (i.e., whether to repair or not) is modeled using a binomial logit model. Acquisition choice with leasing and rental services is modeled by a nested logit model assuming a two-stage decision-making process in which ownership status is chosen first (e.g., leasing, renting), followed by choice of the circularity status of the products (e.g., leasing of brand-new or refurbished products). More detailed specifications of utility functions and a list of alternatives are included in SI 1.

3.2.4. Formulation of consideration sets

In the *acquisition sub-model*, we explicitly incorporated the formulation process for consideration sets (Fig. 1(b4); see Section 2.1 for literature review). Following Manski (1977), the probability that household h selects alternative k is comprised of two parts: the probability given consideration sets and the probability of formulating the consideration set (Eq. (3)),

$$P_h(k) = \sum_{C \in A} P_h(k|C) P_h(C|A) \tag{3}$$

where C and A refer to the consideration set and the set of all possible choice sets, respectively. Here, the former term is modeled using the random utility in Eq. (1). The latter term for the formulation of consideration sets is modeled based on Roberts and Lattin (1991), where the expected utility of the consideration set, EU, is determined using Eq. (4),

$$EU(C) = ln\left(\sum_{j\in C}\exp(u_j)\right) \tag{4}$$

where u_j refers to the utility of the alternatives considered. Here, household h compares expected utility obtained by adding one alternative k to consideration set C and costs of considering an additional alternative, and an alternative is added to consideration sets only when its marginal utility exceeds its threshold (Eq. (5)).

$$EU(C\cup k) - EU(C) > c_h \tag{5}$$

where c_h refers to consideration cost, which is assumed to be the same across alternatives but heterogeneous among households in the present study. A default alternative included in the initial consideration set is an alternative that was previously selected by the same household that accounts for the effects of habituation. More alternatives are added to the consideration sets if the marginal utility exceeds the consideration cost, starting from the highest expected utility given by Eq. (2).

3.3. Product circulation

3.3.1. Product obsolescence

Probabilistically, products used by households become obsolete due to either failure of parts (Fig. 1(c3)) or relative obsolescence due to reasons other than failure, such as functional and social factors (Fig. 1 (c4)) (see Section 2.3 for literature review). In the *product obsolescence sub-model*, rates of failure of individual parts and relative obsolescence of a product are given by the respective Weibull distributions. A product consists of a predetermined number of key parts, and the failure of any of these parts causes the entire product to malfunction (i.e., assuming a simple, non-redundant series system). The probability that part i will break at a period since manufacture t is defined by Eq. (6),

$$h_i(t) = \frac{\gamma_{fail}}{\lambda_i^{fail}}\left(\frac{t}{\lambda_i^{fail}}\right)^{\gamma_{fail}-1} \tag{6}$$

where γ^{fail} and λ_i^{fail} refer to the shape and scale parameters, respectively. In addition, household h may render products obsolete for reasons other than failure; the probability of such instances at a period since manufacture t is defined by Eq. (7),

$$h_h(t) = \frac{\gamma_{rel}}{\lambda_h^{rel}}\left(\frac{t}{\lambda_h^{rel}}\right)^{\gamma_{rel}-1} \tag{7}$$

where, γ^{rel} and λ_h^{rel} refer to the shape and scale parameters, respectively. In Eqs. (6) and (7), the scale parameters could be heterogeneous with specific values given by different parts and households, reflecting consumer and part characteristics.

3.3.2. Updates of product operation, standby, and hibernation

For products that are used periodically, such as small electric appliances, the statuses of *operation and standby* are updated (Fig. 1(c2)). The timing of the start of use is determined by a binomial logit model according to the length of the standby period, whereas the length of a one-time operation of products is given by a Weibull distribution. In the event that a C2C sharing strategy is introduced, products under standby status are made available for sharing, waiting for requests of temporal use by another household (Fig. 1(c13)). Products in hibernation (i.e., products kept for some period by households after being used) are discharged according to the probability determined by a Weibull distribution (Fig. 1(c7)). More details of these updating processes are included in SI 1.

3.3.3. Preparation for circular use and disposal

The end-of-use products discharged by households (see Section 3.2.1) and collected by relevant circular supply chain agents need to be prepared for future utilization as reused or refurbished (with/without functional upgrading) products to be owned by households (in Fig. 1 (c10–11)), or for lease, rental, or sharing to households (Fig. 1(c12)) (see Section 2.2 for literature review). These preparation processes, including inspection, cleaning, replacement of parts, and functional upgrading, are activated depending on the choice of product discharge. Product-service systems that combine multiple circular economy strategies are represented, such as repair of products for reuse and refurbishment (with optional functional upgrading in partnership with a manufacturer) of leased or rented products, according to the availability of additional services. The prepared products are then restocked by the provider entities for future selling, leasing, or renting. Products that are held in stock by circular supply chain agents for longer than a certain stock period are sent for recycling (Fig. 1(c9)). More details of these preparation processes are described in SI 1.

3.3.4. Inventory update

At every time step, the number of technical processes involved is recorded for quantification of circularity and sustainability indicators. The technical processes conducted in the simulated world are recorded as a product-level process matrix $INV_{p,j}$ with its product p as rows and process j as columns at every time step. The technical processes considered in the model include assembly, parts production, transport, operation, repairing, preparation for reuse, refurbishing, functional upgrading, leasing, renting, and sharing, recycling, and landfilling.

To quantify the lifecycle environmental impacts, a lifecycle intensity matrix $UI_{j,i}$ with its process j as rows and impact category i as columns is input to the model. The impacts induced for each product $IMP_{p,i}$ are calculated using the matrix (Eq. (8)), which can be summed to obtain the impacts in the whole world IMP_i (Eq. (9)).

$$IMP_{p,i} = INV_{p,j} \times UI_{j,i} \tag{8}$$

$$IMP_i = \sum_p IMP_{p,i} \tag{9}$$

To obtain a breakdown of impacts by technical processes, the sum of the columns containing the product-level process inventory vector INV_j is calculated. This process inventory vector is repeated for each impact category i to formulate a matrix $INV_{j,i}$, before calculating the Hadamard product using an intensity matrix (Eq. (10)),

$$IMP_{j,i} = INV_{j,i} \odot UI_{j,i} \tag{10}$$

4. Numerical example: scenario setting

To demonstrate the use cases of the proposed model, two simulation experiments were conducted with hypothetical home appliances. The first numerical example is a case of product-service systems that combine multiple circular economy strategies (leasing service of refurbished products with functional upgrading) for large household appliances (Numerical Example A). Assuming that the stakeholder (service provider) is considering how to disseminate the new service effectively, we compared the impacts of the introduction of different promotion measures, including pricing, advertising, and service level. Here, six scenarios including the i) *Business as Usual (BaU) scenario* with limited extent of reuse and repair, ii) *without promotions scenario*, which comprises the introduction of new leasing service without any promotion measures, iii-v) *price, advertisement, and service level scenarios* with each of promotion measure introduced for the new leasing service, and (vi) *all promotions scenario*, which combines all three of the promotion measures (Table 1).

The second numerical example compares the different types of product-service systems for the sustainable use of small electronic

Table 1
Overview of scenarios examined in numerical example A.

Scenarios Parameters	Business as usual (BaU)	Without promotions	Price	Advertisement	Service level	All promotions
Availability of reuse selling	✔	✔	✔	✔	✔	✔
Availability of leasing service[1]		✔	✔	✔	✔	✔
Refurbished product price[2]	–	−30%	**−50%**	−30%	−30%	**−50%**
Advertisement frequency for leasing[3]	–	0.1%	0.1%	**5%**	0.1%	**5%**
Period of repair parts availability	9 years	15 years	15 years	15 years	**25 years**	**25 years**
Refurbishment-possible years since manufacturing	–	10 years	10 years	10 years	**15 years**	**15 years**
Upgrade-possible years since manufacturing	–	8 years	8 years	8 years	**10 years**	**10 years**

[1] Leasing of refurbished products with possible functional upgrading.
[2] Discount level relative to brand-new purchase price (brand-new purchase cost = 100%).
[3] Probability that households receive advertisement and successfully update awareness of relevant product-service in each year.
For more details of parameter settings and data sources, see Table S2-1 and S2-2 in SI 2.

equipment (Numerical Example B). In this example, the stakeholder (policymakers) are assumed to be considering which types of product-service systems are preferable within the context of different circular economy strategies for improved sustainability outcomes. For this purpose, four scenarios, including the i) *BaU scenario*, ii) *reuse promotion scenario* which promotes traditional reuse by lower pricing and free repair warranty extension, and iii–iv) *rental and sharing scenarios* that introduce new rental services or C2C sharing services, were developed (Table 2).

As a demonstration, wherever possible, parameters such as product lifetime, topology of social network, and life cycle inventories are determined by referring to existing literature (see Table S2-1 to S2-3 in SI 2 for details of parameters and data sources). Only one impact category of global warming potential is considered, and the state variables describing behavioral rules for households (e.g., utility function) are set as heterogeneous with a normal distribution. A simple design with a fixed set of parameters per scenario was used with 100 simulations, each with different random seeds, for a 30-year period (360 time steps). The number of simulation runs per scenario was confirmed to be sufficient according to the stability of the standard error of the mean by adding simulation runs (see Fig S2-4 and S2-8 in SI 2). Prior to this simulation period, a burn-in period of 120 time steps was added to stabilize the status of product circulation and availability of product stocks.

Table 2
Overview of scenarios examined in numerical example B.

Scenarios Parameters	Business as usual (BaU)	Reuse promotion	Rental	C2C sharing
Availability of reuse selling without repair[1]	✔	✔	✔	✔
Availability of reuse selling with repair[2]		✔		
Availability of rental service[3]			✔	
Availability of C2C sharing				✔
Reused/shared product price[4]	−50%	**−60%**	−50%	−50%
Profit for resale[5]	10%	**20%**	10%	10%
Advertisement[6]	0%	0%	**2%**	**2%**
Free repair warranty period for reuse	0 years	**3 years**	0 years	0 years

[1] Reuse shops only accept functioning products and resell them without repair.
[2] Reuse shops accept non-functioning products and resell them after repair.
[3] Rental service for reused products.
[4] Discount level relative to brand-new product purchase price (brand-new purchase cost = 100%).
[5] Profit for selling second-hand product to reuse shop relative to brand-new product purchase price (brand-new purchase cost = 100%).
[6] Probability that households receive advertisement and successfully update awareness of relevant product-service in each year.
For more details of parameter settings and data sources, see Table S2-1 and S2-3 in SI 2.

In the main scenarios, the number of households was set at 5000, with changes analyzed by sensitivity analysis. The details of the parameter settings used for each scenario, data sources, sensitivity analysis, verification, and validation of the model are included in SI 2.

5. Results and discussion

This section first describes the results of simulation experiments with two numerical examples and discusses the characteristics and applicability of the proposed model. It also describes a sensitivity analysis, verification, and validation of the model. Additional results for the two numerical examples not included in the main text (Fig. S2-9 to S2-14) and descriptive statistics of outcomes (Table S2-4 and S2-5) are included in SI 2.

5.1. Numerical example A: combination of multiple circular economy strategies

5.1.1. Diffusion of leasing of refurbished products with promotion measures

In the simulation experiments, the model could be used to explore an effective combination of promotion measures for the diffusion of new product-service systems. The first numerical example compared different promotion measures for disseminating a product-service system combining multiple circular economy strategies. The model successfully simulated the dynamic diffusion of the combination of leasing and refurbishing over a simulation period of 30 years. Fig. 2 shows how new strategies were disseminated through a variety of promotion measures, such as price discounts, advertisements, and service level improvement compared to the *without promotions scenario*. First, the model captures the pathways and time required to disseminate a new strategy; e.g., advertising appears to contribute to earlier diffusion (cf. up to 20 years in the *advertisement scenario*), whereas service level improvement has a delayed diffusion (cf. after 20 years in the *service level scenario*). Second, the model accounts for the nonlinear synergetic impacts of the combination of multiple promotion measures, e.g., the combination of all measures reaches the highest rate of diffusion (approx. 40% in the *all promotions scenario*). Third, the model identified a bottleneck in circularity; e.g., there is a backlash in diffusion due to limited availability of collected products for further refurbishment in the last 10 years in the *all promotions scenario*.

5.1.2. Product flows with coexistence of multiple circular economy strategies

In terms of circularity, the model quantifies dynamic product flows and stocks as consequences of introducing circular economy strategies and promotion measures that trigger behavioral changes. For example, the product flows in the *all promotions scenario* and the *BaU scenario* in the last 10 years of the simulation periods are visualized in the Sankey chart, which depicts a shift from owning to using, resulting in a higher

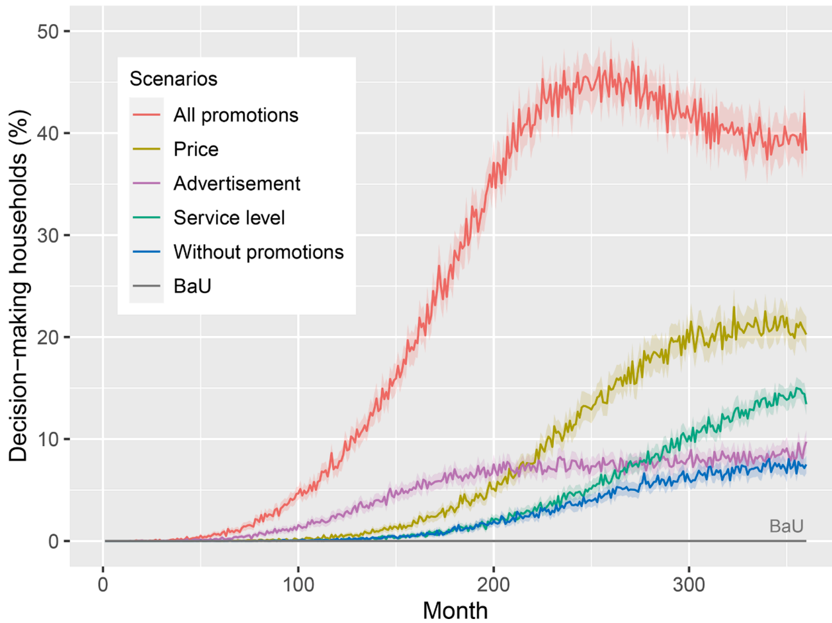

Fig. 2. Share of decision-making households acquiring refurbished (with/without functional upgrading) products with different promotion measures (Numerical example A). Bold lines and light shading indicate means and 95% confidence intervals for 100 simulations, respectively.

rate of product circulation through leasing, refurbishing, upgrading, and repairing compared to the *BaU scenario* (Fig. 3). Based on the product flows being modeled, a variety of product-level circularity indicators could be quantified, e.g., the extent of the reduction in newly manufactured and wasted products (approx. 9 to 5 units per 100 households per year), increased rate of repair (approx. 20% to 80%), and product lifetime (approx. 11 to 16 years). As the model simulates the coexistence of multiple circular economy strategies, the number of reused products in the *all promotions scenario* decreased compared to the *BaU scenario* due to competition with the newly introduced leasing service.

5.1.3. Trends in environmental impacts as a consequence of promotion measures

In terms of environmental impacts, the numerical example demonstrated the model's ability to dynamically quantify the sustainability impacts that arise as a consequence of changes in consumer behavior and product circulation in circular economy. This assessment approach focuses on changes in the entire society by introducing circular economy strategies (e.g., by introducing a leasing service), which is different from the comparison of typical product use cases as in attributional LCA (e.g., typical case of purchasing vs. leasing a product; see Koide et al. (2022) for a systematic review of LCA studies on the circular economy). In the *all promotions scenario*, the combination of all promotion measures may reduce monthly emissions by approx. 10% in the long term compared to the *BaU scenario*, whereas the reduction in emissions with no promotion measures is limited, as shown in the *without promotions scenario* (Fig. 4). The emission reductions reflect a gradual process in the 30-year simulation period, yet in the *all promotions scenario*, there would be some counter change in the last 10 years due to the shortage of collected products for further refurbishing. As demonstrated in this numerical example, the model provides insights into the time required to realize the diffusion and environmental gains. Even though a strategy seems sustainable under an ideal use pattern, as a consequence of interventions, diffusion may take longer with delayed impacts, or there may be some backlash in the long run.

5.2. Numerical example B: comparison of multiple circular economy strategies

5.2.1. Comparison of diffusion potentials of reuse, rental, and sharing services

In addition to being able to simulate a single strategy, the model can also compare the diffusion of multiple product-service systems with different circular economy strategies. Introducing three different strategies, i.e., promoting reuse, rental, and sharing services, produces different diffusion speeds and potentials (Fig. S2-12 in SI 2). In this example, reused products could be disseminated quickly through the traditional sell-out model, but its potential diffusion in the long run is limited (up to slightly below 15%). Conversely, introducing new services, such as rental and sharing, would take time, but could be more effective in the long term (over approx. 50%).

5.2.2. Reduction in product stocks in households due to rental and sharing

In addition to flows, the model also successfully quantified the in-use and hibernated stock of products in households in the whole simulated society, considering the cascaded use of products by multiple users (Fig. 5). As shown in the *rental and sharing scenarios*, by introducing these new services, the needs of households could be satisfied with fewer total products by delivering the products to households only when they need them. Implementing such changes would result in an approximately 25% reduction in the total number of products that are in stock in households under a given scenario. The simulation also identified a bottleneck in circularity related to consumer preferences. Although rental services appear to contribute to reducing the number of overall in-use products, some major parts of rented products are supplied as brand-new products, rather than as reused products, which may cause an increase in manufacturing and waste generation.

5.2.3. Breakdown of consequential environmental impacts among life cycle phases

The model successfully quantified the breakdown of total greenhouse gas emissions in society as a whole as consequences of introducing different circular economy strategies (Fig. 6). In this example, the *sharing scenario* would have the highest reduction potential for emissions, whereas *rental scenario* has a slight backfire; in other words, there is a net increase in emissions (note that this effect was statistically

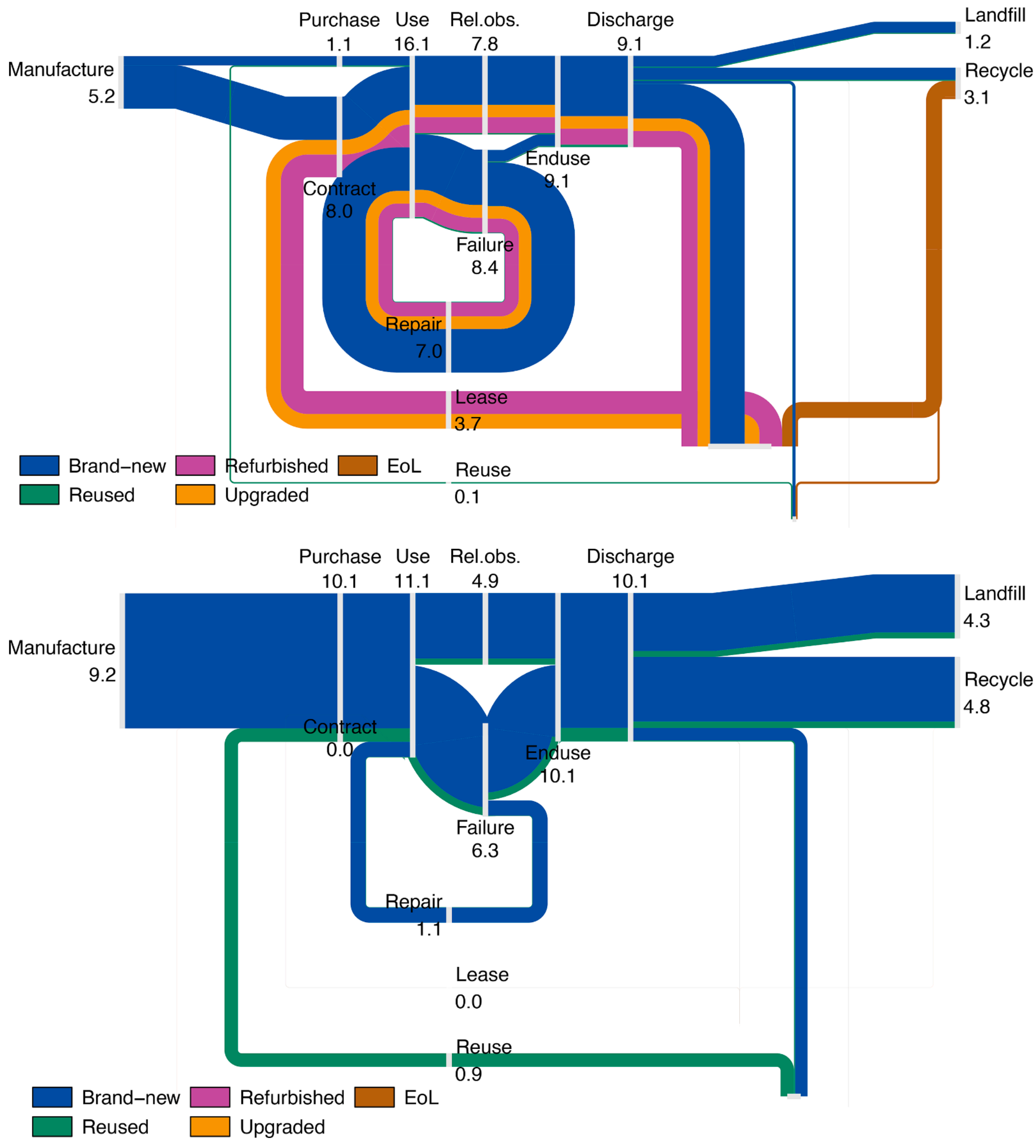

Fig. 3. Product flows in years 21–30 of the simulation period as a mean of 100 simulations (Numerical example A). Values indicate the number of units of products per 100 households per year. Rel. obs.: relative obsolescence; EoL: End of life.

robust, as indicated by the confidence intervals shown in Table S2-5 in SI 2.). The emission reductions for the reuse and sharing scenarios appear to be derived mostly from the reduced necessity of production, whereas transport appears to be increased especially under the rental scenario. The negative sustainability gains under the *rental scenario* would be due to the preference of consumers to rent brand-new products rather than reused ones, and the increased transport required for delivering products for temporary use. As demonstrated in this numerical example, the model could be useful for identifying bottlenecks in circularity (e.g., a preference for brand-new products in the rental service) and for identifying the risks and reasons for rebound effects (e.g., emissions from transport and new manufacturing in the rental service).

5.3. Sensitivity analysis

For the sensitivity analysis, the number of households N_{hh} in Numerical Example A and B was changed to 2000, 5000, and 8000 with 100 simulations runs for each value and each scenario. Variances and standard errors of greenhouse gas emissions and choice share decreased markedly when $N_{hh} = 5000$, but adding more agents did not contribute much to improving these metrics (Fig. S2-3 and S2-7 in SI 2). In addition, traces of monthly simulation results matched well in terms of mean values, whereas variances increased markedly when $N_{hh} = 2000$ (Fig.S2-1, S2-2, S2-5, S2-6 in SI 2). These results confirmed that $N_{hh} = 5000$ was sufficient for the purpose of numerical examples.

5.4. Verification and validation

The model was verified and validated using the procedures described by Dam et al. (2013). Verification was performed to ensure that the model code is correctly implemented. We conducted multi-agent and interaction tests, including sanity checks, to ensure that the agent behaves as expected, and extreme value tests to examine the model outputs on the edges of the parameter ranges, as described in SI 2. Validation was performed to check whether the model accurately represents real-world systems. Given that the model simulates emerging phenomena, we conducted structural validation assessments based on expert opinion and stylized facts from the literature. Marketing and product design experts agreed that the model structure well reflected consumer behavior and technical processes in the circulation of consumer durables. We also confirmed that the results of the experiments matched the stylized facts from the literature, including the S-shaped curve for

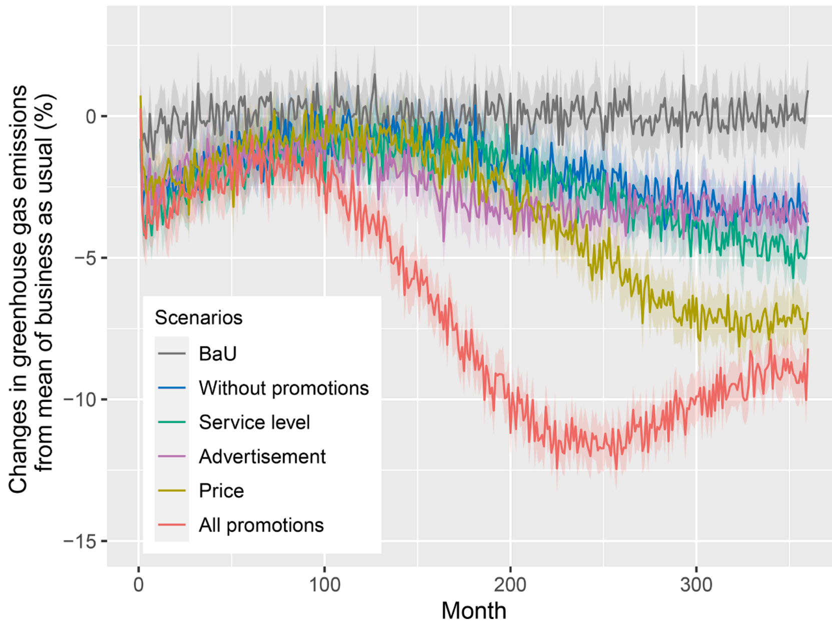

Fig. 4. Changes in lifecycle greenhouse gas emissions over 30 years of the simulation period relative to the mean for the BaU scenario (Numerical example A). Bold lines and light shading indicate means and 95% confidence intervals for 100 simulations, respectively.

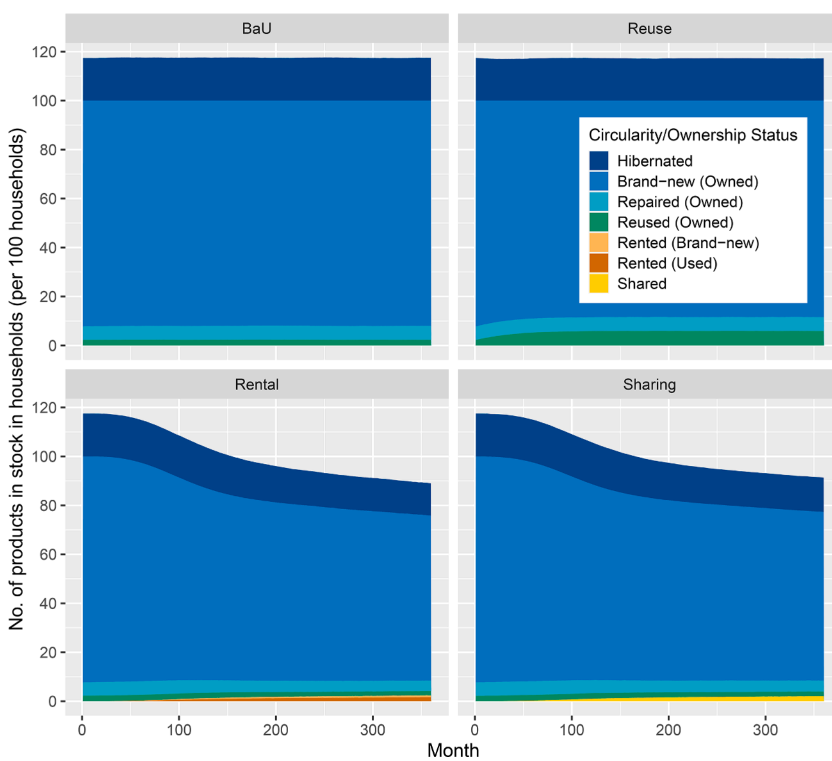

Fig. 5. Quantified product stocks in households over 30-year simulation period (Numerical example B). Means of 100 simulations.

typical diffusion (Kiesling et al., 2012) and rebound effects due to transport and consumer behavior (Koide et al., 2022).

6. Conclusions

In this study, we developed an agent-based simulation model to assess consumer behavior and product circulation in the transition to a circular economy. Simulation experiments with numerical examples confirmed the ability of the model to quantify the diffusion of new product-service systems, product circularity, and environmental sustainability, which is useful for circularity assessment, consequential LCA, and supporting sustainable manufacturing. Such simulations can be extended to include seven explicitly defined product-level circular economy strategies ranging from repair, reuse, refurbishing, functional upgrading, leasing, and rental to C2C sharing. By modeling both consumers and products as distinct entities using an agent-based approach that links micro-level behavior to macro-level consequences in the whole system, the model expands the scope of analysis in the field to

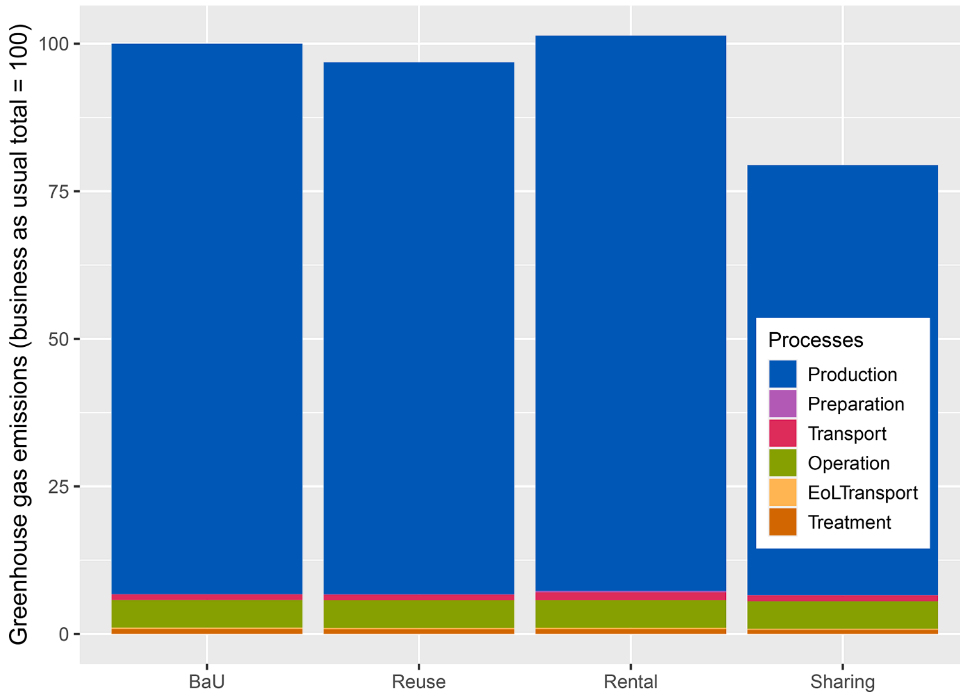

Fig. 6. Process breakdown of lifecycle greenhouse gas emissions in years 21–30 of the simulation period (Numerical example B). Means of 100 simulations.

explore effective measures in re-shaping consumer behavior towards a circular economy that is in harmony with supply-side efforts.

The simulation experiment approach proposed herein provides a basis for the research community, manufacturers, service providers, and policymakers to explore effective measures and possible pathways to reach a net-zero circular economy. In particular, the model contributes to ex-ante assessments of circular economy strategies, which are important for supporting early decision making (Kravchenko et al., 2019). Given the nature of the transition, many circular economy strategies are still new and emerging, and pilot experiments in a real society are considerably costly. Even under such limitations, simulation experiments with various "what-if" scenarios could provide insights into understanding the effective strategies and promotion measures, expected environmental benefits, risks of rebound effects, and bottlenecks hindering the diffusion of a circular economy. The application of sensitivity analysis methods that focus on determining input variability that induces significant output values facilitates the exploration of parameter spaces and scenarios under a given target (Pianosi et al., 2016). Furthermore, participatory social simulations with stakeholder involvement is considered to be a promising approach (Ramanath and Gilbert, 2004). Such application of simulation experiments contribute to addressing sustainability in life cycle engineering (Hauschild et al., 2020), as well as for exploring carbon footprint pathways to meet the decarbonization target from a life-cycle perspective (Koide et al., 2021a; Koide et al., 2021b).

The study has the following limitations. As this study is a first step in applying agent-based modeling to simulate the consequences of multiple product-level circular economy strategies, the focus is on developing the model structure and demonstrating use cases with numerical examples. Given this scope of the study, data-driven calibration and validation with empirical data on specific products or business models were not conducted. Instead, wherever possible, parameters are set by referring to existing literature or by using assumptions based on typical home appliances. Given the nature of the numerical examples, the results should be considered only for demonstration purposes, rather than for providing practical recommendations. Regarding consumer decision-making models, the needs of product-service use by the households in the model are assumed to be stable over time, i.e., the number of products used by one household is assumed to be one. In addition, the household-level variables that determine the behavioral rules (e.g., weight parameters of utility function) are assumed to have a normal distribution. Furthermore, it is assumed that decision making and communication through social network is performed at the household level rather than at the individual level.

The purpose of this study was to propose a model structure and demonstrate use cases of the developed model with numerical examples. To utilize this model to clarify the real implications of design, management, and policymaking, it would be useful to collect the following empirical data for analysis. The effects of word-of-mouth and advertisements on diffusion, social network topology, utility functions, and product obsolescence functions; these could be obtained from a consumer survey. Similarly, life cycle inventory data and operation details of circular supply chains could be obtained from existing databases, such as Ecoinvent (Wernet et al., 2016) and IDEA (2023), and through partnerships with companies. Methods from the marketing sciences, industrial ecology, and complex system sciences, such as discrete choice experiments (Holm et al., 2016), survival analysis (Oguchi et al., 2010), social network and word-of-mouth analyses (Allsop et al., 2007), and data-driven agent-based simulation (Laatabi et al., 2018), could be used to process these data and to calibrate the simulation model. Such applications to real world cases with empirical data collection are well-suited to future research.

Author contributions

All of the authors have approved the final version of the manuscript.

Supporting Information

Supporting Information 1: Model Description (Overview, Design Concepts, and Details) (PDF)

Supporting Information 2: Experimental Setup, Sensitivity Analysis, Verification, and Additional Results (PDF)

CRediT authorship contribution statement

Ryu Koide: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft. **Haruhisa Yamamoto:** Conceptualization, Methodology, Writing – review & editing. **Keisuke Nansai:** Conceptualization, Supervision, Writing – review & editing. **Shinsuke Murakami:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Co-author serves on the editorial board - K.N.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank Yasushi Umeda and Nariaki Nishino (The University of Tokyo), Ernesto Carrella and Nicolas Payette (University of Oxford), and Flaminio Squazzoni (University of Milan) for providing pertinent advice regarding the methodology. We also thank three anonymous reviewers for their valuable comments. This work was supported by Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science [Grant numbers: JP21K12374 and JP19H04325] and the Environment Research and Technology Development Fund of the Environmental Restoration and Conservation Agency Provided by the Ministry of Environment of Japan [Grant number: JPMEERF20223001].

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107216.

References

Ajzen, I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process. 50, 179–211. https://doi.org/10.1016/0749-5978(91)90020-T.

Allsop, D.T., Bassett, B.R., Hoskins, J.A., 2007. Word-of-mouth research: principles and applications. J. Advert. Res. 47, 398–411. https://doi.org/10.2501/S0021849907070419.

Bass, F.M., 1969. A new product growth for model consumer durables. Manag. Sci. 15, 215–227.

Bianchi, F., Squazzoni, F., 2015. Agent-based models in sociology: agent-based models in sociology. Wiley Interdiscip. Rev. Comput. Stat. 7, 284–306. https://doi.org/10.1002/wics.1356.

Blackwell, R.D., Miniard, P.W., Engel, J.F., 2006. Consumer Behavior. Thomson South-Western.

Borshchev, A., Filippov, A., 2004. From system dynamics and discrete event to practical agent based modeling: reasons, techniques. The 22nd International Conference of the System Dynamics Society, Oxford.

Bozdoğan, A., Görkemli Aykut, L., Demirel, N., 2023. An agent-based modeling framework for the design of a dynamic closed-loop supply chain network. Complex Intell. Syst. 9, 247–265. https://doi.org/10.1007/s40747-022-00780-z.

Brisoux, J.E., Cheron, E.J., 1990. Brand categorization and product involvement. Adv. Consum. Res. 17, 101–109.

Camacho-Otero, J., Boks, C., Pettersen, I., 2018. Consumption in the circular economy: a literature review. Sustainability 10, 2758. https://doi.org/10.3390/su10082758.

Cialdini, R.B., Goldstein, N.J., 2004. Social influence: compliance and conformity. Annu. Rev. Psychol. 55, 591–621. https://doi.org/10.1146/annurev.psych.55.090902.142015.

Cooper, T., 2004. Inadequate life? Evidence of consumer attitudes to product obsolescence. J. Consum. Policy 27, 421–449. https://doi.org/10.1007/s10603-004-2284-6.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498 https://doi.org/10.1016/j.resconrec.2019.104498.

Dam, K.H., Nikolic, I., Lukszo, Z., 2013. Agent-Based Modelling of Socio-Technical Systems. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-007-4933-7.

Davis, C., Nikolić, I., Dijkema, G.P.J., 2009. Integration of life cycle assessment into agent-based modeling. J. Ind. Ecol. 13, 306–325. https://doi.org/10.1111/j.1530-9290.2009.00122.x.

Ellen MacArthur Foundation, 2013. Towards the Circular Economy: Opportunities for the Consumer Goods Sector. Ellen MacArthur Foundation.

Elzinga, R., Reike, D., Negro, S.O., Boon, W.P.C., 2020. Consumer acceptance of circular business models. J. Clean. Prod. 254, 119988 https://doi.org/10.1016/j.jclepro.2020.119988.

Farahbakhsh, S., Snellinx, S., Mertens, A., Belderbos, E., Bourgeois, L., Meensel, J.V., 2023. What's stopping the waste-treatment industry from adopting emerging circular technologies? An agent-based model revealing drivers and barriers. Resour. Conserv. Recycl. 190, 106792 https://doi.org/10.1016/j.resconrec.2022.106792.

Ferasso, M., Beliaeva, T., Kraus, S., Clauss, T., Ribeiro-Soriano, D., 2020. Circular economy business models: the state of research and avenues ahead. Bus. Strategy Environ. 29, 3006–3024. https://doi.org/10.1002/bse.2554.

Fujimoto, J., Umeda, Y., Tamura, T., Tomiyama, T., Kimura, F., 2003. Development of service-oriented products based on the inverse manufacturing concept. Environ. Sci. Technol. 37, 5398–5406. https://doi.org/10.1021/es034439d.

Graedel, T.E., 2019. Material flow analysis from origin to evolution. Environ. Sci. Technol. 53, 12188–12196. https://doi.org/10.1021/acs.est.9b03413.

Grimm, V., Railsback, S.F., Vincenot, C.E., Berger, U., Gallagher, C., DeAngelis, D.L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A.S.A., Milles, A., Nabe-Nielsen, J., Polhill, J.G., Radchuk, V., Rohwäder, M.S., Stillman, R.A., Thiele, J.C., Ayllón, D., 2020. The ODD protocol for describing agent-based and other simulation models: a second update to improve clarity, replication, and structural realism. J. Artif. Soc. Soc. Simul. 23 (7) https://doi.org/10.18564/jasss.4259.

Harris, S., Martin, M., Diener, D., 2021. Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustain. Prod. Consum. 26, 172–186. https://doi.org/10.1016/j.spc.2020.09.018.

Hauschild, M.Z., Kara, S., Røpke, I., 2020. Absolute sustainability: challenges to life cycle engineering. CIRP Ann. 69, 533–553. https://doi.org/10.1016/j.cirp.2020.05.004.

Hauser, J.R., 2014. Consideration-set heuristics. J. Bus. Res. 67, 1688–1699. https://doi.org/10.1016/j.jbusres.2014.02.015.

Hicks, A., 2022. Seeing the people in LCA: agent based models as one possibility. Resour. Conserv. Recycl. Adv. 15, 200091 https://doi.org/10.1016/j.rcradv.2022.200091.

Hicks, A.L., Theis, T.L., Zellner, M.L., 2015. Emergent effects of residential lighting choices: prospects for energy savings: agent-based model energy-efficient lighting. J. Ind. Ecol. 19, 285–295. https://doi.org/10.1111/jiec.12281.

Holm, S., Lemm, R., Thees, O., Hilty, L.M., 2016. Enhancing agent-based models with discrete choice experiments. J. Artif. Soc. Soc. Simul. 19, 3. https://doi.org/10.18564/jasss.3121.

Hunka, A.D., Linder, M., Habibi, S., 2021. Determinants of consumer demand for circular economy products. A case for reuse and remanufacturing for sustainable development. Bus. Strategy Environ. 30, 535–550. https://doi.org/10.1002/bse.2636.

Inventory Database for Environmental Analysis (IDEA), 2023. National Institute of Advanced Industrial Science and Technology, version 3.3.

Kahneman, D., 2003. Maps of bounded rationality: psychology for behavioral economics. Am. Econ. Rev. 93, 1449–1475. https://doi.org/10.1257/000282803322655392.

Kiesling, E., Günther, M., Stummer, C., Wakolbinger, L.M., 2012. Agent-based simulation of innovation diffusion: a review. Cent. Eur. J. Oper. Res. 20, 183–230. https://doi.org/10.1007/s10100-011-0210-y.

Kjaer, L.L., Pagoropoulos, A., Schmidt, J.H., McAloone, T.C., 2016. Challenges when evaluating product/service-systems through life cycle assessment. J. Clean. Prod. 120, 95–104. https://doi.org/10.1016/j.jclepro.2016.01.048.

Kjaer, L.L., Pigosso, D.C.A., McAloone, T.C., Birkved, M., 2018. Guidelines for evaluating the environmental performance of product/service-systems through life cycle assessment. J. Clean. Prod. 190, 666–678. https://doi.org/10.1016/j.jclepro.2018.04.108.

Kobayashi, H., Murata, H., Fukushige, S., 2020. Connected lifecycle systems: a new perspective on industrial symbiosis. Procedia CIRP 90, 388–392. https://doi.org/10.1016/j.procir.2020.01.107.

Koide, R., Kojima, S., Nansai, K., Lettenmeier, M., Asakawa, K., Liu, C., Murakami, S., 2021a. Exploring carbon footprint reduction pathways through urban lifestyle changes: a practical approach applied to Japanese cities. Environ. Res. Lett. 16, 084001 https://doi.org/10.1088/1748-9326/ac0e64.

Koide, R., Lettenmeier, M., Akenji, L., Toivio, V., Amellina, A., Khodke, A., Watabe, A., Kojima, S., 2021b. Lifestyle carbon footprints and changes in lifestyles to limit global warming to 1.5 °C, and ways forward for related research. Sustain. Sci. 16, 2087–2099. https://doi.org/10.1007/s11625-021-01018-6.

Koide, R., Murakami, S., Nansai, K., 2022. Prioritising low-risk and high-potential circular economy strategies for decarbonisation: a meta-analysis on consumer-oriented product-service systems. Renew. Sustain. Energy Rev. 155, 111858 https://doi.org/10.1016/j.rser.2021.111858.

Koide, R., Yamamoto, H., Kimita, K., Nishino, N., Murakami, S., 2023. Circular business cannibalization: A hierarchical Bayes conjoint analysis on reuse, refurbishment, and subscription of home appliances. J. Clean. Prod. 422, 138580. https://doi.org/10.1016/j.jclepro.2023.138580.

Kravchenko, M., Pigosso, D.C.A., McAloone, T.C., 2019. Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: consolidation of leading sustainability-related performance indicators. J. Clean. Prod. 241, 118318 https://doi.org/10.1016/j.jclepro.2019.118318.

Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 243, 118531 https://doi.org/10.1016/j.jclepro.2019.118531.
Kumazawa, T., Kobayashi, H., 2006. A simulation system to support the establishment of circulated business. Adv. Eng. Inform. 20, 127–136. https://doi.org/10.1016/j.aei.2005.11.004.
Kwarteng, M.A., Pilík, M., Juřičková, E., 2018. Beyond cost saving. Other factor consideration in online purchases of used electronic goods: a conjoint analysis approach. Manag. Mark. 13, 1051–1063. https://doi.org/10.2478/mmcks-2018-0022.
Laatabi, A., Marilleau, N., Nguyen-Huu, T., Hbid, H., Ait Babram, M., 2018. ODD+2D: An ODD Based Protocol for Mapping Data to Empirical ABMs. J. Artif. Soc. Soc. Simul. 21, 9. https://doi.org/10.18564/jasss.3646.
Lange, K., Korevaar, G., Nikolic, I., Herder, P., 2021a. Actor behaviour and robustness of industrial symbiosis networks: an agent-based modelling approach. J. Artif. Soc. Soc. Simul. 24, 8. https://doi.org/10.18564/jasss.4635.
Lange, K., Korevaar, G., Oskam, I., Nikolic, I., Herder, P., 2021b. Agent-based modelling and simulation for circular business model experimentation. Resour. Conserv. Recycl. Adv. 12, 200055 https://doi.org/10.1016/j.rcradv.2021.200055.
Lieder, M., Asif, F.M.A., Rashid, A., 2017a. Towards circular economy implementation: an agent-based simulation approach for business model changes. Auton. Agents Multi-Agent Syst. 31, 1377–1402. https://doi.org/10.1007/s10458-017-9365-9.
Lieder, M., Asif, F.M.A., Rashid, A., Mihelič, A., Kotnik, S., 2018. A conjoint analysis of circular economy value propositions for consumers: using "washing machines in Stockholm" as a case study. J. Clean. Prod. 172, 264–273. https://doi.org/10.1016/j.jclepro.2017.10.147.
Lieder, M., Asif, F.M.A., Rashid, A., Mihelič, A., Kotnik, S., 2017b. Towards circular economy implementation in manufacturing systems using a multi-method simulation approach to link design and business strategy. Int. J. Adv. Manuf. Technol. 93, 1953–1970. https://doi.org/10.1007/s00170-017-0610-9.
Lüdeke-Freund, F., Gold, S., Bocken, N.M.P., 2019. A review and typology of circular economy business model patterns. J. Ind. Ecol. 23, 36–61. https://doi.org/10.1111/jiec.12763.
Manski, C.F., 1977. The structure of random utility models. Theory Decis. 8, 229–254. https://doi.org/10.1007/BF00133443.
Mansuy, J., Verlinde, S., Macharis, C., 2020. Understanding preferences for EEE collection services: a choice-based conjoint analysis. Resour. Conserv. Recycl. 161, 104899 https://doi.org/10.1016/j.resconrec.2020.104899.
Mathur, N., Last, N., Morris, K.C., 2023. A process model representation of the end-of-life phase of a product in a circular economy to identify standards needs. Front. Manuf. Technol. 3 https://doi.org/10.3389/fmtec.2023.988073.
McFadden, D., 1986. The choice theory approach to market research. Mark. Sci. 5, 275–297. https://doi.org/10.1287/mksc.5.4.275.
McFadden, D., 1974. The measurement of urban travel demand. J. Public Econ. 3, 303–328. https://doi.org/10.1016/0047-2727(74)90003-6.
Mela, C.F., Roos, J., Deng, Y., 2013. Invited paper —a keyword history of marketing science. Mark. Sci. 32, 8–18. https://doi.org/10.1287/mksc.1120.0764.
Meng, X., Wen, Z., Qian, Y., 2018. Multi-agent based simulation for household solid waste recycling behavior. Resour. Conserv. Recycl. 128, 535–545. https://doi.org/10.1016/j.resconrec.2016.09.033.
Michelini, G., Moraes, R.N., Cunha, R.N., Costa, J.M.H., Ometto, A.R., 2017. From linear to circular economy: PSS conducting the transition. Procedia CIRP 64, 2–6. https://doi.org/10.1016/j.procir.2017.03.012.
Micolier, A., Loubet, P., Taillandier, F., Sonnemann, G., 2019. To what extent can agent-based modelling enhance a life cycle assessment? Answers based on a literature review. J. Clean. Prod. 239, 118123 https://doi.org/10.1016/j.jclepro.2019.118123.
Mohamed, A.A., Leemis, L.M., Ravindran, A., 1992. Optimization techniques for system reliability: a review. Reliab. Eng. Syst. Saf. 35, 137–146. https://doi.org/10.1016/0951-8320(92)90033-H.
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.
Niazi, M., Hussain, A., 2011. Agent-based computing from multi-agent systems to agent-based models: a visual survey. Scientometrics 89, 479–499. https://doi.org/10.1007/s11192-011-0468-9.
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.
Onat, N.C., Noori, M., Kucukvar, M., Zhao, Y., Tatari, O., Chester, M., 2017. Exploring the suitability of electric vehicles in the United States. Energy 121, 631–642. https://doi.org/10.1016/j.energy.2017.01.035.
Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H., 2019. Measuring the circular economy - a multiple correspondence analysis of 63 metrics. J. Clean. Prod. 210, 200–216. https://doi.org/10.1016/j.jclepro.2018.10.357.
Pérez-Belis, V., Braulio-Gonzalo, M., Juan, P., Bovea, M.D., 2017. Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment. A Spanish case study. J. Clean. Prod. 158, 261–275. https://doi.org/10.1016/j.jclepro.2017.04.143.
Pianosi, F., Beven, K., Freer, J., Hall, J.W., Rougier, J., Stephenson, D.B., Wagener, T., 2016. Sensitivity analysis of environmental models: a systematic review with practical workflow. Environ. Model. Softw. 79, 214–232. https://doi.org/10.1016/j.envsoft.2016.02.008.
Planing, P., 2018. Towards a circular economy - how business model innovation will help to make the shift. Int. J. Bus. Glob. 20, 71. https://doi.org/10.1504/IJBG.2018.10009522.
Polizzi di Sorrentino, E., Woelbert, E., Sala, S., 2016. Consumers and their behavior: state of the art in behavioral science supporting use phase modeling in LCA and ecodesign. Int. J. Life Cycle Assess. 21, 237–251. https://doi.org/10.1007/s11367-015-1016-2.
Puschmann, T., Alt, R., 2016. Sharing economy. Bus. Inf. Syst. Eng. 58, 93–99. https://doi.org/10.1007/s12599-015-0420-2.
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.
Rai, V., Henry, A.D., 2016. Agent-based modelling of consumer energy choices. Nat. Clim. Change 6, 556–562. https://doi.org/10.1038/nclimate2967.
Raihanian Mashhadi, A., Behdad, S., 2018. Environmental impact assessment of the heterogeneity in consumers' usage behavior: an agent-based modeling approach. J. Ind. Ecol. 22, 706–719. https://doi.org/10.1111/jiec.12622.
Raimbault, J., Broere, J., Somveille, M., Serna, J.M., Strombom, E., Moore, C., Zhu, B., Sugar, L., 2020. A spatial agent based model for simulating and optimizing networked eco-industrial systems. Resour. Conserv. Recycl. 155, 104538 https://doi.org/10.1016/j.resconrec.2019.104538.
Ramanath, A.M., Gilbert, N., 2004. The Design of Participatory Agent-Based Social Simulations, 7. J. Artif. Soc. Soc. Simul.
Rand, W., Stummer, C., 2021. Agent-based modeling of new product market diffusion: an overview of strengths and criticisms. Ann. Oper. Res. 305, 425–447. https://doi.org/10.1007/s10479-021-03944-1.
Razaque, A., Rizvi, S., khan, M.J., Almiani, M., Rahayfeh, A.A., 2022. State-of-art review of information diffusion models and their impact on social network vulnerabilities. J. King Saud Univ. - Comput. Inf. Sci. 34, 1275–1294. https://doi.org/10.1016/j.jksuci.2019.08.008.
Roberts, J.H., Lattin, J.M., 1997. Consideration: review of research and prospects for future insights. J. Mark. Res. 34, 406–410.
Roberts, J.H., Lattin, J.M., 1991. Development and testing of a model of consideration set composition. J. Mark. Res. 28, 429–440.
Sabbaghi, M., Esmaeilian, B., Raihanian Mashhadi, A., Behdad, S., Cade, W., 2015. An investigation of used electronics return flows: a data-driven approach to capture and predict consumers storage and utilization behavior. Waste Manag. 36, 305–315. https://doi.org/10.1016/j.wasman.2014.11.024.
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.
Salecker, J., Sciaini, M., Meyer, K.M., Wiegand, K., 2019. The NLRX R package: a next-generation framework for reproducible NetLogo model analyses. Methods Ecol. Evol. 10, 1854–1863. https://doi.org/10.1111/2041-210X.13286.
Salvador, R., Barros, M.V., Freire, F., Halog, A., Piekarski, C.M., De Francisco, A.C., 2021. Circular economy strategies on business modelling: identifying the greatest influences. J. Clean. Prod. 299, 126918 https://doi.org/10.1016/j.jclepro.2021.126918.
Siebers, P.O., Macal, C.M., Garnett, J., Buxton, D., Pidd, M., 2010. Discrete-event simulation is dead, long live agent-based simulation! J. Simul. 4, 204–210. https://doi.org/10.1057/jos.2010.14.
Simon, H.A., 2000. Bounded rationality in social science: today and tomorrow. Mind Soc 1, 25–39. https://doi.org/10.1007/BF02512227.
Stahel, W.R., Clift, R., 2016. Stocks and flows in the performance economy. In: Clift, R., Druckman, A. (Eds.), Taking Stock of Industrial Ecology. Springer International Publishing, Cham, pp. 137–158. https://doi.org/10.1007/978-3-319-20571-7_7.
Sutherland, J.W., Skerlos, S.J., Haapala, K.R., Cooper, D., Zhao, F., Huang, A., 2020. Industrial sustainability: reviewing the past and envisioning the future. J. Manuf. Sci. Eng. 142, 110806 https://doi.org/10.1115/1.4047620.
Tong, X., Yu, H., Han, L., Liu, T., Dong, L., Zisopoulos, F., Steuer, B., de Jong, M., 2023. Exploring business models for carbon emission reduction via post-consumer recycling infrastructures in Beijing: an agent-based modelling approach. Resour. Conserv. Recycl. 188, 106666 https://doi.org/10.1016/j.resconrec.2022.106666.
Tukker, A., 2004. Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. Bus. Strategy Environ. 13, 246–260. https://doi.org/10.1002/bse.414.
Tukker, A., Tischner, Ursula, 2006. Product-services as a research field: past, present and future. Reflections from a decade of research. J. Clean. Prod. 14, 1552–1556. https://doi.org/10.1016/j.jclepro.2006.01.022.
Tunn, V.S.C., Van den Hende, E.A., Bocken, N.M.P., Schoormans, J.P.L., 2021. Consumer adoption of access-based product-service systems: the influence of duration of use and type of product. Bus. Strategy Environ. 30, 2796–2813. https://doi.org/10.1002/bse.2894.
Umeda, Y., Nonomura, A., Tomiyama, T., 2000. Study on life-cycle design for the post mass production paradigm. Artif. Intell. Eng. Des. Anal. Manuf. 14, 149–161. https://doi.org/10.1017/S0890060400142040.
Van der Laan, A.Z., Aurisicchio, M., 2019. Archetypical consumer roles in closing the loops of resource flows for fast-moving consumer goods. J. Clean. Prod. 236, 117475 https://doi.org/10.1016/j.jclepro.2019.06.306.
Van Loon, P., Diener, D., Harris, S., 2021. Circular products and business models and environmental impact reductions: current knowledge and knowledge gaps. J. Clean. Prod. 288, 125627 https://doi.org/10.1016/j.jclepro.2020.125627.
Van Weelden, E., Mugge, R., Bakker, C., 2016. Paving the way towards circular consumption: exploring consumer acceptance of refurbished mobile phones in the Dutch market. J. Clean. Prod. 113, 743–754. https://doi.org/10.1016/j.jclepro.2015.11.065.

Vasconcelos, A.S., Martinez, L.M., Correia, G.H.A., Guimarães, D.C., Farias, T.L., 2017. Environmental and financial impacts of adopting alternative vehicle technologies and relocation strategies in station-based one-way carsharing: an application in the city of Lisbon, Portugal. Transp. Res. Part Transp. Environ. 57, 350–362. https://doi.org/10.1016/j.trd.2017.08.019.
Wakolbinger, L.M., Stummer, C., Günther, M., 2013. Market introduction and diffusion of new products: recent developments in agent-based modeling. Int. J. Innov. Technol. Manag. 10, 1340015 https://doi.org/10.1142/S0219877013400154.
Wallner, T.S., Magnier, L., Mugge, R., 2022. Do consumers mind contamination by previous users? A choice-based conjoint analysis to explore strategies that improve consumers' choice for refurbished products. Resour. Conserv. Recycl. 177, 105998 https://doi.org/10.1016/j.resconrec.2021.105998.
Walzberg, J., Burton, R., Zhao, F., Frost, K., Muller, S., Carpenter, A., Heath, G., 2022. An investigation of hard-disk drive circularity accounting for socio-technical dynamics and data uncertainty. Resour. Conserv. Recycl. 178, 106102 https://doi.org/10.1016/j.resconrec.2021.106102.
Walzberg, J., Carpenter, A., Heath, G.A., 2021a. Role of the social factors in success of solar photovoltaic reuse and recycle programmes. Nat. Energy 6, 913–924. https://doi.org/10.1038/s41560-021-00888-5.
Walzberg, J., Lonca, G., Hanes, R.J., Eberle, A.L., Carpenter, A., Heath, G.A., 2021b. Do we need a new sustainability assessment method for the circular economy? A critical literature review. Front. Sustain. 1, 620047 https://doi.org/10.3389/frsus.2020.620047.
Watts, D.J., 1999. Networks, dynamics, and the small-world phenomenon. Am. J. Sociol. 105, 493–527. https://doi.org/10.1086/210318.
Weibull, W., 1951. A statistical distribution function of wide applicability. J. Appl. Mech. 18, 293–297. https://doi.org/10.1115/1.4010337.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life. Cycle. Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.
Wilensky, U., 1999. NetLogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. http://ccl.northwestern.edu/netlogo/.
Wilson, T.D., 1997. Information behaviour: an interdisciplinary perspective. Inf. Process. Manag. 33, 551–572. https://doi.org/10.1016/S0306-4573(97)00028-9.
Yamamoto, H., Murakami, S., 2021. Product obsolescence and its relationship with product lifetime: an empirical case study of consumer appliances in Japan. Resour. Conserv. Recycl. 174, 105798 https://doi.org/10.1016/j.resconrec.2021.105798.
Yuriev, A., Dahmen, M., Paillé, P., Boiral, O., Guillaumie, L., 2020. Pro-environmental behaviors through the lens of the theory of planned behavior: a scoping review. Resour. Conserv. Recycl. 155, 104660 https://doi.org/10.1016/j.resconrec.2019.104660.
Zamagni, A., Guinée, J., Heijungs, R., Masoni, P., Raggi, A., 2012. Lights and shadows in consequential LCA. Int. J. Life Cycle Assess. 17, 904–918. https://doi.org/10.1007/s11367-012-0423-x.
Zhang, H., Vorobeychik, Y., 2019. Empirically grounded agent-based models of innovation diffusion: a critical review. Artif. Intell. Rev. 52, 707–741. https://doi.org/10.1007/s10462-017-9577-z.