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RESEARCH ARTICLE

Beyond Recycling: Uncovering The Sustainability – Safety Paradox in Circular Healthcare Systems

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Abstract

Health crises expose the fragility of healthcare systems and the environmental burden of disposable medical waste. This study couples Circular Economy (CE) principles with System Dynamics (SD) modeling to evaluate reuse, sterilization, and recycling of N95 masks in the Brazilian healthcare system. Simulations reveal an unexpected sustainability–safety paradox: while reuse and sterilization deliver the largest reductions in waste, emissions, and costs, recycling alone yields only marginal environmental benefits despite its economic appeal. More circular configurations not only lower resource dependency but also enhance resilience, mitigating personal protective equipment (PPE) scarcity during crises. By integrating real health system data (DATASUS) into a dynamic model using the Vensim® software, we identify systemic leverage points for designing durable PPE and shaping policies that balance safety and sustainability. Our analysis spans all three pillars of sustainability (environmental, social, and economic) providing a holistic assessment of PPE circular strategies. This work demonstrates how SD–CE integration can inform evidence-based strategies to build more sustainable and resilient healthcare systems capable of facing future public health emergencies. Even though the analysis was focused on the case of N95 masks, the framework employed in this work can be generalized for many other cases in the healthcare system.

Keywords Sustainable Healthcare · Healthcare Resilience · System Dynamics Modeling · Healthcare Policy Management

1. Introduction

Sustaining essential healthcare functions during prolonged crises has proven far more complex than traditional models anticipated, exposing profound structural weaknesses in health systems (WHO, 2020). Health system resilience is defined as the ability to absorb, adapt, and transform when faced with a shock while maintaining core functions and structures (WHO, 2016). Understanding such resilience requires exploring adaptive capacity, that is, the ability to plan, respond to, and recover from unforeseen disruptions while maintaining operational management (Ponomarov & Holcomb, 2009). Scenario planning and

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simulation have emerged as valuable tools to navigate this complexity (Rockström et al., 2023), since adaptive capacity represents a critical success factor for healthcare systems (Biddle et al., 2020).

In parallel, Circular Economy (CE) principles have been recognized as promising pathways to minimize waste and optimize resources in healthcare (Kane et al., 2018). Because these circular strategies unfold across interdependent clinical, logistical, and regulatory processes, CE in healthcare is inherently systemic (Vederhus et al., 2025). System Dynamics (SD) complements CE by modeling the interconnected behaviors of complex systems, enhancing the understanding of healthcare system dynamics (Homer & Hirsch, 2006a; Meadows, 2008). Together, CE and SD can identify leverage points to increase efficiency and resilience during disruptions.

Previous literature shows that CE has been applied mainly in manufacturing and agriculture, with emerging frameworks exploring transitions through SD-based approaches (Guzzo et al., 2022). In electronics, SD has been used to model circular strategies involving manufacturers and consumers (Alamerew & Brissaud, 2020; Guzzo et al., 2021). Regional case studies, such as in China, have demonstrated how SD supports CE development strategies by linking population growth to resource policies (Gao et al., 2020). Despite these insights, healthcare applications remain fragmented, with CE and SD still studied largely in isolation when addressing medical supply chains (Iacovidou et al., 2021). Even where SD has been applied to healthcare circularity (Zeinalnezhad et al., 2025), analyses remain primarily qualitative and have not progressed to full simulation capable of dynamically testing CE policy alternatives.

Recent crises intensified the environmental burden of disposable PPE, particularly masks and respirators, revealing both their criticality and the challenge of safe reuse (Battegazzore et al., 2020; Prata et al., 2020). Conventional recycling methods have proven limited due to contamination risks (Rubio-Romero et al., 2020), and while hygienic recovery or sterile recycling of medical products has been suggested (Kane et al., 2018), the scalability of decontamination strategies remains uncertain (Liao et al., 2020; Rowan & Moral, 2021; Sarumathi et al., 2020). Barriers to CE in healthcare also include economic constraints, regulatory hurdles, and safety concerns regarding reused equipment (Gaustad et al., 2018; Kazancoglu et al., 2021). Recent evidence specific to PPE reinforces these challenges. Sterilization can degrade polymer integrity and restrict the number of safe reuse cycles (Hossain et al., 2025). Reprocessing may also dominate the environmental footprint of reusable masks and depends strongly on energy demand and the number of achieved cycles (Webb et al., 2025). Even alternative materials such as PLA can perform worse than single-use polypropylene respirators in several impact categories (Klose & Fröhling, 2025).

Designing effective circular strategies for PPE requires reliable system-level data to estimate waste volumes and evaluate interventions. In Brazil, the public healthcare system is supported by DATASUS, a nationwide administrative database that has already been used to analyze pandemic dynamics and hospital activity at scale (see (Maia et al., 2021; Moreira, 2020; Veiga et al., 2020). This combination of a large integrated health system and national-level administrative data makes Brazil a particularly suitable setting for simulating PPE circularity scenarios. At the same time, empirical studies show that healthcare waste management in Brazil is still dominated by incineration, with low recycling rates and uneven segregation quality (Felipe Fernandes et al., 2024; A. T. R. de Sousa et al., 2024a). This mix of scale, data availability, and structural constraints renders the Brazilian case an emblematic context for examining how circular strategies for PPE might perform under realistic policy and infrastructure conditions.

Building on this context, N95 respirators constitute an exemplary case for studying circularity in healthcare because they combine high consumption, safety-critical performance, multimaterial construction, contamination risk, and complex reprocessing requirements. Recent studies show that reusable respirators or masks only outperform single-use alternatives under strict operational conditions (Webb et al., 2025), that material degradation imposes limits on the number of safe reuse cycles (Hossain et al., 2025), and those regulatory constraints restrict reprocessing or require certified pre-treatment (Ganesh et al., 2025; Vederhus et al., 2025).

Accordingly, this study addresses the following research question: *How can modeling and simulation using health system data support the development of circular economy–based health transition policies?* To answer this, we combine CE principles with SD modeling to simulate reuse, sterilization, and recycling of N95 masks in the Brazilian healthcare system. By revealing a sustainability and safety paradox, in which reuse and sterilization outperform recycling in reducing waste, emissions, and costs, the model highlights how circular strategies can generate multidimensional impacts that extend beyond this specific product category. In doing so, the simulation uncovers system-level mechanisms that can inform the design of more resilient and resource-efficient pathways for PPE and other critical medical supplies.

This paper is organized as follows: Section 2 reviews the state of circularity in healthcare and consolidates technical and operational evidence for PPE circular strategies. Section 3 details the System Dynamics model construction, from problem articulation and the dynamic hypothesis of three sub-models (mask middle-of-life, end-of-life, and materials recycling), alongside data sources and parameterization with DATASUS, calibration, and the design of five policy scenarios. Section 4 reports simulation results across environmental, social, and economic indicators. Finally, section 5 synthesizes implications by articulating the sustainability–safety paradox, offering policy recommendations for resilience, and outlining limitations and directions for future research.

2. Literature Review

2.1. Circularity in Healthcare Systems

Recent literature indicates that the circular economy in healthcare remains at an early stage, with progress unfolding unevenly across countries, institutions and product categories. Studies from diverse settings describe emerging initiatives that lack consolidation, such as the nascent CE agenda identified in India (Dixit & Dutta, 2024) and the fragmented CE adoption reported for medical devices and clinical equipment in European contexts (Horn et al., 2025; Hoveling et al., 2024; Mayer et al., 2025). Similar patterns appear across the Global South, where regulatory arrangements remain heterogeneous, as observed in Latin America (Felipe Fernandes et al., 2024), and where basic capacities for segregation and decontamination continue to shape what is feasible in practice, as highlighted in African hospital settings (Apevienyeku et al., 2025). Even in countries with more established infrastructures, structural gaps persist, including limited data on the composition of hospital waste in Australia (Harris & McCabe, 2024) and a predominance of studies centered on isolated product flows, such as medical packaging (Cho et al., 2024), pharmaceuticals (Klasen et al., 2025) and respirators (Klose & Fröhling, 2025). Taken together, these contributions portray a field in which circularity emerges in localized, material-specific ways, without yet forming an integrated set of principles capable of guiding systemic change.

Within this emerging landscape, circularity is operationalized predominantly through waste-oriented interventions rather than through the reconfiguration of healthcare processes. Most studies concentrate on improving segregation, treatment or end-of-life routing, whether by refining local routines for managing clinical waste (Apevienyeku et al., 2025; A. T. R. de Sousa et al., 2024a), evaluating alternative technologies for disinfection or conversion (Ganesh et al., 2025; Harris & McCabe, 2024; Nematollahi et al., 2024) or modeling reverse-logistics arrangements for recyclable materials (Singh et al., 2025). Analyses targeting specific products or technologies likewise tend to propose isolated interventions that optimize the fate of materials or devices while leaving broader organizational structures unchanged, as seen in studies on packaging, single-use clinical items and medical devices (Apevienyeku et al., 2025; Cho et al., 2024; Horn et al., 2025; Mayer et al., 2025). Collectively, this body of work situates circularity primarily at the downstream end of healthcare operations, with limited engagement with how environmental strategies intersect with economic and social considerations.

The predominance of localized and end-of-life interventions is reflected in the analytical frameworks adopted across the field, where environmental, economic and social dimensions are seldom examined in an integrated manner. Existing studies tend to combine only two pillars, most often linking environmental impacts with cost considerations, as seen in comparisons of reusable and single-use devices (Webb et al., 2025), evaluations of waste-treatment technologies (Harris & McCabe, 2024; Klose & Fröhling, 2025) and models of reverse-logistics arrangements for recyclable materials (Singh et al., 2025). Other contributions incorporate regulatory or organizational aspects without developing a unified view of trade-offs, whether focusing on technological and legal constraints in circular solutions for healthcare plastics (Ganesh et al., 2025), organizational conditions that shape adoption (Dixit, 2024), or performance indicators for supply-chain transitions (Alfina et al., 2025). Even detailed environmental assessments of pharmaceutical flows or waste-treatment scenarios do not integrate economic and social implications within a single analytical structure (Klasen et al., 2025; Nematollahi et al., 2024). Across these strands, social dimensions tend to appear as operational considerations rather than as an explicit pillar of sustainability, underscoring how early-stage and infrastructure-dependent conditions continue to limit the development of more holistic frameworks.

The feasibility of circular practices in healthcare consistently reflects the technological and regulatory conditions that surround waste treatment, material recovery and product reprocessing. Studies repeatedly show that options such as sterilization, chemical or thermal treatment, and recycling depend on access to appropriate equipment, qualified operators and regulatory clearance for their use, and that these conditions vary markedly across health systems (Ganesh et al., 2025; Harris & McCabe, 2024). At the same time, the potential to adopt circular strategies for multimaterial products or medical packaging is shaped by the availability of segregation capacity, the technical suitability of decontamination methods and the presence of external recycling pathways, all of which constrain the viability of such practices in routine clinical settings (Hossain et al., 2025; Klose & Fröhling, 2025; Kumar & Chopra, 2022). These dependencies illustrate how circularity in healthcare remains closely tied to local infrastructural realities rather than to abstract assessments of environmental performance. As a result, environmental improvements often coexist with safety constraints, operational risks or regulatory limitations, underscoring the need for analytical approaches capable of capturing the environmental–safety tensions that shape circular strategies in practice.

2.2. Technical and Operational Evidence for PPE Circularity

Circular strategies for personal protective equipment require targeted examination because PPE combines high consumption with strict performance and safety requirements. Evidence shows that the functional integrity of filtering materials can deteriorate under repeated handling and decontamination, with sterilization altering physical and chemical properties in ways that restrict the number of safe reuse cycles (Hossain et al., 2025). Environmental assessments further indicate that reusable masks only outperform single-use alternatives when a minimum number of effective reuses is achieved, since reprocessing carries substantial energy demand (Webb et al., 2025). For multimaterial respirators, design adaptations introduced to support reuse, including additional layers and dedicated packaging, may increase overall material inputs and, in some cases, generate higher impacts than well-designed single-use options (Klose & Fröhling, 2025). These characteristics place PPE at the edge of circular feasibility, where potential environmental gains must be balanced against strict operational and performance constraints.

Across recent studies, reuse, sterilization and recycling emerge as distinct pathways governed by different technical and infrastructural conditions. For reuse, material degradation after a limited number of cycles and the energy intensity of reprocessing set clear functional and environmental thresholds (Hossain et al., 2025; Webb et al., 2025). Sterilization constitutes a separate process because decontamination technologies differ markedly in emissions and energy profiles, and because some methods are incompatible with plastics that require preservation of mechanical properties for downstream recycling (Apevienyeku et al., 2025; Harris & McCabe, 2024; Nematollahi et al., 2024). Emerging alternatives such as microwave-based disinfection illustrate how changes in technology can open different end-of-life routes (Ganesh et al., 2025). Recycling, in turn, remains limited by contamination risks, multimaterial construction and the availability of specialized segregation and treatment infrastructure. Empirical evidence shows that hazardous waste is routed predominantly to incineration, with low recycling rates even for non-hazardous fractions (Cho et al., 2024; Hossain et al., 2025; Singh et al., 2025; A. C. Sousa et al., 2021), and that effective recovery depends on consistent classification, reliable separation of clean streams and access to external recycling pathways (Sousa et al., 2024; Cho, 2024; Hossain et al., 2025; Singh, 2025).

Appendix 1 summarizes the empirical findings that inform the parameter ranges adopted for reuse cycles, sterilization capacity and energy demand, and recycling feasibility, consolidating the constraints and performance drivers identified across these studies.

We argue that reuse, sterilization and recycling represent fundamentally different forms of circularity, each shaped by its own technical limits and infrastructural dependencies. Reuse requires modeling a capped number of safe cycles and distinguishing between nominal and effective reprocessing. Sterilization must be represented as a separate process whose energy requirements, capacity constraints and compatibility with material recovery influence both environmental outcomes and mask availability. Recycling contributes meaningfully only under conditions of reliable segregation and specialized downstream processing, making it a complementary and infrastructure-dependent pathway with more modest system-level effects. These characteristics justify modeling the three strategies as interacting subsystems that influence demand, waste generation and emissions through different mechanisms, providing the empirical basis for the parameter ranges and scenarios explored in the simulation.

System Dynamics is well suited to this study because PPE circularity depends on interactions among demand, sterilization capacity, material degradation and waste flows that evolve over time. These dynamic feedbacks cannot be captured through static approaches such as Life Cycle Assessment (LCA) OR Material Flow Analysis (MFA). SD allows us to represent operational bottlenecks, capacity-dependent delays and policy timing in an integrated way. The Brazilian healthcare system provides an appropriate setting for this analysis given its nationwide scale, availability of administrative data and uneven waste-management infrastructure.

3. Model Construction

Our SD modeling process and simulation follow the reference method proposed by Sterman (2000). The modeling process comprised four main steps: (i) Problem Articulation, (ii) Formulation of Dynamic Hypothesis, (iii) Model Testing, and (iv) Policy Design and Evaluation. The scope of our investigation includes evaluating circular strategies applied to face mask use during the COVID-19 pandemic in Brazil.

To strengthen the CE perspective within the classical SD process, we incorporated the structured modeling guide proposed by Guzzo et al. (2022), which is fully grounded in Sterman's methodology. This guide does not constitute a data collection instrument. Rather, it is a structured set of reflective questions used by the modeling team during the model-building stages to ensure that key circular economy dimensions are systematically considered. The guide supports boundary definition, identification of feedback structures, clarification of transition mechanisms, and alignment between circular strategies and system behavior. Appendix 2 presents the application of this structured modeling guide to the present study. The documented responses reflect the analytical reasoning undertaken during model construction and illustrate how circular economy considerations were integrated into each stage of the System Dynamics process.

This research utilizes System Dynamics to create a comprehensive model of mask acquisition, use, and reuse. The model captures key aspects such as mask inventory, usage rates, and disposal/reuse dynamics through interconnected stocks and flows. Using Vensim software Version PLE Plus 9.3.2, we constructed a visually intuitive diagram of the system and ran simulations to explore the impact of various variables, including mask purchase, distribution, use, and disposal, as well as the circular strategies applicable in this context—reuse, sterilization, and recycling.

3.1. Problem Articulation

Managing N95 masks under sustained health-system pressure reveals a dynamic problem in which demand, safety requirements and waste-management constraints interact. Studies show that disposable PPE contributes substantially to clinical waste and that end-of-life practices remain dominated by incineration, with limited segregation or recycling capacity in many settings (Felipe Fernandes et al., 2024; A. C. Sousa et al., 2021). At the same time, mask materials degrade under repeated handling and sterilization, restricting the number of safe reuse cycles (Hossain et al., 2025), and reusable systems only outperform single-use alternatives when sufficient reprocessing cycles are achieved because sterilization carries significant energy demand (Webb et al., 2025). For multimaterial respirators, design adaptations introduced to support reuse can increase material inputs and, in some cases, lead to higher impacts than well-designed single-use options (Klose & Fröhling, 2025).

These findings indicate that PPE circularity is shaped by the joint evolution of reuse limits, sterilization throughput, material degradation and waste-treatment pathways. These interdependencies influence waste generation, emissions, procurement needs and mask availability over time, making it necessary to represent how these stocks, flows and constraints interact as reuse, sterilization and recycling are combined in practice.

3.2. Formulation of Dynamic Hypothesis

The patterns described previously suggest that PPE circularity in healthcare emerges from the interaction of three coupled structures: the stock of masks available for use, the capacity to reprocess them through sterilization and reuse, and the pathways that govern end-of-life treatment. Demand fluctuations, material degradation and heterogeneous waste-management conditions determine how quickly masks move between these structures and how reuse, sterilization and recycling interact in practice (Hossain et al., 2025; A. T. R. de Sousa et al., 2024b; Webb et al., 2025).

Within this configuration, reuse lowers the demand for new masks but increases pressure on sterilization capacity, where throughput limits and energy needs create delays and potential performance losses (Harris & McCabe, 2024; Nematollahi et al., 2024). Recycling contributes only when clean fractions can be reliably segregated and routed to external processing, a condition that is often constrained by contamination risks and infrastructural gaps (Cho et al., 2024; Singh et al., 2025). These mechanisms create reinforcing and balancing feedbacks that shape mask availability, waste generation and environmental impact over time.

The dynamic hypothesis advanced here is that the coevolution of these three structures, (i.e. mask stocks, reprocessing capacity and end-of-life routes) drives the system's behavior. Variations in demand, sterilization throughput, reuse limits and segregation capacity generate the observed tensions between availability, safety and environmental performance. The model therefore represents these interacting feedbacks to examine how different combinations of reuse, sterilization and recycling influence system-level outcomes under realistic healthcare conditions.

The model focuses on the endogenous relations linking mask availability, reuse cycles, sterilization capacity and end-of-life routing. These structures capture the internal feedbacks that drive the coevolution of demand, material degradation, reprocessing constraints and waste-treatment outcomes within healthcare facilities. Several external dynamics were deliberately excluded because they operate at system layers beyond hospital decision-making and do not modify the feedback mechanisms represented in the model. These include upstream manufacturing capacity, global supply disruptions, regulatory shocks and macro-level logistics constraints. Their omission keeps the model at the operational scale appropriate for analyzing how circular strategies perform under realistic healthcare conditions. These boundaries are reported in Appendix 2.

3.3. Model structure

3.3.1. The circular PPE use model The first block illustrates the health system's linear use of PPE, with two arrows indicating circular alternatives: reuse and sterilization. Sterilization is not widely accepted as a circular strategy, though it can be argued that it enables reuse. However, in this research, we distinguish between reuse and sterilization. Reuse is defined as the new cycle of use that requires no processing, whereas sterilization involves processing and using technologies to neutralize biological contamination. It is important to note that after PPE decontamination, the equipment must be redistributed to users, resulting in a longer and more complex reuse cycle, which requires specific resources and processes.

The second block addresses the conventional PPE end-of-life, with the most common options for discarded PPE: incineration, landfilling, and irregular disposal. Each of these end-of-life alternatives depends on the local context and public policies. Incineration, for instance, is common in regulated environments and is a popular method for treating healthcare waste. Waste treatment strategies may vary significantly across regions, using different levels of technology and methods to manage emissions. Landfilling may also occur in regulated contexts as the final step after sterilizing shredded waste with a microwave, autoclave, or other equipment. In this case, while contamination is neutralized and volume reduced, the waste is not destroyed but buried. Irregular disposal refers to alternatives that violate regulations, such as illegal dumping on the ground without technical considerations.

Finally, the third block focuses on the amount of PPE sent for recycling and the two types of material that allow for recycling. Polymer materials are widely used in most PPEs due to their properties, including light weight, durability, flexibility, and low cost. Aluminum is found in fewer PPE items, such as nasal clips or other small components.

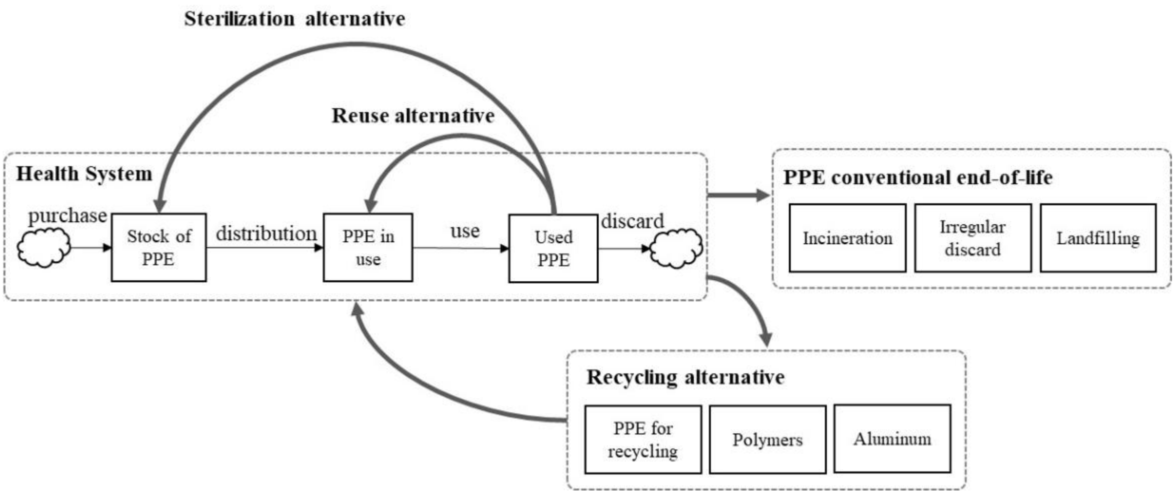

Figure 1. Circular PPE model

Applying the circular PPE model to the N95 mask used by health professionals during the COVID-19 pandemic in Brazil, using the SD method, we obtained the N95 mask circularity model shown in Figure 2. This model examines the circular strategies of reuse, sterilization, and recycling, based on historical data acquired from government platforms and interviews with hospitals. The model consists of three sub-models: (1) Mask middle-of-life, (2) Mask end-of-life, and (3) Mask recycling (Figure 2). The figure also highlights the selected environmental, social, and economic variables, which are central to the development of scenarios.

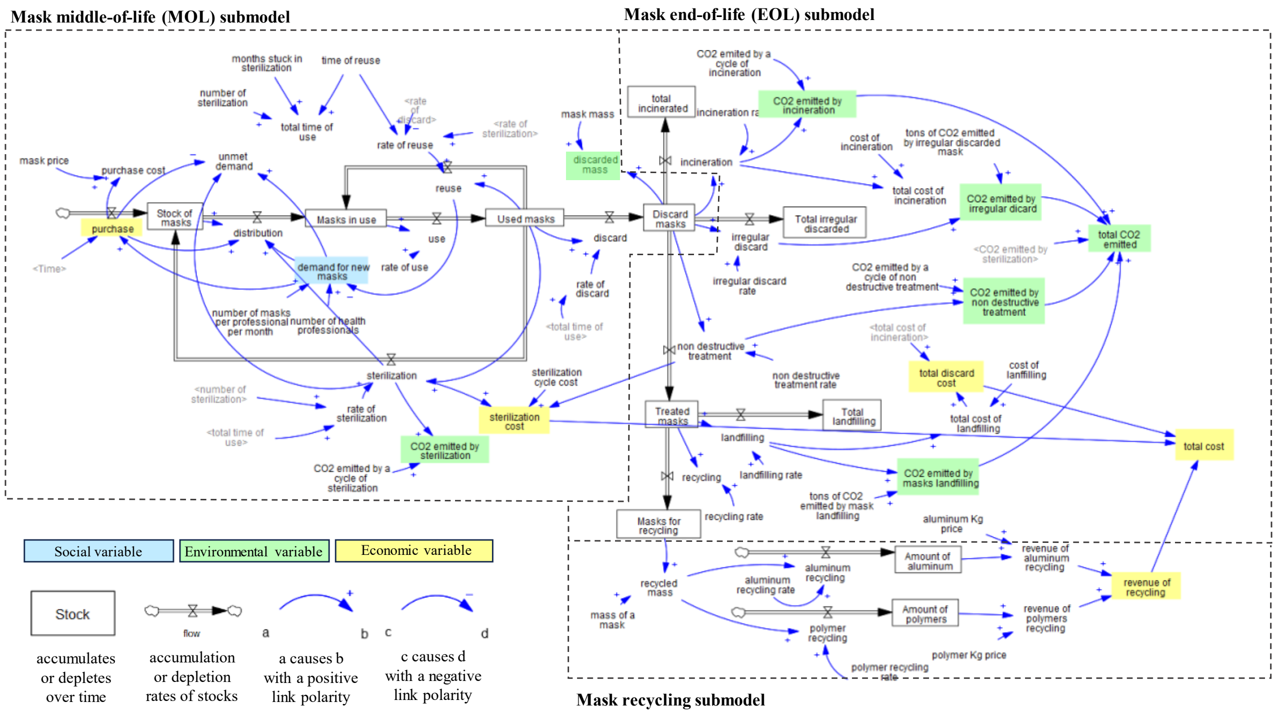

Figure 2. Model composition, with three sub-models

3.3.2. Mask middle-of-life sub-model The "mask middle-of-life" sub-model aims to represent the main steps in face mask use, and its scope begins from the moment masks are procured until they are discarded. This sub-model includes four stocks:

- **Stock of masks:** representing the supply of masks in healthcare facilities
- **Masks in use**: the masks currently being used by healthcare professionals to perform the function they were designed for
- **Used masks**: the masks that have completed the use phase and are stored in the healthcare facility
- **Discarded materials**: the masks that have reached the end-of-life and are stored in appropriate containers.

It is essential to consider the proposed sterilization flow, which returns used masks to the stock of masks for redistribution. This hypothetical flow was largely conceptual during the pandemic and was featured in some studies, unlike reuse, where the same professional uses the mask multiple times. In the sterilization alternative, microbiological contaminants are sufficiently eliminated, restoring the material's aseptic state and allowing for reuse. Several variables are represented in the model, with the economic variables highlighted in yellow: "purchase" and "sterilization cost."

- **Purchase**: controls the inflow for the entire model. The purchase data was retrieved from a dedicated COVID-19 portal provided by the Brazilian Ministry of Health.
- **Sterilization cost**: accounts for the energy costs associated with operating a typical autoclave.

The sub-model also includes an environmental variable highlighted in green:

- **CO2 emissions from sterilization:** calculated based on the emissions associated with energy consumption, considering the Brazilian energy production profile.
- Discarded mass: represents the mass of masks discarded in this sub-model.

Finally, the variable highlighted in blue represents the demand for new masks, which depends on the number of healthcare professionals. This sub-model includes sterilization as a circular strategy that enables the continued use of masks. This alternative falls into the recovery family, as it restores the sanitary safety of the product. It differs from direct reuse, which involves simply using the mask again, by requiring processing to neutralize biological contaminants. The routine sterilization of surgical instruments supports safe, repeated use, making it a well-established circular practice in healthcare. Figure 3 shows the face mask middle-of-life sub-model.

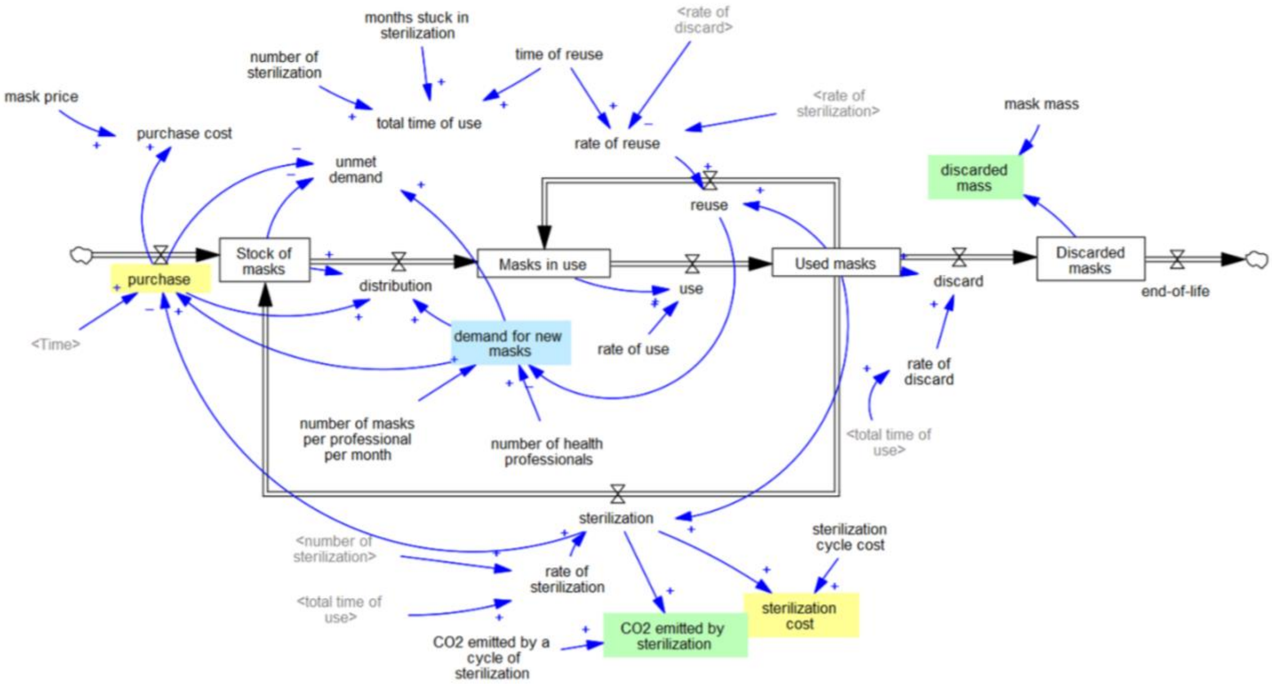

Figure 3. Mask middle-of-life sub-model

3.3.3. Face mask end-of-life sub-model The face mask end-of-life sub-model aims to represent the end-of-life alternatives for discarded masks, represented by four stocks:

- **Total incinerated:** waste treated using furnaces;
- **Total irregular discard**: waste that goes to illegal dumping grounds or burning sites operating in violation of regulations;
- **Total landfilling**: waste that goes to licensed landfills;
- **Masks for recycling**: hypothetical recovery of materials from face masks.

The sub-model is composed of the following key variables:

- **Total CO2 emitted**: the total CO2 emitted from all sources;
- **Total discard cost**: the end-of-life cost, considering the quantities flowing to each alternative.

Figure 4 below shows the face mask end-of-life sub-model.

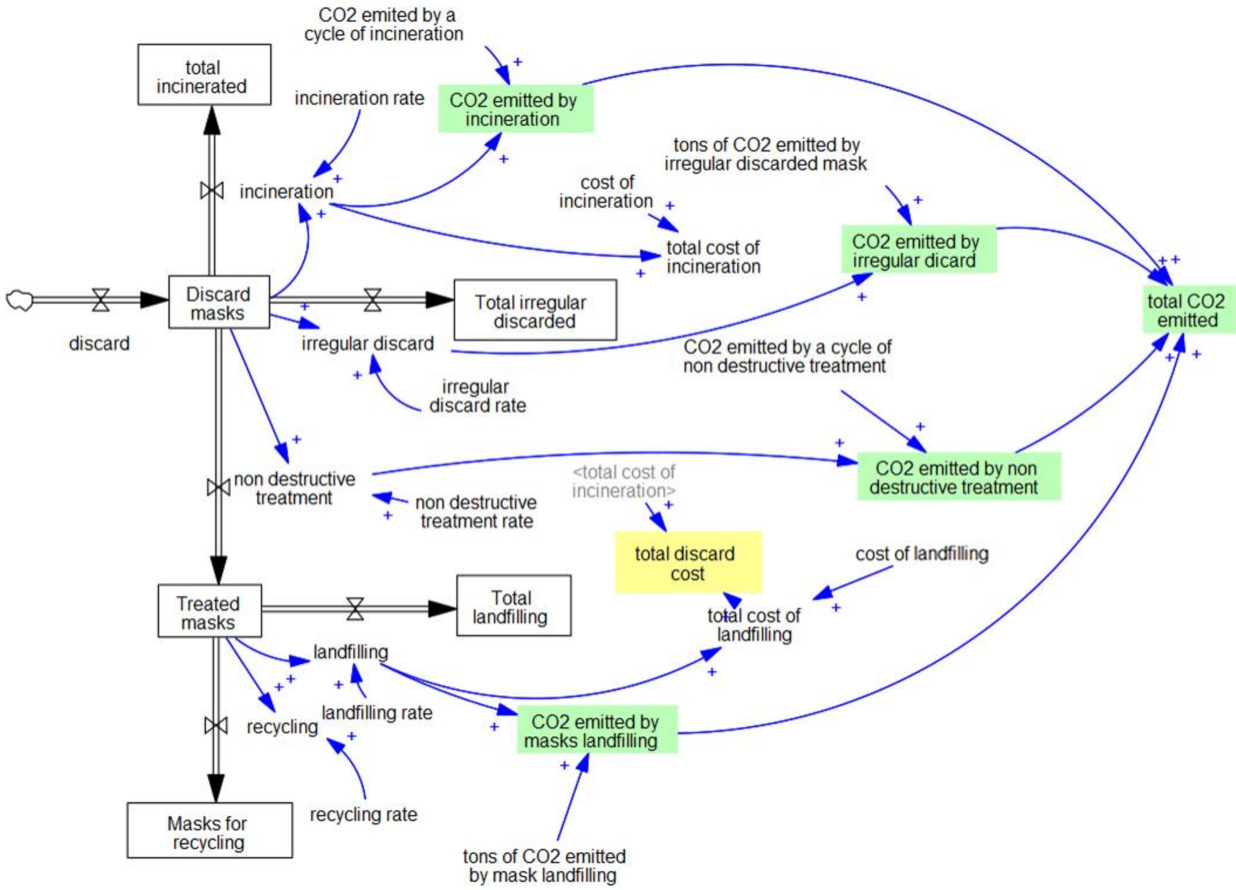

Figure 4. Mask end-of-life sub-model

3.3.4. Mask materials recycling sub-model Although mask recycling was rarely observed in practice globally and was almost never implemented in Brazil, this sub-model aims to explore this alternative by representing the main materials with potential economic value. Therefore, the stocks in this model are the "amount of aluminium" and the "amount of polymers." The key variable in this model is the "revenue from recycling," which indicates the potential to generate income from this strategy. Figure 5 below shows the mask recycling sub-model.

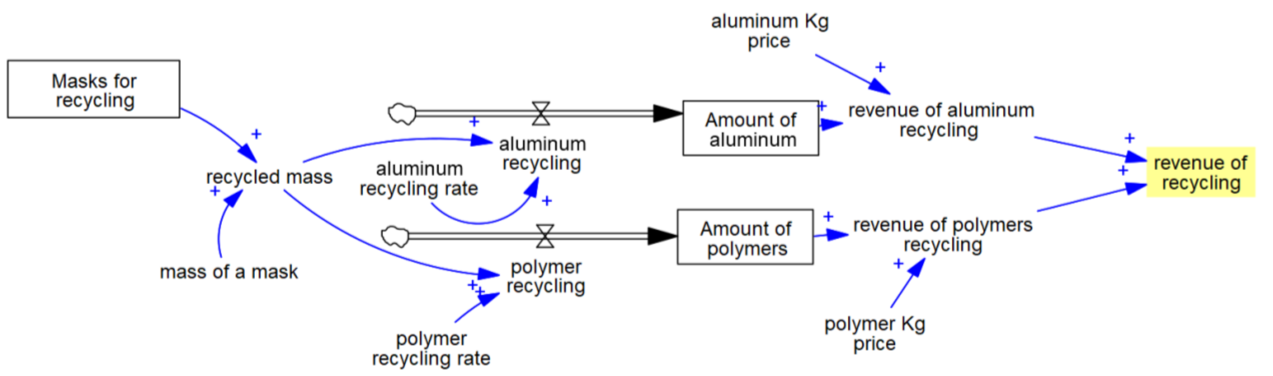

Figure 5. Mask recycling sub-model

3.4. Data sources and parameterization

The model integrates quantitative and qualitative evidence to represent the dynamics of N95 acquisition, use and circulation in the Brazilian health system. Demand flows were constructed using DATASUS, which provides national information on procedures and workforce volume and supports realistic estimates of consumption patterns (Maia et al., 2021; Veiga e Silva et al., 2020). All data used in this study are derived from publicly available sources and are fully anonymized, containing no personally identifiable information. Accordingly, their use does not raise privacy or ethical concerns.

Reuse parameters are in line with studies showing that repeated sterilization alters the physical and chemical properties of filtering materials, limiting the number of cycles that can be achieved safely (Hossain et al., 2025). Environmental assessments indicate that reusable masks only outperform single-use options when a minimum number of reuses is achieved, given the energy intensity of reprocessing (Webb et al., 2025), and that design adaptations intended to support reuse may increase total material inputs (Klose & Fröhling, 2025). These insights support modeling a capped number of cycles and distinguishing between nominal and effective reuse.

Sterilization is modeled as a separate process because decontamination technologies differ in energy demand, throughput and emissions (Harris & McCabe, 2024; Nematollahi et al., 2024), and because some methods are incompatible with plastics requiring mechanical integrity for downstream recycling (Apevienyeku et al., 2025). These characteristics justify treating sterilization as a capacity-limited process with distinct resource requirements.

Recycling parameters reflect the predominance of incineration for hazardous waste and the low recycling rates observed even for non-hazardous fractions (A. T. R. de Sousa et al., 2024b). Evidence indicates that clean fractions can yield substantial benefits when properly segregated (Cho, 2024), although multimaterial construction and the need for prior decontamination often require specialized operators and reverse-logistics arrangements (Hossain et al., 2025; Singh et al., 2025). Recycling is therefore represented as an infrastructure-dependent pathway with modest system-level influence.

Economic parameters incorporate unit mask cost and the operational cost of reprocessing and recycling. Prior work shows that energy and staffing requirements shape the economic performance of reusable systems (Webb et al., 2025) and that recycling depends on specialized operators whose availability constrains feasibility (Singh et al., 2025). Social variables reflect operational and regulatory barriers documented by recent studies, which can translate into shortages or delays in access (Hossain et al., 2025; Vederhus et al., 2025). All assumptions, parameter ranges and data sources are summarized in Appendix 1 to ensure transparency and reproducibility.

In addition to quantitative sources, the model draws on qualitative operational insights obtained through targeted consultations with hospitals belonging to the EBSERH federal teaching-hospital network. This network comprises approximately 45 institutions, of which 30 were contacted during the study. Following recommendations from EBSERH's central administration, five hospitals were selected on the basis of, first, their interest in the project and, second, their ability to provide reliable information on mask-use routines. In each institution, the designated respondent was a senior nursing professional (i.e. the head nurse or the staff member responsible for infection control) who was directly involved in the day-to-day management of PPE.

Although the number of participating hospitals was small, this purposive selection ensured access to detailed, practice-based information from actors with explicit responsibility for operational decisions. This made the qualitative input appropriate for the explanatory role it plays in supporting the construction of system structure within a System Dynamics model.

These consultations followed a short, standardized protocol that explored three core topics: whether the hospital had a formal protocol for mask use; how mask use, reuse and replacement were operationalized in practice; and whether any sterilization initiatives had been attempted during the pandemic. The conversations were conducted by telephone and supplemented by follow-up exchanges via e-mail, with all information recorded in a project logbook and subsequently transcribed for internal documentation. The material was analyzed qualitatively with two purposes: first, to validate the plausibility of the behavioral rules represented in the model by grounding them in real operational routines; and second, to identify numerical values (such as typical replacement intervals or observed reuse frequencies) that could inform the parameterization of the simulation.

The qualitative evidence did not constitute a standalone dataset but contributed directly to the design of the model by contextualizing key assumptions and supporting the interpretation of the quantitative parameters. Qualitative insights informed (i) the definition of behavioral rules embedded in the model, such as replacement practices and the feasibility of reuse and sterilization under routine hospital conditions, and (ii) the selection of plausible parameter values and ranges, including typical replacement intervals and effective reuse frequencies, where context-specific empirical data were unavailable. In this way, qualitative evidence directly supported parameterization choices without constituting an independent qualitative dataset.

3.5. Model Calibration and use

The "circular mask use model" collects data from various sources, with an emphasis on the DATASUS database from the Brazilian Ministry of Health, which provided the number of healthcare professionals and the face mask price. The model was calibrated by adjusting key variables (Table 1) to match real-world data, ensuring the simulations accurately reflected observed behavior. This process involved fine-tuning parameters such as the number of healthcare professionals and mask usage rates, using available data. We emphasize the use of data to determine the expected behavior of variables or as direct input into the model, as in the case of the variable "number of healthcare professionals."

Table 1. Calibrated variables

Variable	Description	Source
Number of health professionals	Number of health professionals working during the pandemic period	DATASUS
Mask price	Average price paid per mask by the government	DATASUS
Sterilization cost	Cost for sterilization, both for reuse and correct disposal. Calculations made using technical data from the Getinge GSS67H13 autoclave model used by van Straten et al., 2021, energy costs per 30 30-minute cycle, considering energy commercial tariff	GSS67H (Steam Sterilizer for Healthcare applications Product Specification) / CPFL[6]
Cost of landfilling	Cost per kg for landfilling waste	São Paulo waste treatment fee[7]
Cost of incineration	Cost per kg for waste incineration	São Paulo waste treatment fee
Polymer Kg price	Cost per kg of recycled polymer	"Sale of Recycled Polyethylene | Purchase and sale of wholesale Recycled Polyethylene | SoloStocks Brasil"
Aluminium Kg price	Cost per kg of recycled aluminium	"Understand why the aluminium chain has the enviable mark of 98% recycling", 2022

[6] https://www.cpfl.com.br/empresas/tarifas
[7] https://www.prefeitura.sp.gov.br/cidade/secretarias/fazenda/servicos/taxaderesiduos/

Table 1 (cont.). Calibrated variables

Variable	Description	Source
Aluminium recycling rate	Percentage of aluminium in a mask to estimate the amount of recycled aluminium	Cornelio et al. (2022)
Polymer recycling rate	Percentage of polymer in a mask to estimate the amount of recycled polymer	Cornelio et al. (2022)
CO_2 emitted by a cycle of incineration	Tons of CO2 emitted per sterilization cycle of a mask	van Straten et al. (2021)
Tons of CO2 emitted by irregularly discarded mask	Tons of CO2 emitted by grounding a mask	Vanapalli et al. (2021)
CO2 emitted by a cycle of sterilization	Tons of CO2 emitted when sterilizing a mask using an autoclave	van Straten et al. (2021)
CO2 emitted by a cycle of non-destructive treatment	Tons of CO2 emitted when sterilizing a mask using an autoclave	van Straten et al. (2021)
Tons of CO2 emitted by mask landfilling	Tons of CO2 emitted by grounding a mask	Vanapalli et al. (2021)
Incineration rate	Percentage of healthcare waste that goes to incineration	ABRELPE 2020, 2021, 2022; ABREMA, 2023
Irregular discard rate	Percentage of healthcare waste that is irregularly discarded	ABRELPE, 2020, 2022; ABREMA, 2023
Non-destructive treatment	Percentage of healthcare waste that undergoes treatment for disposal	ABRELPE, 2020, 2022; ABREMA, 2023

The simulation horizon covers the period from March 2020 to September 2022, corresponding to the first 30 months of the COVID-19 pandemic in Brazil. This timeframe aligns with the period of unprecedented PPE demand, consistent DATASUS reporting, and stable waste management routines. The model reproduces the historical behavior of mask consumption and total costs observed in Brazil during the pandemic. The baseline (S1 – Linear) was calibrated using DATASUS and national waste-treatment data, and the simulated values match the empirical magnitudes and growth patterns. This behavior reproduction test indicates that the model structure is adequate to represent the real-world dynamics of the phenomenon.

3.6. Scenario simulation

Uncertainty was explicitly explored through different structural scenarios rather than through sensitivity tests. These scenarios represent the main sources of variation in reuse limits, sterilization capacity and end-of-life pathways, in line with practice. Therefore, we established five scenarios to analyze how circular strategies influence the mask life cycle within healthcare settings. Each scenario embodies a distinct waste management approach, allowing us to assess its impact on the system. Below is a brief description of each scenario and the rationale for its selection:

- **S1 – Linear:** This scenario represents the business-as-usual (BAU) case, with no application of circular strategies. All masks are used once and discarded. Using this scenario as a baseline allows us to compare it with other scenarios and evaluate the impact of circular economy strategies relative to the conventional linear (take-make-waste) model.
- **S2 – Recycling**: This scenario introduces a recycling strategy, with a 25% recycling rate for treated discarded masks. It aims to show the effect of partial recycling in reducing solid waste and its environmental impact.
- **S3 – Reuse**: In this scenario, each mask is reused by the same professional five times before being discarded, corresponding to a reuse rate of 0.08. It explores how reuse can extend the mask life cycle and reduce waste, aligning with more sustainable practices.
- **S4 – Reuse + sterilization**: This scenario combines reuse with sterilization after five reuses, allowing an additional five reuses. It demonstrates how sterilization can further extend mask use, with a reuse and

sterilization rate of 0.08. This highlights the importance of sanitary conditions for implementing circular strategies.

- **S5 – Circular**: This scenario integrates all three circular strategies, adding recycling to scenario 4. We maintain the reuse and sterilization rates at 0.08 and the recycling rate at 25%. This scenario provides a comprehensive view of the potential impact when all circular strategies are applied simultaneously.

To address parameter uncertainty and assess the structural stability of the proposed circular strategies, we performed a multivariate Monte Carlo sensitivity analysis using Vensim® (200 simulations). The S5 scenario was subjected to simultaneous variation in two key uncertainty drivers: (i) usage intensity, operationalized as the number of masks per professional per month (15–45, uniform distribution), and (ii) sterilization efficiency, operationalized as the number of feasible reprocessing cycles (0–2).

Figure 6 presents the resulting confidence bounds (50%, 75%, 95%, and 100%) for new mask demand, discarded mass, and total cost, compared with the linear baseline (S1). The results indicate that, across the tested parameter space, the circular configuration remains consistently below the linear baseline in terms of waste generation and total cost. The absence of overlap between the upper confidence bounds of S5 and the S1 trajectory suggests that the relative advantages of circular strategies are robust to the tested behavioral and technical uncertainties. This analysis does not exhaust all potential sources of uncertainty but strengthens confidence in the structural behavior of the model.

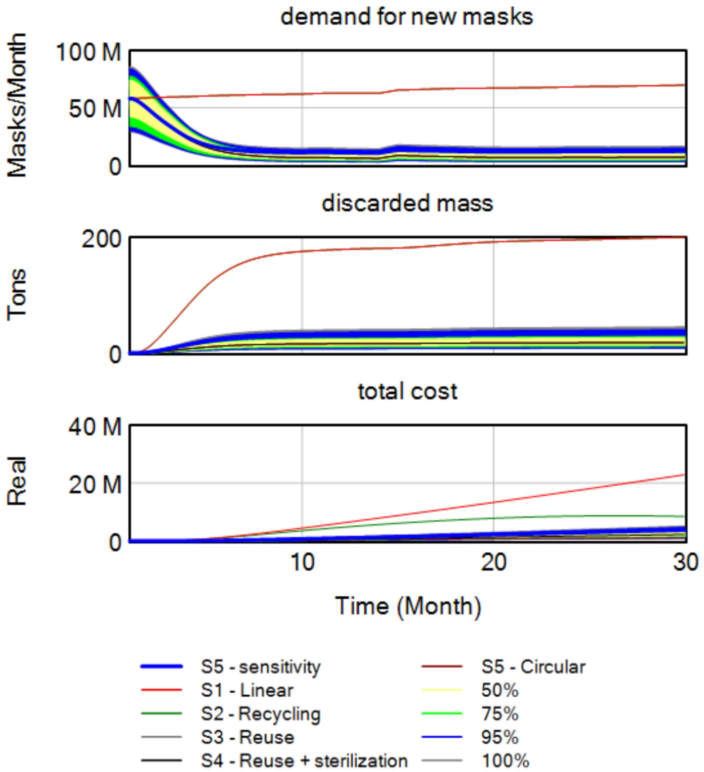

Figure 6. Monte Carlo sensitivity analysis of scenario S5 compared with linear baseline (S1). Multivariate simulation (N = 200) varying mask usage intensity (15–45 masks per professional per month) and sterilization cycles (0–2). Shaded areas represent confidence bounds (50%, 75%, 95%, and 100%) for new mask demand, discarded mass, and total cost. The red line corresponds to the linear baseline scenario (S1).

4. Results

This section examines the simulation results for each scenario to observe how reuse, sterilization, and recycling impact the selected environmental, social, and economic variables. Table 2 presents the selected variables and their accumulated values for each scenario. The values for each variable were generated by the simulations and, therefore, are endogenous to the system.

Table 2. Scenarios and rates

Rate/Scenario	S1	S2	S3	S4	S5
rate of reuse	0	0	0.08	0.08	0.08
rate of sterilization	0	0	0	0.08	0.08
rate of discard	1	1	0.17	0.08	0.08
non-destructive treatment rate	0.25	0.25	0.25	0.25	0.25
recycling rate	0	0.25	0	0	0.25

Table 3. Summary structure of scenarios

Pilar	Variable / Scenario	S1	S2	S3	S4	S5
Environmental	Discarded material(tons)	4717,17	4496,72	788,511	426,774	406,836
	CO2 emitted (tons)	623449	623188	104190	56512,3	56512,3
Social	Total demand for new masks(masks)	1,88E+09	1,88E+09	4,44E+08	3,25E+08	3,25E+08
	Total unmet demand (masks)	-2,35E+07	-2,35E+07	-1,92E+07	-1,69E+07	-1,69E+07
Economic	Total cost (BRL - Brazilian Real)	2,29E+07	1,13E+07	3,83E+06	2,28E+06	1,23E+06
	Total cost (Equivalent in USD - United States Dollar)	4,33E+06	2,13E+06	7,24E+05	4,31E+05	2,32E+05

4.1. The behavior of environmental variables

The environmental variables in Figure 7 reflect the impact of different mask waste management strategies in the healthcare system over 30 months, starting in March 2020. The left chart in Figure 7 shows the amount of material discarded, and the right chart shows the CO2 emissions associated with each simulated scenario.

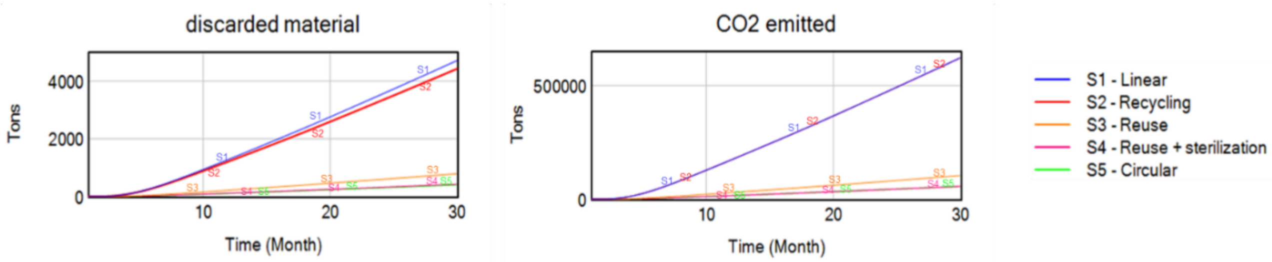

Figure 7. Environmental variables

An analysis of the two charts reveals a noticeable reduction from S1 to S5 in both discarded material and CO2 emissions. Accordingly, Table 3 records an accumulated difference of 4,310.34 tons between the linear and circular scenarios. Notably, the most significant difference between the scenarios occurs after introducing the mask reuse strategy (S3, S4, and S5). Furthermore, the impact decreases even more after combining sterilization with the reuse strategy (S3 and S4). This decrease in environmental variables emphasizes the positive impact of these circular strategies on waste management.

However, adding recycling to the circular scenario (S5) does not result in a significant reduction in environmental impact compared to the reuse and sterilization scenario (S4). This suggests that although recycling is a valuable circular strategy, its effectiveness in reducing waste and emissions may not be as significant as other methods, particularly because of the resources required for recycling. A sensitivity analysis evaluating the influence of each circular strategy revealed that the model's environmental impact, measured by discarded material and CO2 emissions, is more responsive to changes in reuse and sterilization rates than to the recycling rate. This indicates that extending the lifespan of masks through reuse and sterilization has a stronger effect on reducing waste and emissions than recycling alone.

While the results underscore the environmental benefits of circular strategies, it is important to acknowledge that each of the proposed interventions (recycling, reuse, and sterilization) presents significant implementation challenges. Recycling, although potentially easier to implement with existing technologies like shredding and air classification, may not achieve the desired magnitude of impact reduction. Conversely, reuse and sterilization, while more effective in minimizing waste and emissions, may require product design adaptations. For instance, incorporating antimicrobial agents like nanosilver (Assis et al., 2021) into masks could enable safer reuse. Additionally, sterilization processes, especially at scale, may require infrastructure investments and technological advancements to optimize efficacy and mitigate potential negative impacts on mask filtration performance.

The results demonstrate how the prolonged use of masks and their materials has the potential to significantly minimize waste and carbon emissions associated with the large volumes consumed in health systems. Thus, these results confirm the association between circular strategies and environmental impact reduction, while also highlighting the need for a nuanced understanding of the relative effectiveness of different circular approaches when designing healthcare policies.

4.2. The behavior of social variables

Social variables are critical in analyzing the impacts of circular strategies on the healthcare system. Figure 8 shows the demand for new masks and unmet demand in each scenario, demonstrating how different combinations of circular strategies affect mask availability. First, the chart on the left of Figure 8 shows a substantial reduction in the demand for new masks after the mask reuse strategy is introduced in S3, S4, and S5. Furthermore, the introduction of sterilization complements this approach by enabling increased reuse, resulting in a slight reduction in demand for new masks. Considering that un-met demand reflects the peak demand during the COVID-19 pandemic, which caused the Brazilian healthcare system to fail to provide enough masks to healthcare professionals. As such, the most circular scenarios were better able to withstand the shock with less unmet demand. In other words, in this model, greater circularity led to a more consistent supply of masks, or greater resilience.

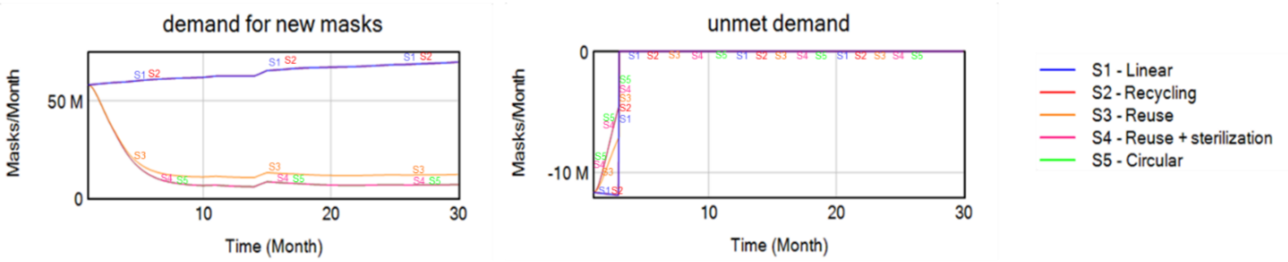

Figure 8. Social variables

The implications of a reliable supply of masks, driven by reduced demand for new masks, are significant. A reduced mask demand lessens the strain on supply chains, decreases shortage risks, and increases opportunities for cost savings. Prior research on ventilator repair has highlighted the potential of circular strategies to effectively address shock demands within healthcare systems (Cobra et al., 2023). The advantages of circular strategies for workers translate into improved protection by mitigating shortages, promoting safety and well-being, and reducing the risk of disease transmission. These benefits rely on the assumption that circularity-enhanced masks function within desirable parameters, and that behavioral aspects of reuse and sterilization also play a key role in determining success.

4.3. The behavior of economic variables

Analyzing economic variables provides deeper insights into the financial aspects of waste management strategies. Figure 9 presents a chart showing the total cost in each scenario. The "total cost" variable is calculated by adding the total purchase, discard, and sterilization costs and subtracting the recycling revenue. As a result, the graph in Figure 9 shows the linear scenario with the highest cost and the circular scenario with the lowest cost, despite the costs associated with sterilization. A brief exploration of the scenario costs reveals that S1 presents the costs of acquiring the masks, plus treating and disposing of the waste. S2 considers the same costs as S1, subtracting the revenue from recycling a quarter of the masks. S3 has minimized mask purchase costs due to direct reuse and proportional treatment and disposal costs. S4 incurs the same costs as S3, with further reduced purchase expenditures, as well as waste treatment and disposal costs, and the added cost of operating the sterilization equipment. This still results in a lower total cost than the reuse scenario (S3); S5 is the same as S4, but subtracting the revenue from recycling.

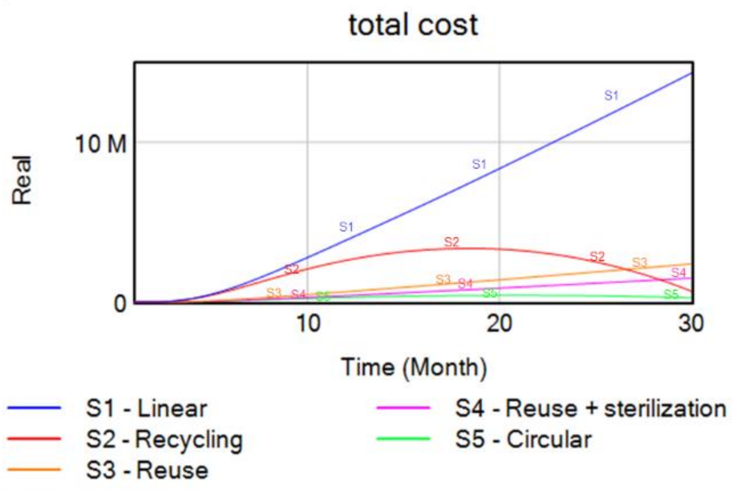

Figure 9. Total cost of the model

The different costs highlight the economic advantage of circular strategies for masks. After estimating the investment costs required to implement circular strategies, decision-makers could calculate the return on investment by considering the disposal and treatment costs avoided and the potential revenues. The sensitivity analysis shows that, once again, the model responds significantly to reuse and its reduced purchase costs. However, this time, the economic advantages of recycling are significant, in contrast to the results for the environmental variables. If these conditions materialize, the budgetary implications for health institutions could foster economic resilience by reducing dependence on external resources. For products optimized for circularity, there would be challenges in transitioning from commodity to technology-enhanced products, which require development investments but offer economic benefits in the long term

5. Discussion

5.1. Triple Bottom Line tensions in circular strategies of PPE provision

The simulation results indicate that environmental, social, and economic outcomes associated with reuse, sterilization, and recycling do not evolve uniformly within PPE provision systems. Instead, each strategy redistributes pressures across the three dimensions, generating structured tensions shaped by material limits, operational capacity, safety requirements, and cost structures. Analyzing these interactions by pillar clarifies how circular configurations produce conditional gains rather than simultaneous improvements across the Triple Bottom Line.

Environmental performance differs across reuse, sterilization, and recycling because each strategy modifies the balance between material throughput and processing requirements within the PPE system. As synthesized in Table 4, established environmental findings, including material degradation, reprocessing energy demand, and recovery limitations associated with multimaterial products, condition the performance of circular strategies. The simulation further indicates that meaningful reductions in waste and emissions require sufficient reuse cycles and energy-efficient processing. Environmental gains therefore depend on system configuration and operational scale rather than arising automatically from circular interventions.

Table 4. Environmental dimension across circular PPE strategies

CE Strategy	Established knowledge on reuse	Tensions revealed by this study
Reuse	Sterilization can alter polymer properties and affect mask integrity, limiting the number of safe reuse cycles (Hossain et al., 2025). Environmental performance is influenced by the number of achieved cycles and by reprocessing energy demand (Webb et al., 2025).	Environmental gains are sensitive to achievable reuse thresholds. When effective cycles remain limited, reductions in discarded material and emissions are proportionally constrained.
Sterilization	Sterilization, as a reprocessing stage, can dominate the environmental footprint of reusable masks, particularly under high energy intensity (Webb et al., 2025).	Net environmental performance depends on sustained energy efficiency and operational scale. Benefits materialize when avoided production and disposal impacts exceed reprocessing burdens at system-level.
Recycling	Recycling of PPE is constrained by multimaterial composition, contamination risk, and low separation efficiency, limiting effective material recovery (Rubio-Romero et al., 2020; Souza, 2024; Singh, 2025).	System-level simulation indicates comparatively modest reductions in emissions and waste volumes under realistic infrastructure conditions, suggesting limited environmental leverage from end-of-life strategies alone.

The social dimension is operationalized in this study as the health system's capacity to ensure adequate mask availability under pandemic conditions. Within healthcare settings, insufficient PPE supply can compromise protection protocols, increase exposure risk, and force extended or unsafe reuse practices, as observed during the COVID-19 crisis. For this reason, total demand and demand satisfaction are not treated as mere logistical inputs, but as proxies for the system's ability to maintain protective standards and avoid exposure-related adverse outcomes. Within the defined operational boundaries of this simulation, broader social impacts, such as community-level effects of waste management or labor conditions in recycling chains, are acknowledged but considered outside the acute crisis-focused scope of the model. As synthesized in Table 5, prior studies emphasize safety constraints and regulatory requirements surrounding reuse and sterilization. The simulation clarifies how circular strategies influence mask availability and unmet demand, thereby affecting the system's capacity to sustain infection control under stress conditions.

Table 5. Social dimension across circular PPE strategies

CE Strategy	Established knowledge on reuse	Tensions revealed by this study
Reuse	Sterilization and repeated use can affect material integrity and protective performance, requiring validated safety limits (Hossain et al., 2025). Regulatory frameworks impose conditions on reprocessing and quality assurance (Ganesh et al., 2025; Vederhus et al., 2025).	Reuse can increase short-term mask availability under supply stress. However, when sterilization capacity is limited, unmet demand rises, constraining the system's ability to maintain consistent protection standards.
Sterilization	Effective sterilization is necessary to ensure safety compliance and restore functional performance under regulated conditions (Hossain et al., 2025; Vederhus et al., 2025).	Sterilization capacity operates as a critical bottleneck in crisis scenarios. When capacity does not scale with demand, protection gaps emerge despite circular configurations.
Recycling	Recycling initiatives in healthcare are shaped by regulatory validation, traceability, and quality assurance requirements (Ganesh et al., 2025; Vederhus et al., 2025).	Recycling has limited immediate influence on mask availability or infection control capacity, as it operates primarily at end-of-life rather than during active clinical use.

Economic performance across circular PPE strategies reflects the interaction between procurement costs, reprocessing expenses, and waste management structures. While circular interventions are often associated with cost reduction potential, their economic implications depend on operational scale, infrastructure requirements, and avoided disposal costs. As synthesized in Table 6, prior studies highlight the role of reprocessing costs, energy inputs, and market conditions in shaping financial feasibility. The simulation clarifies how these cost components interact dynamically, showing that economic gains emerge under specific system configurations rather than uniformly across strategies.

Table 6. Economic dimension across circular PPE strategies

CE Strategy	Established knowledge on reuse	Tensions revealed by this study
Reuse	Cost savings depend on achieving sufficient reuse cycles to offset procurement and reprocessing expenses. Energy and operational costs influence overall feasibility (Webb et al., 2025).	Economic benefits materialize when reuse cycles are high enough to dilute acquisition costs. Under limited cycle conditions, cost reductions remain marginal.
Sterilization	Sterilization requires investment in equipment, energy, and operational capacity, affecting financial viability (Webb et al., 2025; Vederhus et al., 2025).	Sterilization reduces total system costs when integrated with reuse and operated at sufficient scale. As a standalone strategy, its cost-effectiveness is sensitive to utilization rates and energy intensity.
Recycling	Recycling can reduce disposal costs and recover partial material value, though subject to infrastructure and market conditions (Ganesh et al., 2025; Vederhus et al., 2025).	Recycling improves cost performance primarily through avoided disposal expenditures. However, its economic contribution remains structurally separated from procurement and infection-control dynamics.

5.2. Safety versus sustainability paradox

Our study indicates that the more circular the configuration of the health system, the lower the total cost when the mask middle-of-life and end-of-life stages are considered. This creates an implementation gap, since the configurations with the strongest environmental and economic performance are not necessarily the ones most readily deployable in routine healthcare operations. The proposed sustainability–safety paradox refers to a structural tension in which the circular pathways with the strongest system-level sustainability and cost performance are also the most constrained by safety assurance and operational feasibility requirements. In the PPE context, reuse combined with sterilization is a prominent example of this pattern, because its benefits depend on validated safety thresholds and sufficient processing capacity. This interpretation is consistent with evidence on material performance limits under reuse and sterilization (Hossain et al., 2025). It also reflects the footprint relevance of reprocessing energy demand and the dependence on effective cycles (Webb et al., 2025). In addition, it aligns with the governance and compliance constraints that shape circular feasibility in healthcare settings (Vederhus et al., 2025).

Beyond technical uncertainty, the adoption of circular PPE configurations is shaped by legislative and regulatory regimes in which infection control, compliance, and risk mitigation are dominant decision criteria (Hossain et al., 2025; Vederhus et al., 2025). Regulatory frameworks in the medical device domain tend to prioritize patient safety over environmental considerations, which can complicate the adoption of circular economy practices (Hossain et al., 2025). In hospital settings, circular practices such as converting single-use devices to reusable options must also be balanced against ethical and legal concerns and the risk of cross-infections (Vederhus et al., 2025). Under these conditions, requirements for safety validation, traceability, quality assurance, and liability allocation can narrow the admissible set of reuse, sterilization, and recovery pathways, shifting implementation from technical potential to organizational capability and compliance capacity (Hossain et al., 2025; Vederhus et al., 2025). At the waste and reprocessing interface, the classification of contaminated healthcare plastics and the need for validated decontamination can restrict sorting and downstream recovery, since meeting explicit sterilization requirements can be necessary to reduce infection-risk uncertainty and enable handling and routing to recycling operators (Ganesh et al., 2025). In the logic of our model, these governance constraints translate into operational limits through safe reuse thresholds and sterilization throughput, shifting system performance through tighter capacity ceilings and higher monitoring requirements.

Another fundamental aspect of our result is that, since circularity may confer greater resilience to health systems by reducing dependence on continuous inflows of new PPE, scarcity mitigation becomes a relevant intermediate mechanism linking circular strategies to crisis response. Within the model boundary, lower scarcity supports adherence to protection protocols by reducing pressure for extended or improvised reuse under peak demand. This motivates a hypothesis for future investigation: if reduced PPE scarcity contributes to stronger infection control performance during crises, circular configurations could indirectly influence epidemiological severity and mortality. Testing this proposition requires coupling circularity models with epidemiological dynamics and explicitly accounting for potential rebound effects and risk compensation mechanisms (Castro et al., 2022).

On the social side, the implications of establishing circular PPE solutions vary depending on the vulnerability of the community and the maturity of local infrastructures and compliance routines. In the short term, circular PPE is better suited for well-developed health infrastructures with lower vulnerability levels, due to the availability of skilled personnel and equipment for sterilization and controlled recovery pathways. Introducing circular PPE in vulnerable communities could lead to significant rebound effects. Since circular PPE solutions require substantial upfront investments, they could make vulnerable communities dependent on external aid, hindering the development of self-sustaining initiatives. Even more durable PPE could be prematurely discarded in vulnerable communities that lack the proper means to maintain these products or face educational and cultural barriers. For these disadvantaged communities, the available options are longer-term approaches: (a) implementing circularity in phases, with strong parallel educational and infrastructural programs; (b) focusing on properly managing standard PPE waste before introducing experimental solutions; (c) enforcing extended producer responsibility, which is already part of some regulatory frameworks.

5.3. Theoretical contributions

Building on the synthesis of established knowledge and the tensions identified across the environmental, social, and economic pillars (Tables 4–6), this study positions its theoretical contribution in three connected literature streams.

First, the circular economy in healthcare has been described as an early-stage and fragmented field, where circularity is often operationalized through localized and downstream interventions rather than through system-level reconfiguration (Horn et al., 2025; Hoveling et al., 2024; Mayer et al., 2025). While prior work recognizes that circular strategies in healthcare are inherently systemic, their analysis frequently remains separated from dynamic assessments of operational constraints and feedback effects (Iacovidou et al., 2021; Zeinalnezhad et al., 2025). By modeling reuse, sterilization, and recycling as interacting stock-and-flow structures, grounded in the System Dynamics tradition of representing complex public systems (Homer & Hirsch, 2006b; Sterman, 2000), this study conceptualizes circularity as a dynamic system property. The results show that circular performance is contingent on configuration and scale, since the same circular strategy can generate different outcomes depending on demand variability, processing capacity, and end-of-life routing. This shifts the analytical focus from isolated interventions to the conditions under which circular configurations become feasible and effective in healthcare settings.

Second, the study advances theorizing on the sustainability and safety paradox by locating it in system-level interdependencies that connect technical limits, risk governance, and infrastructure alignment. The PPE circularity literature highlights material degradation and capped reuse cycles (Hossain et al., 2025), the energy intensity and potential dominance of reprocessing in environmental footprints (van Straten et al., 2021; Webb et al., 2025), and the contamination and separation constraints that restrict effective recycling in healthcare waste streams (Rubio-Romero et al., 2020; Singh et al., 2025). In parallel, regulatory and operational requirements shape what is considered permissible in reuse, sterilization, and recycling pathways (Ganesh et al., 2025; Vederhus et al., 2025). The contribution of this study is to demonstrate, using the tensions summarized in Tables 4–6, that these constraints do not act independently. They interact through capacity bottlenecks and timing effects, so that strategies with stronger environmental and economic potential, such as reuse coupled with sterilization, are also more exposed to safety validation requirements and throughput limitations. Conversely, recycling remains comparatively decoupled from middle-of-life dynamics and therefore provides limited environmental leverage under realistic infrastructural conditions.

Third, the findings contribute to resilience theory by clarifying how circular configurations can operate as structural determinants of adaptive capacity in healthcare supply systems. Resilience in health systems is commonly framed as the ability to absorb, adapt, and transform under shock while maintaining core functions (WHO, 2016, 2020), and adaptive capacity has been linked to planning and response capabilities under disruption (Ponomarov & Holcomb, 2009). Scenario-based approaches have been emphasized as a means to navigate such complexity (Rockström et al., 2023). In this context, our Circular PPE model indicates that configurations that reduce dependence on continuous inflows of new PPE can mitigate scarcity under shock conditions by stabilizing availability through resource recirculation and capacity management. This reframes resilience as an emergent property of how circular strategies are organized and constrained within operational systems, rather than as an objective that is analytically separate from circularity.

5.4. Practical and policy contributions and recommendations

This study provides actionable guidance for healthcare managers and policymakers seeking to operationalize circular PPE strategies. The simulations indicate that reuse and sterilization generate stronger system-level benefits than recycling under realistic infrastructure conditions. Accordingly, priority should be given to expanding validated reuse practices and strengthening sterilization capacity, particularly under conditions of supply stress. The identification of leverage points such as sterilization throughput, safe reuse thresholds, and segregation quality offers concrete parameters to inform hospital protocols, procurement strategies, and workforce planning.

Regulatory frameworks play a central role in enabling circular transitions. Clear standards regarding safety validation, liability, traceability, and quality assurance are necessary to reduce institutional resistance and support adoption of reusable and reprocessed PPE. In addition, procurement policies can serve as strategic instruments to stimulate demand for circular solutions while safeguarding performance requirements. Aligning regulatory clarity with procurement incentives can lower uncertainty and accelerate diffusion of safe circular practices.

From a system perspective, circular configurations can reduce dependence on continuous inflows of new PPE, thereby mitigating vulnerability to supply disruptions. Translating this potential into practice requires coordinated investment in processing infrastructure, training, and monitoring mechanisms. Rather than pursuing isolated technological substitutions, policy efforts should address both technical capabilities and institutional arrangements that govern adoption and oversight.

Finally, experimentation remains essential. Pilot programs and phased implementation strategies allow health systems to test circular interventions under controlled conditions while monitoring safety and environmental performance. Such approaches enable learning without compromising protection standards and create a structured pathway for scaling circular PPE strategies where contextually appropriate.

Although the structural dynamics represented in the model are broadly applicable, the quantitative magnitudes reported in this study are influenced by calibration choices that reflect the Brazilian healthcare system. The model incorporates national administrative demand and price inputs (DATASUS), an incineration-dominated waste-treatment baseline with low recycling rates and uneven segregation quality, and an emissions factor for sterilization based on the Brazilian energy production profile. Selected cost parameters for waste treatment are also operationalized using available local fee structures.

At the same time, the direction of the main mechanisms is expected to remain relevant in other institutional settings, since the model structure represents general feedbacks among demand variability, reuse limits, sterilization throughput constraints, and end-of-life routing. However, the relative leverage of reuse, sterilization, and recycling is likely to shift with differences in three conditions: the baseline waste-treatment mix and segregation performance; the availability and efficiency of sterilization infrastructure; and the carbon intensity of the energy system that supplies reprocessing. Transferability also depends on the permissibility of reuse and reprocessing pathways under local safety validation, liability, and quality assurance requirements, since governance constraints may limit adoption even when infrastructure is available. These conditions define the parameters and boundary assumptions that should be re-estimated when applying the model logic to other healthcare systems.

Finally, experimentation remains essential for operationalizing circular PPE strategies under context-specific constraints. In the Brazilian case, scalability may be facilitated by regulatory refinements that reduce ambiguity at the interface between environmental objectives and sanitary requirements, clarifying authorized circular pathways such as validated sterilization and safe material recovery while maintaining clinical safety and economic feasibility. More generally, the generalizability of the practical recommendations depends on the alignment between environmental and healthcare safety regimes, as well as on the regulatory and organizational maturity of each national context. Pilot programs and phased implementation strategies allow health systems to test circular interventions under controlled conditions while monitoring safety and environmental performance, enabling learning without compromising protection standards and providing a structured pathway for scaling where appropriate.

6. Conclusions

This study examined how circular economy strategies for personal protective equipment perform when modeled dynamically within a national healthcare system. By integrating demand variability, processing capacity, material degradation, and waste management structures, the analysis shows that circular configurations generate conditional and asymmetric outcomes across environmental, social, and economic dimensions. Rather than producing uniform improvements, reuse, sterilization, and recycling redistribute pressures within the system, giving rise to structured tensions shaped by safety requirements, infrastructure capacity, and cost structures.

The findings indicate that strategies centered on reuse and sterilization can deliver stronger system-level benefits than end-of-life recycling under realistic operating conditions. At the same time, their performance remains contingent on regulatory validation, energy efficiency, and operational scale. By conceptualizing circularity as a dynamic system property and linking it to adaptive capacity under supply stress, the study contributes to ongoing debates on the implementation of circular economy principles in critical public systems.

This study is subject to several limitations that define the scope of its conclusions. First, the analysis reflects the Brazilian healthcare context, where circular economy practices in medical waste management remain at an early stage and where incineration continues to dominate treatment pathways. Legislative and regulatory constraints, including safety validation requirements and liability considerations, may limit the speed and scale of circular adoption. Future research should examine how different regulatory environments influence system performance.

Second, the model is calibrated to the COVID-19 emergency period, characterized by heightened PPE demand and supply instability. Changes in usage requirements and infection control protocols following the end of the pandemic may alter demand patterns and reduce the intensity of supply shocks. Future studies should reassess model behavior under post-pandemic conditions and evaluate the robustness of circular strategies across varying epidemiological scenarios.

Third, the social dimension is operationalized as the health system's capacity to meet protective demand under stress conditions. While this captures the relationship between PPE availability and exposure risk within healthcare settings, it does not directly quantify epidemiological outcomes or broader indirect costs. Further research could integrate epidemiological modeling, broader health impact assessment, and detailed capital investment analysis to provide a more comprehensive evaluation of circular transitions.

Finally, extending the model to other medical products and combining dynamic simulation with life cycle assessment could strengthen external validity and enable cross-sector comparison. Such extensions would help clarify the conditions under which circular configurations can be safely and effectively scaled across healthcare systems.

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Data Availability The data supporting the findings of this study are available from the corresponding author upon reasonable request. Part of the data used in the study was obtained from publicly available databases from DATASUS (Departamento de Informática do Sistema Único de Saúde, Brazil). The simulation model and supplementary materials may be shared for academic and research purposes upon request.

Declarations

Competing Interests The authors declare no competing interests.

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Appendix 1 - Parameter Sources

Strategy	Technical parameter	Empirical evidence (quantitative or constrained range)	Implication for model structure	Sources
Reuse	Safe number of reuse cycles	Repeated sterilisation leads to physical and chemical degradation of material, limiting the number of safe reuse cycles	Set a maximum allowable number of cycles; distinguish nominal vs effective cycles	Hossain (2024)
	Environmental breakeven	Reusable masks outperform single-use only when sufficient reuse cycles are achieved; reprocessing can dominate total impact when reuse is low	Model environmental benefit as a function of reuse cycles; include a minimum breakeven threshold	Webb (2025)
	Material burden from reusable designs	PLA-based reusable systems can generate impacts up to four times higher per kg of granulate; reinforced layers and added packaging increase overall material mass	Include material-intensity scenarios and design-driven trade-offs	Klose (2025)
	Operational feasibility	Stakeholders perceive reusable devices as less practical, requiring disassembly and reprocessing; effective cycles are often lower than the technical maximum	Parameterise operationally achievable reuse cycles	Mayer (2025)
Sterilisation	Energy demand of reprocessing	Energy load of reprocessing equipment strongly influences environmental outcomes	Assign explicit energy coefficients to sterilisation processes; allow sensitivity to energy mix	Webb (2025)
	Technology-specific conditions	Autoclaving requires exposure around 140°C for 30–40 min followed by shredding; chemical disinfection exhibits lower GWP than pyrolysis	Treat sterilisation technologies as distinct processes with different parameters	Harris (2024); Nematollahi (2024)
	Compatibility with mechanical recycling	Autoclaving is not practically suitable for plastics destined for mechanical recycling (PP/PE), due to moisture and thermal effects	Link sterilisation method to end-of-life feasibility for recycling	Apevienyeku (2025)
	Alternative disinfection enabling chemical recycling	Microwave-based disinfection + shredding can prepare plastics for pyrolysis, enabling integration with chemical recycling	Include technology-dependent end-of-life routes	Ganesh (2025)
Recycling	Baseline recycling rates	Non-hazardous recycling around 2.4%; hazardous waste predominantly incinerated	Set a low baseline recycling fraction reflecting real-world conditions	Souza (2024)
	Environmental advantage of clean recycling	Recycling plastic packaging reduces impact to 11.8% of hazardous incineration scenario	Include high-segregation scenarios with significantly lower impacts	Cho (2024)
	Multi-material and contamination constraints	Many SUMDs are multi-material, requiring prior decontamination; biological risk increases cost and complexity	Restrict recycling to strictly clean and segregated streams	Hossain (2024)
	Need for specialised operators	Recycling systems depend on third-party reverse logistics providers (3PRLPs) and specialised processing	Model recycling as infrastructure- and network-dependent	Singh (2025)
	Compatibility with decontamination	Mechanical recycling only feasible when streams are properly segregated at source; disinfection route determines recyclability	Couple recycling feasibility to the chosen sterilisation pathway	Apevienyeku (2025); Ganesh (2025)
Others	Packaging as environmental hotspot	Packaging accounts for 19–50% of total FFP2 impacts; intensive care units generate 1.7 kg of packaging per patient per day	Represent packaging explicitly in material mass and impact calculations	Klose (2025); Klasen (2025)
	Alternative waste-treatment performance	Autoclaving + gasification reduces landfill disposal by 95.9%; composting and material recovery reduce smog formation and fossil fuel depletion	Justify multiple end-of-life routes in scenario design	Harris (2024); Nematollahi (2024)

Appendix 2- Questionnaire on the model's alignment with CE transition

SD modeling stage (Sterman 2000)	Questions on SD for CE transition (Guzzo 2022)	Modeling scope in the context of this research
Problem articulation	Q1.1.: How can the modeling effort contribute to a CE transition in that system?	-The model supports Strategies/policies for reuse, sterilization and recycling. -Gives a new spatial/temporal/volumetric perspective of what happened and its impacts on policies. -Provides insights for innovation -Creates artefacts for communication of the complex systems for circular strategies in medical supplies
	Q1.2.: Are the CE system-level of analysis, the transition direction, and the industry clearly stated for the modeling purpose?	Yes, we target a macro system of healthcare with a special focus on PPE supplies.
	Q1.3.: Is the research protocol adequate to investigate a shift in that system?	Yes, some references indicate the possibility of applying circular strategies for face masks(Liao et al., 2020; Parashar & Hait, 2021; Rubio-Romero et al., 2020).
Formulation of dynamic hypothesis	Q2.1.: Are the logic for product demand, resource usage, and circularity comprehensively understood for the system under investigation? Are the relevant life cycle stages considered?	- Demand was estimated using another variable, the number of health professionals. -Resources for the production of masks are proportional to the number of masks purchased and distributed. -Our model focuses on the half-life (MOL) of masks, as it includes the use and reuse of masks, and the end-of-life (EOL), which includes recycling and disposal.
	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?	- Our limits are hospital processes that involve the use and reuse of masks and other stakeholders relevant to this process, such as healthcare professionals, health regulations, and product composition. - Behaviors such as maximum usage time and sterilization cycles are endogenous, while the demand for masks represented by the variable of healthcare professionals is an exogenous behaviour.
Formulation of simulation model	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?	Our time scale is within the pandemic, which contains the event to be studied, unprecedented volumes of face masks, and the increased importance of this resource.
	Q3.2.: Which are stock and flow structures capable of operationalizing the logics of the resources' flows? Could you adapt available SD models and structures?	We had inspiration from general supply models as well as academic studies depicting reuse flows (Cheng et al., 2019; Daniel Guzzo et al., 2021).
	Q3.3.: Are you taking advantage of (and contributing to) the communities of practice? What modeling skills and features you still need to master?	We aimed to contribute to increasing the community that is using SD to tackle the gap in dealing with CE complexity.
Model testing	Q4.1: Can you define a reference mode to calibrate the model? Is it a reliable BAU, linear economy scenario?	We created a linear economy scenario based on historical data, which serves to contrast the other scenarios.
	Q4.2: Can you ensure model fitness to purpose? Which are the contextual, structural, and behavioural validity tests performed?	The behaviour of our model is consistent with behaviours expected in the real world and conforms to basic physical laws.
	Q4.3: Is the model widely available for verification by other modelers/users?	Our model is available on GitHub link

SD modeling stage (Sterman 2000)	Questions on SD for CE transition (Guzzo 2022)	Modeling scope in the context of this research
Policy and design evaluation	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?	See the results and conclusion sections for the insights.