Enhancing Resilience: A Stochastic Mathematical Model for Optimizing Investments in Sustainable Reverse Supply Chains

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Abstract. The objective of this paper is to determine the effective allocation of financial resources in order to make resilient Sustainable Reverse Supply Chains (SRSC) that are subject to random interruptions. To this end, a stochastic optimization model was proposed that considers the resilient capabilities of absorption, adaptation and recovery, and it was applied in a supply chain in the southeast region of Brazil that deals with lead-acid battery waste by reintroducing it to the production cycle or for the business of recovering its value and minimizing environmental impacts. Hence, four scenarios were analyzed with different probabilities of disruptive events occurring so as to allocate investments. We found that the portion of the costs of the reverse supply chain that include post-event costs and penalties resulting from interruptions remains relatively constant between the different scenarios. However, when analyzing pre-disruptive event investments in alternative transport and purchase of waste from other chains, it was observed that restoring the supply of waste was reestablished well before the deadline for all experiments of lesser severity. This demonstrates the relevance of the proposed model in the decision-making process for investments in resilience involving an SRSC.

Keywords: Waste management, Closed-loop Supply Chain, Sustainable, Resilience, Lead-Acid Batteries.

1 Introduction

The growing demand for efficient management of solid waste after the end of its life cycle is driven mainly by society's growing awareness of potential threats to the environment and intense pressure from regulatory authorities. By engaging in sustainable supply chain management (SSCM) practices, for example, reintroducing waste to the production cycle to recover its value partially or completely, companies can distinguish themselves from their competitors due to their corporate reputation and achieve sustainable competitive advantages by demonstrating greater efficiency in using resources, greater social responsibility, and better financial performance [1]. SSCM integrates issues related to the triple bottom line (environmental, financial, and social) in addition to the systemic coordination of the main inter-organizational business processes [2-3].

However, companies often face unwanted and unexpected events that cause interruptions to supply [4]. To deal with the risks from these events, the supply chain (SC) needs to be resilient. SC resilience can be defined as the ability of the supply chain to absorb the effects of disturbances during disruptive events [5]. Organizations increasingly appreciate the relationship between sustainability and resilience and need to understand how to take advantage of emerging opportunities arising from the integration between these two approaches in supply chain management [6]. Balancing the sustainability of the Supply Chain and disruptions in it requires a complex organizational approach and high investment [4].

Therefore, the aim of this paper is to develop a stochastic optimization with a view to determining the effective allocation of financial resources, for the purpose of seeing to it that the management of lead-acid battery waste in a reverse supply chain (RSC) that is subject to random disruptions is resilient.

There is empirical evidence showing that sustainability and resilience influence each other, but research into the intersection between sustainability and supply chain resilience is still incipient [6]. Thus, the proposed model aims to fill a theoretical and practical gap related to managing lead-acid battery waste in RSCs to make them more resilient and sustainable, and places a greater focus on their resilient capabilities of absorption, adaptation and recovery, i.e., so as to analyze the investments that can be made before and/or after disruptive events occur.

2 Literature Review

Studies related to supply chain resilience have been undertaken by several researchers over time. This is due to increased uncertainty due to business being volatile, rapid urbanization, climate change and political instability [7]. In this context, it is clear that there are several studies regarding resilience in the supply chain (SC) that identify factors relevant to SC resilience [8-9], that developed models related to resilience maturity [7], that formulate strategies for resilience in the supply chain [10-12], and that develop models for analyzing resilience and its impacts on SCs [13].

Regarding factors relevant to SC resilience, [8] presented an integrated approach to understanding SC resilience by conducting a comprehensive review of the literature. [9] add that the management of knowledge factor and its progression is also important for resilience. However, it is important to note that the conclusions presented in these studies are part of one perspective among several possible ones, due to the exploratory nature of this field of research.

Additionally, as to maturity models for assessing resilience, [7] proposed a tool to assess the current state of resilience in SCs, with a view to identifying interrelationships between vulnerabilities and capabilities essential for achieving balanced resilience. It is crucial to highlight, however, that the large-scale application of this instrument is necessary to validate the measurement scales, thus expanding the coverage of the resilience scores obtained.

Furthermore, with regard to how best to develop resilient SC strategies [12] presented a model of resilient retail priorities in SCs, aiming at the post-pandemic context. On the other hand, [11] explored the complex configurations and interactions between SC resilience strategies and capabilities. The model emphasizes several configurations using absorptive, reactive, and restorative capabilities, but highlights the need to improve the temporal analysis of strategies and capabilities by taking the post-pandemic period into account.

Finally, with regard to resilience analysis models and their impacts on the SC, [13] presented a hybrid tool called the Failure Mode and Effect Analysis and Supply Chain Resilience (FMEA-SCR) with the aim of quantifying the disruptive impacts caused by the Coronavirus pandemic.

Therefore, despite the undeniable contribution of the studies mentioned above, the papers that deal with the resilience of reverse supply chains and the investments that need to be made in them in order to manage waste from lead-acid batteries do not seem to be well explored. In this sense, the present study responds to the problem, and it is hoped that the findings will be regarded as contributing to the enrichment of the literature on this topic.

3 Formulating the Model

3.1 Setting the Context Definition

A Reverse Supply Chain (RSC) can be defined as a network represented by using graphs. In this graph, the nodes represent the various stages or entities throughout the reverse process. The edges, in turn, represent the paths and waste flows along this network. In Fig. 1, the twelve nodes of this graph represent key points of an RSC in the southeastern region of Brazil for managing the waste from lead-acid batteries.

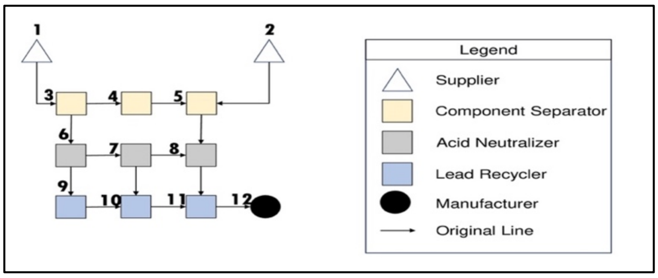

Fig. 1. RSC under analysis

Integrating the analysis of graphs into the management of an RSC can allow organizations to develop more efficient, sustainable, and resilient systems, which are aligned with current demands for environmental and social responsibility. This enables a more comprehensive view of material flows, the identification of opportunities for improvement and the ability to make decisions that are more aligned with the principles of sustainability and corporate social responsibility.

Therefore, this study analyzes the RSC represented in Fig. 1 that could become inoperative due because disruptive events take place.

3.2 Assumptions, Parameters and Variables

To formulate the model used in the RSC analysis, the following assumptions were adopted: the RSC layout is pre-defined; the flow of battery waste is unidirectional; the demands of the facilities are known and constant over time; the maximum capacity of the facilities is known; the disruptive event occurs at time t=0; there is no occurrence of a disruptive event after time t=0; the demand for waste is equal to its supply during normal operating time; technical issues such as speed and type of materials are not considered; the order of repair of the facilities and paths is not considered; the resources of recuperation are different for different types of installation; at the beginning of each period, the resources of recuperation are always available; the paths are considered similar regardless of the geographic region in which they are located.

The notations used in the model are explained in Tables 1-3 respectively.

Table 1. Sets of the optimization model

Set	Description
N	All the nodes of the Supply Chain k and $i \in N$
N_j	Nodes of supplies, $N_j \in N, j \in N_j$
N_n	Nodes of demand $N_n \in N, n \in N_n, m \in N_n$
N_p	Nodes of priority $N_p \in N, p \in N_m$
N_s	Nodes without priority $N_s \in N, s \in N_s$
G	Degrees of severity of the disruptive events $g \in G$
T	Intervals of Time t, t $\in T$
C	Scenarios c, $c \in C$

Table 2. Parameters of the optimization model

Parameter	Description	Range or Unit
θ	Cost of Unit of Additional Capacity	\$
α	Cost of acquiring and installing a backup path	\$/Km
γ	Investments for increasing the rate of recovery in the facility	\$/unit/hour
β	Investments for increasing the rate of recovery of the path	\$/Km/hour
ρ_c	Probability of the disruptive event occurring c	[0,1]
∂	Cost of using waste recovered for facilities	\$/unit/hour
π	Cost of using waste recovered for paths	\$/Km/ hour
ϑ	Cost of alternative transport of wastes	\$/unit
ζ	Purchase cost of wastes	\$/unit
η	Cost of meeting the demand	\$/unit
φ	Penalty of not meeting the demands of the nodes without priority	\$/unit
ϖ_p	Penalty of not meeting the demands of the nodes with priority	\$/unit
ψ	Penalty for passing the stipulated time of recovery	\$/hour
ϱ	Cost of using an input unit at supplier *i*	\$/unit
ς	Cost of using a unit of product in facility *i*	\$/unit
υ	Cost of transporting a unit of input/product between nodes *k* and *i*	\$/Km
ϕ	Cost of using an input unit at supplier *i* at time *t* and in scenario *c*	\$/unit/hour
ι	Cost of using a unit of product in facility *i*	\$/unit/hour

	at time t and in scenario c	
Ω	Cost of transporting a unit of input/output between nodes k and i at time t and in scenario c	\$/Km/hour
cr_{ki}	Maximum amount of waste between nodes k and i	Unit
MW_n	Minimum service level for facility	%
aw_t	Availability of waste to be purchased at time t	Unit
tl_t	Alternative transportation limit at time t	Unit
P_{jc}	Part of facility j that is affected by the disruptive event	[0,1]
tx_cd_g	Facility recovery rate given the occurrence of a disruptive event of severity g	Unit/hour
tx_l_g	Path recovery rate given the occurrence of a disruptive event of severity g	Km/hour
l_g	Maximum recovery rate of the facility given the occurrence of a disruptive event of severity g	Unit/hour
w_g	Maximum route recovery rate given the occurrence of a disruptive event of severity g	Km/hour
ts	Time allowed without a minimum supply level for non-priority facilities	Hour
tp	Time allowed without a minimum supply level for facilities are priority	Hour
tr	Deadline for recovery allowed without incurring additional costs to the supply chain	Hour

Table 3. Variables of the optimization model

Variable	Description	Range or Unit
Ra_j	Additional capacity for facility j	Unit
Ri_{jt}	Initial capacity of facility j at time t	Unit
dl_{ki}	Distance of the path between nodes k and i	Km
Ar_{ki}	Assigned backup path from node k to node i	0 or 1
Scd	Increase in the rate of recovery of the facility	Unit/hour
Sl	Increase in the rate of recovery of the path	Km/hour
scd_{jtc}	Recovery resources used to recover facility j at time t and in scenario c	Unit/hour
sl_{kitc}	Recovery resources used to recover the path between nodes k and i in time t and in scenario c	Km/hour
QA_{jntc}	Quantity of waste transported from facility j, by alternative means of transport, to serve collection point n, in period t and in scenario c	Unit
WA_{ntc}	Quantity of waste purchased from another supply chain to supply collection point n, in period t and in scenario c	Unit
D_{nt}	Waste demand at collection point n, in period t	Unit
da_{ntc}	Demand met at node n, in period t and in scenario c	[0,1]
dn_{stc}	Unmet demand at node n, in period t and in scenario c	[0,1]
Td_{tc}	Damaged route in period t and scenario c	0 or 1
EF_i	CO_2 emission to produce a unit of input at supplier i	gCO2/unit
EM_i	CO_2 emission to produce a unit of product in facility i	gCO2/unit
ET_{ki}	CO_2 emission to transport a unit of input/product between nodes k and i	gCO2/unit
sf_{ki}	Flow of items between nodes k and i	Unit
f_{kic}	Flow of items between nodes k and i in scenario c	Unit
Olt_{kitc}	Route defined between nodes k and i in operation in period t and in scenario c	0 or 1
De_{kic}	Occurrence of a disruptive event between the path of nodes k and i	0 or 1
LT_{ki}	Predefined route between nodes k and i	0 or 1
Tt_{kitc}	Original paths between nodes k and i are in operation	0 or 1

Ort_{jntc}	Route defined between installation j to serve collection point n is in operation	0 or 1
Tr_{kitc}	Backup path between nodes k and i is in operation	0 or 1
Y_{kitc}	Existence of a route between nodes k and i in operation in period t and in scenario c	0 or 1
fr_{kitc}	Amount of waste between nodes k and i in operation in period t and in scenario c	Unit/hour
Q_{ntc}	Quantity of waste received by facility n, in period t and in scenario c	Unit

This is how the optimization model was defined.

3.3 Objective Function

Initially, we define the Objective Function (OF) of the optimization model as presented in Eq.1, which seeks to minimize investments in SC resilience in pre and post disruptive events, as long as to minimize de CO_2 emission on its recovery process.

$$\begin{aligned} Min\, Z = {} & \theta \sum_j Ra_j + \alpha \sum_k \sum_i dl_{ki} Ar_{ki} + \gamma Scd + \beta Sl + \varrho \sum_k \sum_i EF_i sf_{ki} + \varsigma \sum_k \sum_i EM_i sf_{ki} \\ & + \upsilon \sum_k \sum_i ET_{ki} sf_{ki} \\ & + \sum_c \rho_c \left[\partial \sum_j \sum_t scd_{jtc} + \pi \sum_k \sum_i \sum_t sl_{kitc} + \vartheta \sum_k \sum_n \sum_t QA_{jntc} + \zeta \sum_n \sum_t WA_{ntc} \right] \\ & + \sum_c \rho_c \left[\eta \sum_n \sum_t D_{nt} da_{ntc} + \varphi \sum_s \sum_{t>ts} D_{st} dn_{stc} + \sum_p \varpi_p \sum_{t>tp} D_{pt} dn_{ptc} + \psi \sum_{t>tr} Td_{tc} \right] \\ & + \sum_c \rho_c \left[\phi \frac{\sum_k \sum_i EF_i f_{kic}}{t} + \iota \frac{\sum_k \sum_i EM_i f_{kic}}{t} + \Omega \frac{\sum_k \sum_i ET_{ki} f_{kic}}{t} \right] \end{aligned} \tag{1}$$

3.4 Constraints of the Model

Over a set of problem constraints, the OF is applied so that the solutions generated are viable.

$$\sum_j Ar_{jn} < 1 \quad \forall\, n \tag{2}$$

$$\sum_j Ar_{nj} = 0 \quad \forall\, n \tag{3}$$

$$\sum_n Ar_{nm} \leq 1 \quad \forall\, m \tag{4}$$

$$Ar_{ii} = 0 \quad \forall i \tag{5}$$

During the restrictions of Eqs. 2-5, backup alternatives are considered, either by adding new routes or simply by duplicating existing routes.

$$Ar_{ik} = 0\, \forall (i,k) \text{ pre-defined} \tag{6}$$

$$Ar_{ik} + Ar_{ki} \leq 1 \;\; \forall\, k, i \tag{7}$$

$$Ar_{ik} + Ar_{ki} \leq 1 \;\; \forall\, k, i \tag{8}$$

If any project limitation occurs, equations 6-8 only guarantee the creation of backup paths in the presence of conditions favorable to the project. These backup paths must be unidirectional and do not exceed the value of a backup for each facility, and so that they have the same direction as the initial routes, previously defined, respectively.

$$Olt_{kitc} \leq (1 - De_{kic})LT_{ki} + \sum_{t=1}^{t-1} sl_{kitc} \quad \forall\, k, i, t, c \tag{9}$$

$$Olt_{kitc} \leq LT_{ki} \qquad \forall\, k, i, t < T, c \tag{10}$$

$$Olt_{kitc} = LT_{ki} \qquad \forall\, k, i, t < T, c \tag{11}$$

According to Eq. 9, the route is available if no disruptive event occurs and is otherwise unavailable until t=1. Additionally, in Eq.10, before time T of the experiment, predefined routes may or may not work based on the disruptive event occurring. Consequently, in accordance with Eq. 11, the pre-defined routes must be fully operational before the experiment is completed.

$$Tt_{kitc} \leq \; Olt_{kitc} \; \forall\, k, i, t, c \tag{12}$$

$$Tt_{jntc} \leq \; Ort_{jntc} \; \forall\, j, n, t, c \tag{13}$$

$$Tr_{kitc} \leq Ar_{ki} \forall\, k, i, t, c \tag{14}$$

$$Tr_{jntc} \leq \; Ort_{jntc} \; \forall\, j, n, t, c \tag{15}$$

The continuity of the flow of wastes is guaranteed by Eq. 12 if the pre-defined path is available for circulation. Eq. 13 requires the presence of facilities available to receive wastes that leave suppliers. The same logic is used for the flow of wastes on routes, backups and that are additional to the suppliers to ensure the continuity of operations in Eq.14-15, respectively.

$$Tt_{kitc} + Tr_{kitc} \leq 1 \; \forall\, k, i, t, c \tag{16}$$

Eq. 16 guarantees that the flow of wastes may occur along only one path, even if there are redundant or additional paths.

$$Y_{kitc} \;\; \leq Tt_{kitc} + Tr_{kitc} \; \forall\, k, i, t, c \tag{17}$$

Eq. 17 establishes the route between facilities to give continuity to the flow of wastes.

$$fr_{kitc} \leq cr_{ki} \times \; Y_{kitc} \;\; \forall\, k, i, t, c \tag{18}$$

Eq. 18 determines that the waste flow between nodes for periods t are less than or equal to the structural capacity of the path defined between the nodes and even if there is an available path between the nodes.

$$Q_{ntc} \; = \sum_{k} fr_{kntc} - \; \sum_{i} fr_{nitc} \; \forall\, , n, t, c \tag{19}$$

$$D_{nt} \; \times \; da_{ntc} = \; Q_{ntc} \; + \; WA_{ntc} + \sum_{j} QA_{jntc} \quad \forall\, , n, t, c \tag{20}$$

Eq. 19 guarantees the idea of mass preservation. Eq. 20 indicates that the demand determined for the period will be supplied by the amount of waste being transported along pre-defined routes, by waste purchased from another supply chain and by waste on alternative transport to the demand facility.

$$Q_{stc} + WA_{stc} + \sum_{j} QA_{jstc} \geq MW_s D_{st} \quad \forall\, s, t > ts, c \tag{21}$$

$$Q_{ptc} + WA_{ptc} + \sum_{j} QA_{jptc} \geq MW_p D_{pt} \quad \forall\, s, t > tp, c \tag{22}$$

In Eq. 21-22, it can be seen that a minimum service level is established for facilities, whether critical or not, after the disruptive events occurred.

$$\sum_{t=1}^{T} \left[Q_{ntc} + WA_{ntc} + \sum_{j} QA_{jntc} \right] = \sum_{t=1}^{T} D_{nt} \tag{23}$$

When the experiment time ends, the amount of waste supplied to the facility must be equal to its installation, as in Eq. 23.

$$\sum_{t} WA_{ntc} \leq aw_t \; \forall\, t, c \tag{24}$$

$$\sum_{j} \sum_{n} QA_{jntc} \leq tl_t \; \forall\, t, c \tag{25}$$

In Eq. 24-25, we see that the amount of waste purchased from another supply chain, as well as the amount of waste in alternative transport during the period when a disruptive event occurs, is limited.

$$dn_{ntc} + da_{ntc} = 1 \; \forall\, n, t, c \tag{26}$$

The proportion of demand that is not met plus the proportion of demand that is met when the disruptive event occurs must be equal to one according to Eq.26.

$$Rd_{jtc} - Ri_{jtc} \times Ort_{jntc} \geq 0 \;\; \forall\, n, j, t, c \tag{27}$$

After the disruptive event occurs and the supplier returns to work at its supply capacity, which must be greater than or equal to its initial supply capacity guaranteed by Eq. 27.

$$\sum_{n} \left(QA_{jntc} + fr_{jntc} \right) \leq Rd_{jtc} \; \forall\, j, t, c \tag{28}$$

$$Rd_{jtc} = \left(1 - P_{jc}\right)\left(Ri_j + Ra_j \right) + \sum_{t=1}^{t-1} scd_{jtc} \; \forall\, j, t, c \tag{29}$$

Eq. 28 prevents excess supply capacity. Eq. 29 deals with the recovered supplier's capacity using recovery resources, added since the initial recovery period until the limit established for the recovery period.

$$Rd_{jtc} \leq \left(Ri_{jt} + Ra_j \right) \; \forall\, j, t, c \tag{30}$$

$$Rd_{jTc} = \left(Ri_{jT} + Ra_j \right) \; \forall\, j, c \tag{31}$$

From Eq. 30-31, we see that initially the supply capacity in each period after the disruptive event occurs must be less than or equal to its initial supply capacity and its additional capacity and at the end of the limit of the recovery period, the supply capacity must be the same.

$$tx\_cd_g + Scd \leq l_g \quad \forall\, t, c \tag{32}$$

$$tx\_l_g + Sl \leq w_g \quad \forall\, t, c \tag{33}$$

From Eq.32-32 it is important to recognize that disruptive events with different degrees of severity require different responses for resilience.

$$\sum_k \sum_i sl_{kitc} \leq tx\_l_g + Sl \;\forall\, t, c \tag{34}$$

$$\sum_i scd_{jtc} \leq \; tx\_cd_g + Scd \quad \forall\, t, c \tag{35}$$

Eq.34-35 guarantee that the recovery resources available for each time interval should not be exceeded.

$$Td_{tc} \;\geq 1 - \left(\frac{\sum_k \sum_l Olt_{kitc}}{\sum_k \sum_l Ar_{ki}}\right) \forall\, t, c \tag{36}$$

$$Td_{tc} \;\geq 1 - \left(\frac{\sum_j \sum_n Ort_{jntc} Ar_{jn}}{\sum_j \sum_n Ar_{jn}}\right) \forall\, t, c \tag{37}$$

Eq.36-37 evaluate the RSC recovery time when its operation was interrupted by a disruptive event.

$$Ar_{ki}, Olt_{kitc}, Y_{kitc}, Tr_{kitc}, Ort_{jntc}\;, Tt_{kitc}, LT_{ki}, De_{kic}, Td_{tc} \;\in \{0,1\} \forall\, k, i, j, n, t, c \tag{38}$$

$$Scd, Sl, sl_{kitc}, scd_{jtc}, dn_{ntc}, da_{ntc}, f_{kic}, Q_{ntc}\;, Rd_{jtc}, QA_{jntc}, WA_{ntc}, Ra_j \;\geq 0 \;\; \forall\, k, i, j, n, t, c \tag{39}$$

Finally, Eq. 38-39 respectively ensure that the highlighted decision variables are binary and non-negative.

4 Results and Discussion

Table 4 presents the scenarios in which disruptive events occurred that affect the flow of battery waste along the RSC.

Table 4. Disruptive Scenarios

Scenario Code	Disruptive Event	Affected Links*
Sc_1	Random	$S_1, CS_{3,4}, LR_{10,11}$
Sc_2	Intentional Act	$CS_{1,3}, CS_{2,5}, LR_{11,12}$
Sc_3	Natural Disaster	$CS_{3,6}, AN_{6,7}, AN_{6,9}, AN_{7,10},$
Sc_4	None	-

* Where: S (Supplier), CS (Component Separator), LR (Lead Recycler) and AN (Acid Neutralizer).

Thereafter, it was necessary to determine the probabilities of occurrence of disruptive events as shown in Table 5.

Table 5. Probability of Scenario

Scenario Code	Probability	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Sc_1	3p	0.0600	0.1900	0.3000	0.4000
Sc_2	2p	0.0400	0.1300	0.2000	0.2700
Sc_3	p	0.0200	0.0630	0.1000	0.1300
Sc_4	q	0.8800	0.6170	0.4000	0.2000
Total	1	1	1	1	1

Other information and characteristics were obtained through market analysis and were made available by the facilities that are part of the RSC analyzed, as shown in Table 6.

Table 6. Recovery rates

Parameter	g=1	g=2	g=3	Scale
tx_cd_g	1,000	500	500	Unit/hour
tx_l_g	290	190	59	Km/hora
l_g	1,900	930	883	Unit/hour
w_g	690	490	290	Km/hora

The model was implemented in IBM ILOG CPLEX version 13.6.1 by adding the data mentioned.

The study analyzed the total costs of the reverse supply chain (RSC) at different severity levels (g=1, g=2, g=3) and probabilities, for which four experiments were conducted. The magnitude of severity directly impacts overall costs, especially in recovery time, showing a more significant increase of 57.84% from g=1 to g=3, compared to 16% in Experiment 3.

The increase in total costs is more significant with the increase in severity than with the probability of the disruptive event occurring. The share of the post-event costs and penalties remains constant, highlighting the need for investments in resilient capabilities to reduce the severity of the event [14].

Investments prior to the disruptive event are crucial, as they show the impact after the occurrence, thus allowing a smooth adaptation of the reverse supply chain. After a disruptive event, investment options include purchasing waste from other chains and using alternative transport as secondary protection.

Alternative transport is financially recommended in all experiments, while purchasing waste from other chains is not advisable in Experiment 4. Investments in backups, including additional routes, anticipate the restoration of the supply of waste, but at severities g=2 and g=3, deadlines are exceeded, thus highlighting the importance of severity in decision-making.

Finally, the severity of the disruptive event and the likelihood of occurrence are crucial in determining the impacts on reverse supply chain costs and recovery, thus highlighting the need for investments in resilient capabilities and alternative transportation options as effective measures.

5 Conclusions

A resilient and sustainable SC can significantly contribute to reducing much of the disruption and negative environmental impacts throughout its operation. The development of strategies related to investment decisions continues to be a relevant challenge for Reverse Supply Chains, especially due to the unpredictability of disruptions. Dealing with unpredictability requires adaptive approaches and flexible strategies to ensure sustainability and operational efficiency of the reverse supply chain.

The proposed model was able to fill a theoretical and practical gap related to lead-acid battery waste management in the RSC by making it more resilient and sustainable. It focuses on resilient absorption, adaptation, and recovery capabilities, thereby analyzing investments that can be made both before and after disruptive events occur. This highlights the importance of considering not only prevention, but also the ability to respond and recover from disruptions to improve sustainability and resilience.

The relationship between the magnitude of the severity of the disruption and the total cost of the RSC is direct, also affecting the recovery time proportionally. Therefore, the anticipation of more substantial impacts on the reverse supply chain can be identified from the increased probability of disruption. Establishing scenarios in the model helped to understand the impact of the severity of the disruptive event and its probability of occurrence, these being crucial elements for making decisions about investments throughout the supply chain.

This study not only enhances the resilience and sustainability of the reverse supply chain for lead-acid batteries but also brings significant environmental benefits. By implementing strategies focused on efficient waste management, the model reduces energy consumption, minimizes greenhouse gas emissions, and promotes a circular economy approach. Moreover, the insights gained have implications beyond this specific supply chain, offering valuable guidance for improving resilience and sustainability across various industries worldwide. By adopting flexible strategies and fostering collaboration among stakeholders, companies can mitigate the impacts of disruptions, enhance operational efficiency, and contribute to a more environmentally responsible future.

For future work, we propose the simultaneous consideration of multiple issues in a multi-objective stochastic model, contemplating different configurations for the RSC of lead-acid batteries. This will allow us to deepen the analysis and obtain a broader understanding of how to make them more resilient and sustainable at their various stages.

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