Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

ARTICLE

A Reverse Logistics Network Model for Efficient End-of-Life Vehicle Management in Morocco

Imane Rouichat [1*], ***Miloudia Slaoui*** [1], ***Houria El Bakraoui*** [1], ***Jamal Mabrouki*** [2], ***Mohamed El Allaoui*** [3]

[1] *Energy, Materials and Sustainable Development (EMDD) Laboratory-Higher School of Technology—SALE, Center of Water, Natural Resources, Environment and Sustainable Development (CERN2D), Faculty of Science, Mohammed V University, Rabat 10106, Morocco*

[2] *Laboratory of Spectroscopy, Molecular Modelling, Materials, Nanomaterials, Water and Environment, 7 CERN2D, Mohammed V University in Rabat, Faculty of Science, AV IbnBattouta, Agdal, Rabat 10106, Morocco*

[3] *Microbiology and Molecular Biology Laboratory, Research Center: Plant and Microbial Biotechnology, Biodiversity and Environment (BIOBIO), Faculty of Sciences, Mohammed V University in Rabat, Rabat 10106, Morocco*

ABSTRACT

The Moroccan automotive industry is experiencing steady growth, positioning itself as the largest manufacturer of passenger cars in Africa. This expansion is leading to a significant increase in waste generation, particularly from end-of-life vehicles (ELVs), which require proper dismantling and disposal to minimize environmental harm. Millions of tonnes of automotive waste are generated annually, necessitating efficient waste management strategies to mitigate environmental and health risks. ELVs contain hazardous substances such as heavy metals, oils, and plastics, which, if not properly managed, can contaminate soil and water resources. To address this challenge, reverse logistics networks play a crucial role in optimizing the recovery of used components, enhancing recycling efficiency, and ensuring the safe disposal of hazardous and non-recyclable waste. This paper introduces a mathematical programming model designed to minimize the total costs associated with ELVs collection, treatment, and transportation while also accounting for revenues from the

*CORRESPONDING AUTHOR:
Imane Rouichat, Energy, Materials and Sustainable Development (EMDD) Laboratory-Higher School of Technology—SALE, Center of Water, Natural Resources, Environment and Sustainable Development (CERN2D), Faculty of Science, Mohammed V University, Rabat 10106, Morocco; Email: jamal.mabrouki@um5r.ac.ma

ARTICLE INFO
Received: 1 November 2024 | Revised: 12 December 2024 | Accepted: 25 December 2024 | Published Online: 12 March 2025
DOI: https://doi.org/10.30564/jees.v7i3.7660

CITATION
Rouichat, I., Slaoui, M., El Bakraoui, H., et al., 2025. A Reverse Logistics Network Model for Efficient End-of-Life Vehicle Management in Morocco. Journal of Environmental & Earth Sciences. 7(3): 341–350. DOI: https://doi.org/10.30564/jees.v7i3.7660

resale of repaired, directly reusable, or recycled components. The proposed model determines the optimal locations for processing facilities and establishes efficient material flows within the reverse logistics network. By integrating economic and environmental considerations, this model supports the development of a sustainable and cost-effective automotive waste management system, ultimately contributing to a circular economy approach in the industry.
Keywords: Supply Chain; ELV; Reverse Logistics; Recycling Network; Environmental Impacts; Circular Economy

1. Introduction

The Moroccan automotive industry has experienced significant growth over the last decade. Its performance is especially notable for export and in terms of job creation, indicators for which this sector generated double-digit annual growth.

Morocco's positioning as a platform of production and export of equipment and motor vehicles is supported by the planting of renowned foreign groups (suppliers and manufacturers)[1].

With a production of 403007 vehicles in 2021 (see **Figure 1**), increased tenfold in the last decade, Morocco ranks second among producers in Africa, just behind South Africa (499087). On the scale of 80 million vehicles produced in the same year in forty countries, Morocco ranks 26th, i.e., 0.5% of the world market[2].

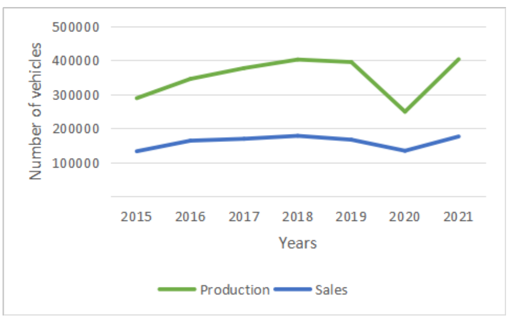

Figure 1. Production and Sales of New Vehicles in Morocco (2015–2021)[2, 3].

This rapid development contributed significantly to the vehicle fleet growth between 2002 and 2017, rising from 1.81 million vehicles to more than 4 million, all categories combined leading to more cars on the road[1].

As the issues related to the automotive sector remain complex and multiple, they lead us to question the changes necessary to encourage the respect of social and environmental standards, guaranteeing equitable and sustainable development in the country (creation of decent jobs, use of clean technologies, open innovation).

In this paper, our main concern is end-of-life vehicles (ELVs) management in Morocco.

As the automotive sector creates about 5% of industrial waste in the world[4]. Waste streams management is a global challenge to sustainability[5] and ELVs are one of its most important subjects[6–8].

Basically, ELVs are motor vehicles that have reached the end of their useful lives, and they are categorized as waste. ELVs can be classified into two categories; Natural ELVs usually vehicles over ten years old and inoperable, this type of ELV will be de-polluted and recycled for scrap metal, and premature ELVs referring to the vehicles that are severely damaged due to unnatural reasons such as accidents and vehicle testing for automotive industry, and with efficient management of collecting and recovery process they could be used again or returned to the production cycle[9, 10].

Above all, an ELV is considered particularly polluting and dangerous for the environment. it contains liquid and solid waste classified in the category of hazardous waste (waste oil, lead batteries, etc.). Without proper treatment and recycling, the ELVs are detrimental to the environment[11].

On the other hand, ELVs consist of 75% metallic and 25% non-metallic substances (tires, fluids, and other materials). Basically, through proper recycling, ELVs can improve the circular economy and address environmental concerns linked to them[12].

It is worth noting that the composition of ELVs can vary depending on factors such as the age of the vehicle, its manufacturing date, and regional differences in vehicle design and manufacturing.

Overall, it is difficult to provide a specific estimate of the future composition of ELVs, as it will depend on a range of complex and interrelated factors. However, it is likely that the composition of ELVs will continue to evolve and change in response to technological advancements, changes in manufacturing processes, and evolving end-of-life management practices.

Thus, there is a great need for reverse logistics networks that optimize the whole supply chain covering recovery of used components, efficient recycling of materials and disposal of hazardous and non-recyclable waste.

The recycling and reuse of ELVs has made them an essential source of secondary raw materials for use in the industry [13].

Waste management entails a diverse set of operations and shareholders [14]. Although both the rate and volume of ELVs generated in Morocco are lower compared to developed countries, their management is a must because scrapping is carried out most of the time by informal companies. This situation needs to be addressed as soon as possible, it is top priority in order to limit environmental degradation like pollution, resource shortages and wastage and high carbon footprints [15].

Morocco is confronted with complexity of ELV management and the limitations of the environment to handle the pressure of both resource consumption and waste generation.

Reverse logistics is a relevant strategy enabling the recovery of value from the materials that have diminished it [16]. This reverse flow is a process where the manufacturer returns used products from consumers for recycling or remanufacturing [17].

This research aims to create an ELV reverse logistics network in Morocco. To achieve this, two requirements should be fulfilled. One is to build an industrial consortium on a national level grouping together the representatives of the future reverse logistics network and industrial companies should be encouraged to invest in reverse logistics activities. The second condition is to prove that this kind of industrial investment is profitable for the entire reverse logistics actors, which is the objective of this paper.

Thus, this paper presents a mathematical model for ELV reverse logistics network in order to minimize its total cost. The monetary factors considered in the model are the cost of collection, treatment, transportation, and the revenue from ELVs. The proposed model allows to determine the optimal facility locations and material flows in the reverse logistics network.

2. Reverse Logistics Model

Reverse logistics operations extend the traditional supply chain with additional activities, procedures and resources to better assist in the collection and recovery of materials and products as they reach their end-of-life [18].

According to Rogers and Tibben-Lembke, Reverse logistics is the "process of planning, implementing and controlling the efficient and cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" [19].

De Brito and Dekker [20] state that reverse logistics activities include the recovery of materials; hence, the activities involved are collection, inspection, sorting, reprocessing, and redistribution. Reprocessing options include direct ones, like reusing, and other ones that call for processes, such as reconditioning, restoration, remanufacturing, recycling, and final disposal. The parties involved in these processes are solid waste managers, retailers, distributors, and manufacturers.

The integration of reverse logistics into waste management systems has increasingly gained attention in the literature, reflecting its pivotal role in addressing the environmental and economic challenges posed by ELVs. As a major waste stream, ELVs offer significant opportunities for resource recovery, supporting circular economy goals and promoting environmental sustainability. Existing research emphasizes that well-structured reverse logistics networks can mitigate the environmental impacts of ELVs while simultaneously creating economic value [21, 22]. For instance, life cycle assessments and mathematical optimization models have proven effective in designing dismantling and recycling networks, helping maximize material recovery and minimize waste [23, 24].

However, challenges such as inadequate infrastructure, non-standardized dismantling processes, and weak regulatory frameworks remain prevalent, particularly in developing countries [25, 26].

Comparative studies reveal stark contrasts between developed and developing nations in ELV management. Countries with advanced legislative frameworks, such as those in the European Union and Japan, demonstrate high recovery rates, thanks to robust systems that enforce producer responsibility and establish clear guidelines for recycling processes [27, 28].

By contrast, emerging economies often face obstacles related to informal recycling practices, insufficient technological capacity, and limited policy enforcement. Informal sectors play a dominant role in these regions, handling ELVs without regard for environmental safety or efficient resource recovery [25, 29].

For example, SWOT analyses of ELVs recycling in developing countries have highlighted significant opportunities, such as low labor costs and a growing demand for secondary raw materials, alongside threats such as regulatory weaknesses and environmental degradation [29].

This study extends the current understanding of Reverse logistics systems by integrating informal sector activities into formal frameworks and proposing an optimization model tailored to the specific socio-economic and environmental context of Morocco. By leveraging global best practices while addressing local challenges, this research not only highlights the novelty of its approach but also underscores its relevance in advancing sustainable resource management. The findings contribute to bridging the gap between policy and practice in reverse logistics, providing a pathway for implementing circular economy principles in regions where formal recycling infrastructure is lacking.

So far, few countries in the world have succeeded in implementing an ELV recycling system with energy recovery, such as the European Union, China, Japan and Korea. Other countries are preparing to adopt this type of legislative system for the management of ELVs.

The EU Directive on ELVs (2000/53/EC) aims to increase reuse, recycling, and other forms of recovery to minimize waste disposal [30]. No later than 1 January 2015 it sets two targets for ELVs; the reuse and recovery should increase to 95% at least and the reuse and recycling should also increase to at least 85% by an average weight per vehicle and year (see **Figure 2**), and this concerns passenger cars with seating capacity of nine or less and commercial vehicles with gross vehicle weight of 3.5 t or less.

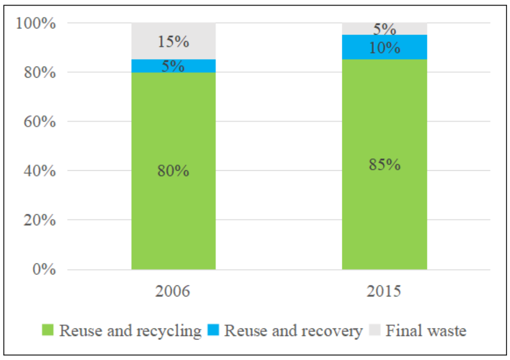

Figure 2. ELV Recovery Targets as Outlined in the 2000/53/EC Directive.

Materials from ELVs are either recovered, disposed of in landfills, or both. Recovery operations include using sub-assemblies or parts as spare parts, as well as recovering materials or energy from waste.

Products could be recovered in several ways, and at different levels; product recovery at a lower level refers to "recycling", in other words the materials contained in the product are recovered.

At a higher level, reusing sub-assemblies and parts of the product is often referred to as "remanufacturing", "reconditioning" or "refurbishing".

A remanufactured product is frequently the term used to refer to a worn, broken, or used product that has either been restored to its original specification or upgraded to a new one. Thus, remanufacturing not only encourages multiple reuse of materials, but also enables continuous development of product functionality and quality instead of manufacturing all-new products and disposing of used products [31].

Reconditioning refers to the process of returning components to a satisfactory and/or functional state, but not beyond their original specification, through methods like resurfacing, repainting, sleeving [32].

According to the EU Directive on ELVs (2000/53/EC), energy recovery refers to the use of combustible waste as a source to generate energy with direct incineration either with or without other waste, but with heat recovery [21]. This is especially the case for materials that are not profitable after recycling or due to the lack of processing centers or technologies in the current market.

Overall, the recycling industry is key in moving from a linear economy to a circular one. Furthermore, increased recycling rates reduce environmental footprint, decrease the country's dependence on imported raw materials, and reduce manufacturing energy [33] as shown in **Figure 3**.

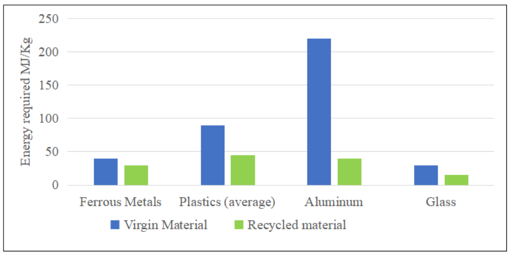

Figure 3. Energy Required to Produce Vehicle Materials, MJ per Kg.

The proposed model in this paper is a multi-echelon reverse logistics network involving collection, disassembly, processing (repairing, recycling), and final sites (primary and secondary markets and disposal), as represented in **Figure 4**.

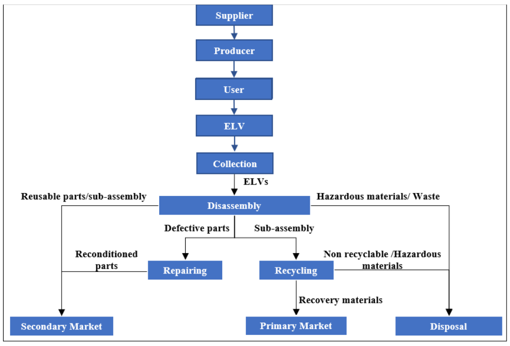

Figure 4. Reverse Logistics Network System for ELVs in Morocco.

Note: The producer refers to a vehicle manufacturer or a professional importer of vehicles into Morocco. The process of deregistering ELVs is subject to country-specific rules. Depending on the county, users, collectors, or dismantlers may be involved in the process. However, one mandatory requirement in most cases is a certificate of destruction. This certificate is typically provided by the recycling facility that processes the vehicle and serves as proof that the vehicle has been properly disposed of and recycled according to environmental regulations.

As shown in **Figure 4** First, ELVs are collected in collection sites, next they are sent to disassembly sites that involves depollution where hazardous materials (fluids, batteries, and heavy metals) are taken out first for environment friendly dismantling.

ELVs are separated into sub-assemblies or components, that are divided into four types: repairable, reusable, recyclable, and disposal. The parts are sent to the treatment centers, where defective parts are reconditioned at repairing centers while recycling centers handle materials according to their nature and, moreover, non-recyclable and hazardous materials are also sent to disposal centers.

Finally, materials generated from recycling are sold at primary markets, and reusable, reconditioned parts are sold at the secondary markets.

The transportation of ELVs plays a crucial role in the reverse logistics network and its cost strongly affects the profits from product recovery. Moreover, excessive transportation contributes to environmental degradation and diminishes the motivation for recycling. The maximum benefit can only be achieved through careful design and efficient coordination between sites.

The two major elements impacting the transportation costs are the volume and weight of products.

Both criteria do not vary during transportation of ELVs from collection to disassembly sites. However, they do change after being processed at disassembly sites as shown in **Figure 5**.

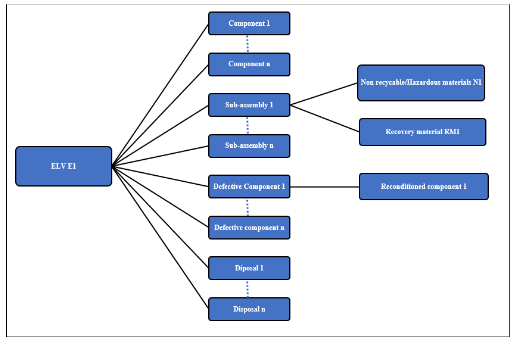

Figure 5. Disassembly Tree for an ELV.

3. Mathematical Model

The model aims to minimize the cost structure of the recycling system, in other words, the difference between the fixed costs from each site (the cost of collecting, transporting, and processing of ELVs) and the total revenue earned from selling reused/repaired parts and recycled materials.

While designing the network, we made the following assumptions related to the mathematical model for ELVs:

1. The model is a multi-echelon, multi-returned ELVs reverse logistics network
2. Collection and Processing sites are already established and certified (licenced)
3. A certificate of destruction is provided for the deregistration of each ELV
4. The number of collection and final sites is fixed
5. The capacities of disassembly, repairing, recycling and disposal centers are limited.
6. No energy recovery processing is included, waste is sent to disposal centers
7. Transportation costs are proportional to the distance traveled
8. Cost parameters are known (transportation, operation, material, disassembly, recycling, fixed)
9. Holding charges and shortage costs are not considered

The following notation is used in the formulation of the model:

Sets:

C set of collection sites

D set of disassembly sites

R set of recycling centers

A set of repair centers

B set of secondary markets

P set of primary markets

E set of disposal centers

PR set of ELVs

SA set of sub-assembly components

DR set of directly reusable components

IC set of defective components

RC set of reconditioned components

RM set of recovery materials

NR set of non-recyclable materials

DC set of disposal components

TP_i^j amount of materials or number of components of type j produced from every ELV, component or material i, for S = (i,j) :i,j $\in$ PR $\cup$ SA $\cup$ DR $\cup$ DC $\cup$ IC $\cup$ RC $\cup$ RM $\cup$ NR

Parameters:

C_i unit transportation cost for ELV, component or material i $\in$ S

$D_{\lambda\beta}$ distance between sites λ and β, $(\lambda, \beta) \in T = C \times D \cup D \times R \cup R \times E \cup D \times E \cup D \times A \cup A \times B \cup R \times P \cup D \times B$

α_s fixed cost of site s $\in$ D $\cup$ R $\cup$ A

O_i unit cost of disposal component and non-recyclable material, i $\in$ DC $\cup$ NR

Ω_r operation efficiency at recycling center r $\in$ R

Ω_a operation efficiency at repair center a $\in$ A

EL_i^C demand at collection site c $\in$ C for ELV i $\in$ PR

DP_i^p demand of primary market p $\in$ P for component or material i $\in$ RM

DB_i^r demand of secondary market b $\in$ B for component i $\in$ RC $\cup$ DR

KD_i^d capacity for handling product i $\in$ PR at disassembly site d $\in$ D

KR_i^l capacity for handling product i $\in$ SA at recycling center r $\in$ R

KA_i^f capacity for handling product i $\in$ IC at repair center a $\in$ A

G_i revenues from repaired components, directly reusable or recycled types i $\in$ DR $\cup$ RC $\cup$ RM

VD_i^d unit processing cost of product i $\in$ PR at disassembly site d $\in$ D

VR_i^r unit processing cost of product i $\in$ SA at recycling center r $\in$ R

VA_i^a unit processing cost of product i $\in$ IC at repair center a $\in$ A

Decision variables:

$X_i^{\lambda\beta}$ amount of products transported from site λ to site β, $(\lambda, \beta) \in T$

Q_d 1 if disassembly site d $\in$ D is used, and 0 otherwise

Q_r 1 if recycling center r $\in$ R is used, and 0 otherwise

Q_a 1 if repair center a $\in$ A is used, and 0 otherwise

In terms of the above notation, the mathematical model can be formulated as follows:

$$\begin{aligned}\text{Minimize } Z = &\sum_{c\in C}\sum_{d\in D}\sum_{i\in PR} X_i^{cd}\left(D_{cd}C_i + VD_i^d\right) + \sum_{d\in D}\sum_{r\in R}\sum_{i\in SA} X_i^{dr}(D_{dr}C_i + VR_i^r) \\ &+ \sum_{r\in R}\sum_{e\in E}\sum_{i\in NR} X_i^{re}(D_{re}C_i + O_i) \\ &+ \sum_{d\in D}\sum_{e\in E}\sum_{i\in DC} X_i^{de}(D_{de}C_i + O_i) \\ &+ \sum_{d\in D}\alpha_d Q_d + \sum_{r\in R}\alpha_r Q_r \\ &+ \sum_{a\in A}\alpha_a Q_a + \sum_{d\in D}\sum_{a\in A}\sum_{i\in IC} X_i^{da}(D_{da}C_i + VA_i^a) \\ &- \sum_{a\in A}\sum_{b\in B}\sum_{i\in RC} X_i^{ab}(G_i - D_{ab}\times C_i) \\ &- \sum_{r\in R}\sum_{p\in P}\sum_{i\in RM} X_i^{rp}\left(G_i - D_{rp}\times C_i\right) - \sum_{d\in D}\sum_{b\in B}\sum_{i\in DR} X_i^{db}(G_i - D_{db}\times C_i)\end{aligned} \tag{1}$$

$$\sum_{\substack{d\in D\\ c\in C}} X_i^{cd} = EL_i\ ; \forall i \in PR \tag{2}$$

$$\sum_{\substack{i\in PR\\ c\in C}} X_i^{cd} \times TP_i^j = \sum_{b\in B} X_j^{db}\ ; \forall d \in D, \forall j \in DR \tag{3}$$

$$\sum_{\substack{i\in PR\\ c\in C}} X_i^{cd} \times TP_i^j = \sum_{e\in E} X_j^{de}\ ; \forall d \in D, \forall j \in DC \tag{4}$$

$$\sum_{\substack{i\in PR\\ c\in C}} X_i^{cd} \times TP_i^j = \sum_{r\in R} X_j^{dr}\ ; \forall d \in D, \forall j \in SA \tag{5}$$

$$\sum_{\substack{i\in PR\\ c\in C}} X_i^{cd} \times TP_i^j = \sum_{a\in A} X_j^{da}\ ; \forall d \in D, \forall j \in IC \tag{6}$$

$$\sum_{\substack{i\in SA\\ d\in D}} X_i^{dr} \times TP_i^j \times \Omega_r = \sum_{p\in P} X_j^{rp}\ ; \forall r \in R, \forall j \in RM \tag{7}$$

$$\sum_{\substack{d\in D\\ i\in SA}} X_i^{dr} \times TP_i^j = \sum_{e\in E} X_j^{re}\ ; \forall r \in R, \forall j \in NR \tag{8}$$

$$\sum_{\substack{i\in IC\\ d\in D}} X_i^{da} \times TP_i^j \times \Omega_a = \sum_{b\in B} X_j^{ab}\ ; \forall a \in A, \forall j \in RC \tag{9}$$

$$\sum_{d\in D} X_i^{db} \leq DB_i^b;\ \ \forall b \in B, \forall i \in DR \tag{10}$$

$$\sum_{a\in A} X_i^{ab} \leq DB_i^b;\ \ \forall b \in B, \forall i \in RC \tag{11}$$

$$\sum_{r\in R} X_i^{rp} \leq DP_i^p;\ \ \forall p \in P, \forall i \in RM \tag{12}$$

$$\sum_{c\in C} X_i^{cd} \leq KD_i^d;\ \ \forall d \in D, \forall i \in PR \tag{13}$$

$$\sum_{d\in D} X_i^{dr} \leq KR_i^l;\ \ \forall r \in R, \forall i \in SA \tag{14}$$

$$\sum_{d\in D} X_i^{da} \leq KA_i^a;\ \forall a \in A, \forall i \in IC \tag{15}$$

$$X_i^{\lambda\beta} \geq 0;\ \forall(\lambda, \beta) \in\ C\times D \cup D\times E \cup D\times R \cup D\times A \cup D\times B \cup A\times B \cup R\times P \cup R\times E \tag{16}$$

$$Q_d, Q_r, Q_a \text{ are binary } \ \forall\ d, r, a \tag{17}$$

Constraint (2) ensure that all ELVs leave the collection site. Constraints (3)–(6) assure that the incoming flow of returned products at the disassembly site d multiplied by TP_i^j equals the outgoing flow to secondary markets, disposal centers, and primary markets, respectively. Constraints (7) and (8) require that the incoming flow of returned products at the recycling center r multiplied by TP_i^j and operation efficiency is equal to the outgoing flow from recycling center to primary market and disposal center, respectively. Constraint (9) state that the incoming flow of returned products at the repair center a multiplied by TP_i^j and operation efficiency is equal to the outgoing flow from the secondary market. Constraints (10)–(12) ensure that the amount of components and recovery materials do not surpass the demand of primary and secondary markets.

Constraint (13) assure that the amount of ELVs sent from collection site c to disassembly site d cannot surpass its capacity. Constraint (14) ensure that the sub-assemblies sent from disassembly site d to recycling centers r do not exceed its full capacity. Constraint (15) assure that the faulty components sent from disassembly site d to repair centers a do not surpass its capacity.

Constraint (16) confirm that the number of transported products is positive. Constraint (17) are binary variables.

4. Numerical Example

The numerical example of the proposed model, which will be presented in a second article, is based on simulated data and does not use real-world figures. It employs the AMPL modeling language and the CPLEX solver, translating the mathematical formulation into a solver-compatible format to ensure precise application of constraints and objectives. The optimization process identifies optimal locations for collection, treatment, and recycling facilities, minimizing costs. It also maximizes revenues from recycled materials, enhancing cost efficiency. Additionally, the model reduces the environmental footprint by improving material recovery and minimizing hazardous waste disposal. These simulated results demonstrate the potential of the proposed model to achieve both economic and environmental sustainability in ELV management.

5. Conclusions

In this paper, we have tackled the problem of a reverse logistics network for ELV management in Morocco by developing a multi-echelon and multi-returned ELV reverse logistics network to model it. This paper is intended to extend previous research to model a more complete recycling network featuring different treatment and final sites for multiple types of ELVs. The responsible entities should determine the most appropriate sites and the number of services needed. The proposed model involves four levels of the recycling process, covering collection, disassembly treatment (recycling and repair centers) and final sites (disposal centers, secondary and primary markets). Furthermore, each type of waste undergoes a different recycling process according to its nature.

For practitioners, the model shows that the most effective way to reduce the cost structure of the recycling system is by reducing the transportation cost (by outsourcing transportation, for instance). In terms of future work, the current model can be extended in several important ways to enhance its applicability and sustainability:

- **Bridging Forward and Reverse Logistics:**
  One promising direction is to align forward and reverse logistics into a unified circular supply chain. This could involve using the same transportation routes and storage facilities for delivering new vehicle components and collecting recyclable materials. Moreover, encouraging manufacturers to design vehicles with modular and easily disassembled parts would simplify end-of-life recovery and recycling processes.
  For instance, a pilot project could involve automotive companies producing vehicles with standardized components that can be easily reused or recycled, reducing costs and environmental impact.
- **Incorporating Green Logistics Practices:**
  Integrating environmentally friendly logistics strategies is essential for reducing the carbon footprint of ELV management. Facilities could adopt renewable energy sources, such as solar power, and switch to low-emission transportation methods, like electric or hybrid trucks, for material collection and distribution. For example, logistics companies could deploy electric vehicles for transporting dismantled parts, significantly cutting emissions compared to traditional diesel-powered fleets.
- **Recovering Energy from Non-Recyclable Waste:**

Another promising avenue is exploring energy recovery methods for materials that cannot be recycled economically. Techniques such as pyrolysis or gasification could convert waste plastics and other materials into synthetic fuels or energy sources, supporting sustainable industrial practices.

For example, waste plastics from ELVs could be processed into synthetic fuel using pyrolysis, reducing reliance on fossil fuels and decreasing landfill waste.

- **Incorporating Advanced Modeling for Uncertainty:**

  To account for variability in factors like waste generation rates, transportation costs, and demand for recycled materials, the model could incorporate stochastic methods or simulations. This would ensure robustness and adaptability to real-world changes and uncertainties.

  For instance, Monte Carlo simulations could evaluate how fluctuations in fuel prices or recycling demand might affect logistics costs and overall efficiency.

These directions for future research aim to make ELV management more integrated, sustainable, and responsive to evolving environmental and economic challenges.

Author Contributions

Conceptualization, I.R.; methodology, I.R., M.S.; research, I.R.; writing—original draft preparation, I.R.; writing—review and editing, M.S., Jamal Mabrouki, H.E.B., M.E.A.; supervision, M.S.; project administration, M.S.; manuscript submission, J.M. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflict of Interest

The authors declare no conflicts of interest.

References

[1] Moroccan Ministry of Industry and Trade. Automotive. Available from: https://www.mcinet.gov.ma/en/content/industry-0/automotive-0 (cited 12 August 2024).

[2] Organisation Internationale des Constructeurs Automobiles (OICA). World Vehicles in Use. Available from: https://www.oica.net/category/vehicles-in-use/

[3] CEIC. Morocco Motor Vehicles Sales. Available from: https://www.ceicdata.com/en/indicator/morocco/motor-vehicles-sales

[4] Simic, V., 2013. End-of-life vehicle recycling-A review of the state-of-the-art. Tehnicki Vjesnik. 20, 371–380.

[5] Gupta, S., Chen, H., Hazen, B.T., et al., 2019. Circular economy and big data analytics: A stakeholder perspective. Technological Forecasting and Social Change. 144, 466–474. DOI: https://doi.org/10.1016/j.techfore.2018.06.030

[6] Zhou, F., Lim, M.K., He, Y., et al., 2019. End-of-life vehicle (ELV) recycling management: Improving performance using an ISM approach. Journal of Cleaner Production. 228, 231–243. DOI: https://doi.org/10.1016/j.jclepro.2019.04.182

[7] Wong, Y.C., Mahyuddin, N., Aminuddin, A.M.R., 2020. Development of thermal insulation sandwich panels containing end-of-life vehicle (ELV) headlamp and seat waste. Waste Management. 118, 402–415. DOI: https://doi.org/10.1016/j.wasman.2020.08.036

[8] Azmi, M., Zameri, M., Saman, M., et al., 2010. Proposed Framework for End-Of-Life Vehicle Recycling System Implementation in Malaysia. In Proceedings of the 11th Global Conference on Sustainable Manufacturing; Berlin, Germany, 23–25 September 2013.

[9] Rovinaru, M., Rus, A., 2019. The Economic and Ecological Impacts of Dismantling End-of-Life Vehicles in Romania. Sustainability. 11, 6446. DOI: https://doi.org/10.3390/su11226446

[10] ASM Auto Recycling. End of Life Vehicles. ASM Auto Recycling. Available from: https://www.asm-autos.co.uk/scrap-my-car/end-of-life-vehicle/ (cited 15 August 2024).

[11] Fonseca, A.S., Nunes, M.I., Matos, M.A., et al., 2013. Environmental impacts of end-of-life vehicles' management: recovery versus elimination. International Journal of Life Cycle Assessment. 18(7), 1374–1385. DOI: https://doi.org/10.1007/s11367-013-0585-1

[12] U.S. Environmental Protection Agency (EPA) and Office of Resource Conservation and Recovery, 2017. Processing End-of-Life Vehicles: A Guide for Environmental Protection, Safety and Profit in the United States-Mexico Border Area. EPA530-R-15–007, 2020 10.

[13] Kosacka-Olejnik, M., 2019. How manage waste from End-of-Life Vehicles? - method proposal. IFAC-PapersOnLine. 52(13), 1733–1737. DOI: https://doi.org/10.1016/j.ifacol.2019.11.451

[14] Massoud, M., Mokbel, M., Alaweih, S., et al., 2019. Towards improved governance for sustainable solid waste management in Lebanon: Centralised vs decentralised approaches. Waste Management & Research. 37(7), 686–697. DOI: https://doi.org/10.1177/0734242X19836705.

[15] Mabrouki, J., Azrour, M., Boubekraoui, A., et al., 2022. Simulation and optimization of solar domestic hot water systems. International Journal of Social Ecology and Sustainable Development (IJSESD). 13(1), 1–11.

[16] Kinobe, J., Vinnerås, B., 2012. Reverse logistics related to waste management with emphasis on developing countries-A review paper. Journal of Environmental Science and Engineering. 1, 1104–1118.

[17] Fattah, G., Ghrissi, F., Mabrouki, J., et al., 2021. Control of physicochemical parameters of spring waters near quarries exploiting limestone rock. In E3S web of conferences (Vol. 234, p. 00018). EDP Sciences.

[18] Keh, P., Rodhain, F., Meissonier, R., et al., 2012. Financial Performance, Environmental Compliance, and Social Outcomes: The three Challenges of Reverse Logistics. Case Study of IBM Montpellier. Supply Chain Forum: An International Journal. 13(3), 26–38. DOI: https://doi.org/10.1080/16258312.2012.11517296

[19] Al-Jadabi, N., Laaouan, M., El Hajjaji, S., et al., 2023. The dual performance of Moringa oleifera seeds as eco-friendly natural coagulant and as an antimicrobial for wastewater treatment: a review. Sustainability, 15(5), 4280.

[20] de Brito, M.P., Dekker, R., 2004. A Framework for Reverse Logistics. in Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains. Edited by Dekker, R., Fleischmann, M., Inderfurth, K., et al. Springer: Berlin/Heidelberg, Germany. pp. 3–27. DOI: https://doi.org/10.1007/978-3-540-24803-3_1

[21] Bencheikh, I., Mabrouki, J., Azoulay, K., et al., 2020. Predictive analytics and optimization of wastewater treatment efficiency using statistic approach. In Big data and networks technologies 3 (pp. 310-319). Springer International Publishing.

[22] Zhang, L., Ji, K., Liu, W., et al., 2020. Collaborative approach for environmental and economic optimization based on life cycle assessment of end-of-life vehicles' dismantling in China. Journal of Cleaner Production. 276, 124288. DOI: https://doi.org/10.1016/j.jclepro.2020.124288

[23] Merkisz-Guranowska, A., 2013. Multicriteria Optimization Model For End-of-life Vehicles' Recycling Network. International Journal of Sustainable Development and Planning. 8(1), 88–99. DOI: https://doi.org/10.2495/SDP-V8-N1-88-99

[24] Ghizlane, F., Mabrouki, J., Ghrissi, F., et al., 2022. Proposal for a high-resolution particulate matter (PM10 and PM2.5) capture system, comparable with hybrid system-based internet of things: case of quarries in the western rif, Morocco. Pollution, 8(1), 169–180.

[25] Mgalaa, S., Mabrouki, J., Elouardi, M., et al., 2022. Study and evaluation of the degradation of procion blue dye by the ozonation method: parametric and isothermal study. Nanotechnology for Environmental Engineering, 7(3), 691–697.

[26] Lu, Y., Broughton, J.G., Winfield, P., 2014. A Review of Innovations in Disbonding Techniques for Repair and Recycling of Automotive Vehicles. ResearchGate. Available from: https://www.researchgate.net/publication/260007118_A_Review_of_Innovations_in_Disbonding_Techniques_for_Repair_and_Recycling_of_Automotive_Vehicles (cited 12 December 2024).

[27] Karagoz, S., Aydin, N., Simic, V., 2020. End-of-life vehicle management: a comprehensive review. Journal of Material Cycles and Waste Management. 22(2), 416–442. DOI: https://doi.org/10.1007/s10163-019-00945-y

[28] Gharfalkar, M., Court, R., Campbell, C., et al., 2015. Analysis of waste hierarchy in the European waste directive 2008/98/EC. Waste Management. 39, 305–313. DOI: https://doi.org/10.1016/j.wasman.2015.02.007

[29] Benchrifa, M., Elouardi, M., Fattah, G., et al., 2023. Identification, simulation and modeling of the main power losses of a photovoltaic installation and use of the internet of things to minimize system losses. In Advanced technology for smart environment and energy (pp. 49–60). Cham: Springer International Publishing.

[30] El Alouani, M., Aouan, B., Rachdi, Y., et al., 2024. Porous geopolymers as innovative adsorbents for the removal of organic and inorganic hazardous substances: a mini-review. International Journal of Environmental Analytical Chemistry. 104(16), 4784–4796.

[31] Sundin, E., 2004. Product and process design for successful remanufacturing. Production Systems, Department of Mechanical Engineering, Linköpings Universitet: Linköping, Sweden.

[32] Rachiq, T., Abrouki, Y., Mabrouki, J., et al., 2021. Evaluation of the efficiency of different materials to remove specific pollutants from landfill leachate. Desalination and Water Treatment. 238, 240–250.

[33] Weiss, M., Heywood, J., Drake, E., et al., 2000. On The Road In 2020 - A life-cycle analysis of new automobile technologies. Available from: http://web.mit.edu/energylab/www/pubs/el00-003.pdf