Titre: Title:	Optimization of the end-of-life tire repartition within the European treatment system to minimize its environmental impacts
Auteurs: Authors:	Lisa Duval, Guillaume Majeau-Bettez, François Saunier, François Maréchal, & Manuele Margni
Date:	2024
Type:	Article de revue / Article
Référence: Citation:	Duval, L., Majeau-Bettez, G., Saunier, F., Maréchal, F., & Margni, M. (2024). Optimization of the end-of-life tire repartition within the European treatment system to minimize its environmental impacts. Journal of Industrial Ecology, 15 pages. https://doi.org/10.1111/jiec.13474

DOI: 10.1111/jiec.13474

RESEARCH ARTICLE

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Optimization of the end-of-life tire repartition within the European treatment system to minimize its environmental impacts

Lisa Duval[1] | Guillaume Majeau-Bettez[2] | François Saunier[2] | François Maréchal[3] | Manuele Margni[1,4]

[1]Department of Mathematics and Industrial Engineering, CIRAIG, École Polytechnique de Montréal, Montréal, Quebec, Canada

[2]Department of Chemical Engineering, CIRAIG, École Polytechnique de Montréal, Montréal, Quebec, Canada

[3]Industrial Process and Energy Systems Engineering, Swiss Federal Institute of Technology in Lausanne, Lausanne, Switzerland

[4]Institute for Sustainable Energy, University of Applied Sciences Western Switzerland (HES-SO), Sion, Switzerland

Correspondence
Lisa Duval, Department of Mathematics and Industrial Engineering, CIRAIG, École Polytechnique de Montréal, Montréal, Quebec, Canada.
Email: lisa.duval@polymtl.ca

Editor Managing Review: Deepak Rajagopal

Funding information
The authors would like to acknowledge the financial support of the industrial partners of the International Chair in Life Cycle Assessment (a research unit of the CIRAIG): Arcelor-Mittal, Hydro-Québec, LVMH, Michelin, Nestlé, Optel, Solvay, TotalEnergies, and Umicore. The authors remain solely responsible for the content of this study.

Abstract

This study contrasts two different approaches to inform European-scale decision-making to mitigate the environmental impacts of the end-of-life tires (ELT) management system. The first analysis is a traditional life cycle assessment (LCA) that compares the environmental performances of the 12 main available European end-of-life (EOL) technologies in ELT processing while restricting the boundaries to the EOL stage. The second analysis has a broader scope, addressing the optimization of the ELT distribution within the 12 considered pathways to minimize the environmental impacts of the total tire use in Europe under present capacity and constraints. The results of the traditional LCA show that, except for landfill, all the tested EOL routes present environmental benefits. Material recovery pathways bring the most environmental credits, whereas civil engineering pathways are the least promising. The LCA results that emerged from the optimization of ELT management technologies yield two optimal technological mixes that maximize the quantity of ELT recycled in molded objects production: such results represent a hypothetical case with no constraints. When considering constraints, that is, limitations on maximum quantities of ELT that can undergo retreading, pyrolysis, or recycling in synthetic turfs, in molded objects and in production, the number of optimal technology mixes increases to five. The type of technologies favored depends on the minimized impact categories (climate change, fossil and nuclear energy use, human health, and ecosystem quality). A comparison between constrained and unconstrained scenarios shows that achieving the best environmental performances is conditional to the accessibility of the EOL technologies as well as their individual environmental impacts.

KEYWORDS
tire, waste management, life cycle assessment (LCA), optimization, circular economy, industrial ecology

1 | INTRODUCTION

The private car is the main means of transport in Europe, where registration rates have surpassed one car per two inhabitants (Eurostat, 2021). As a result, more than 3.5 million tons of end-of-life tires (ELT) have been generated in 2019 according to the European Tyre and Rubber Manufacturers Association (ETRMA), a number that will continue to increase (ETRMA, 2021; Khalili et al., 2019). Besides, over time, the search for performance has led tire-producing firms to increase the complexity of their product. A modern tire is a highly engineered complex composite made from more than 200 different components that can be divided into three main constituents: a metal structure, a reinforcing textile layer, and an external polymer layer based on rubber (Michelin, 2022). The quantity and complexity of tires have made ELT management a technological, economic, and environmental challenge.

1.1 | ELT management in Europe: Current practices

Tire stockpiles provide a habitat for pests and pose a fire hazard, possibly liberating noxious pollutants threatening surrounding populations (Downard et al., 2015; Singh et al., 2015; Valentini & Pegoretti, 2022). Buried in landfills, the tires occupy a vast volume of land and tend to "resurface," breaking the landfill's upper layers (Fiksel et al., 2011). In addition, when manufactured, the rubber part of the tire undergoes an irreversible vulcanization process in which sulfur is added to the polymer blend to create crosslinks between the polymer chains. This procedure hardens the rubber but prevents its remelting for further application and makes it a non-biodegradable product (Grammelis et al., 2021; Sienkiewicz et al., 2012). Therefore, the European Union has banned the landfilling of tires (Council of European Union, 1999) and set a general "waste hierarchy" with the Waste Framework Directive to guide European management policies to prioritize treatment methods in the following order: waste prevention, reuse, recycling, recovery, and disposal (European Parliament and Council of European Union, 2008).

Driven by legal adjustments, other treatment options have been developed. Initially, the tire's lifespan can be extended by retreading, a process that consists in replacing the tire thread, which has been abraded by the use stage, while keeping the old structure (Lebreton & Tuma, 2006). Discarded tires follow different recovery routes. In this study, these routes are grouped into three main categories defined as follows. Material recovery routes consist in reusing elements from the tire, by preserving the properties of the substituted material. The metal part and the rubber part are usually separated in the first steps of the treatment process to be used as, for example, a steel scrap substitute in electric steel factories, a virgin polymer replacement or a polymer blend additive (Karger-Kocsis et al., 2013). Second, energy recovery routes intend to reclaim the embodied energy in the tire by using it as a fuel, commonly referred to as tire-derived fuel (TDF) in the literature. The high calorific value of the tire, around 32 MJ/kg, is equal to or higher than the calorific value of traditional fossil fuels, which makes it a competitive combustible for a wide range of applications (Rowhani & Rainey, 2016; Valentini & Pegoretti, 2022). Third, civil engineering routes aim to reuse the structural properties of the tire or, alternatively, use it as a filling material. There is a wide variety of civil engineering applications for whole, shredded, and/or powdered rubber, from retaining walls to wearing courses (Grammelis et al., 2021; Mohajerani et al., 2020).

Some recovery pathways belong to multiple categories in this classification, such as pyrolysis and treatment in cement works. Pyrolysis itself is considered an intermediate process where the components of the tire are separated by thermal degradation, at temperatures around 500°C. The products are obtained in gaseous, liquid (pyrolytic oil), and solid (pyrolitic char) forms and can be further valorized as fuel (energy recovery) or carbon black (material recovery) (Williams, 2013). In cement factories, tires are used as fuel in rotary kilns (energy recovery) and as iron providers (material recovery) (Vogt, 2020).

None of the current management models developed in Europe (Dabic-Miletic et al., 2021; ETRMA, 2022) impose any established repartition of tires in the available end-of-life (EOL) routes. Nowadays, in Europe, more than half of ELT are sent to be consumed in cement kilns (ETRMA, 2021). Without legal incentives based on environmental concerns, European tire repartition is driven by economic interests.

1.2 | Life cycle assessment of tire waste management

Being able to quantify environmental impacts is essential for providing decision-makers with the necessary information in order to mitigate environmental problems. Life cycle assessment (LCA) is a standard methodology, defined by the norms ISO 14040 and ISO 14044 (Finkbeiner et al., 2006), that is able to quantify the environmental impacts for a product or a service. The strength of LCA is that it considers the whole life cycle of the product, from raw material production to EOL management, and that it assesses a broad variety of impact categories, including climate change, resource use, human health, and ecosystem quality. These abilities allow users to establish an environmental profile of the study's subject and to capture potential environmental impact shifting (Finnveden et al., 2009). Due to the challenges raised by ELT management, the field has attracted much attention during the past years (Dabic-Miletic et al., 2021), and LCA has been widely used to assess environmental impacts of tire waste management in the literature (Dong et al., 2021).

However, most of the existing LCAs are conducted in very specific contexts and only consider a few EOL routes. For example, Feraldi et al. (2013) compared two EOL pathways in a US context, virgin synthetic rubber substitution and use of scrap tires in cement plants. Two EOL pathways were also compared by Vogt (2020), tire use as a fuel in cement plants and as a replacement of several polymers for synthetic football field infill production. Several studies focused on pyrolysis at the pre-industrial testing stage (Banar, 2015; Buadit et al., 2020; Wu et al., 2021). To the extent of the author's knowledge, there are two LCA studies that comprehensively addressed the main EOL routes for tires including civil engineering, energy recovery, and material recycling routes: the one conducted by Fiksel et al. (2011) in the US context, and the one produced by Clauzade et al. (2010) in Europe.

In addition, existing LCAs of ELT management generally build on a narrow scope of study, thereby failing to provide a global overview for large-scale decision-making and biasing the assessment of the EOL management when not considering the system at scale. First, reducing the scope of the study to the EOL stage excludes possible loops from the circular economy perspective. For example, although retreading is considered part of the reuse processes prioritized by the European Waste Hierarchy, it is rarely assessed in ELT LCA studies because it does not strictly correspond to the definition of an EOL process (Dabic-Miletic et al., 2021; Dong et al., 2021). This discrepancy arises because, in LCAs, EOL processes are typically compared with a mass-based functional unit (treating 1 kg of ELT) that cannot describe the functionality of extending a tire's lifetime (i.e., driving an additional distance). Moreover, some LCA studies on ELT tend to disregard the effects shifted to other life cycle stages. For instance, retreaded tires have an influence on the use stage: their higher rolling resistance increases fuel consumption (Lonca et al., 2018). The effects that one stage of the life cycle can have on another must be considered from cradle to grave, even if the study is more focused on the EOL. Therefore the choice of system boundaries shall go beyond the EOL processes only, and the choice of functional unit, usually narrowly focused on the management/treatment of a given mass of ELT, shall be defined in order to include the service of the product itself.

Second, LCAs typically describe the direct and indirect impacts of a technology as inventoried at a specific scale, and results cannot be generalized for broader deployment. The interpretation of LCA results building on "small scale" analysis could be problematic to make large-scale decisions, because (i) it simplistically generalizes results obtained with data from a specific technology that does not necessarily represent the average, and (ii) it disregards physical, technological, and economic constraints that can restrict the deployment of a given technology or affect its environmental performance. Not taking into account such constraints limits the enforceability of LCA results for large-scale decision-making.

The general approach of comparative LCA consists in defining a priori a restricted number of scenarios to be compared based on expert judgments. Typically, these scenarios consist of one technology that is compared to another or a mix of technologies, where the share of each one is determined prior to the analysis. It is likely that such scenarios do not match with optimal solutions, especially in complex systems (Ekvall et al., 2007). Since 1998 (Azapagic & Clift, 1998, 1999), LCA and input–output (IO) practitioners have used an optimization approach for a broad range of applications, such as waste management (Kondo & Nakamura, 2005), energy (Saner et al., 2014), transport (Hung et al., 2022), biofuels (Wietschel et al., 2021), biorefinery technologies (Budzinski et al., 2019), and many others. The method has demonstrated its ability to quickly, explicitly, efficiently, and autonomously provide the optimal technological combination by exploring the whole solution space. Furthermore, it enables the user to define constraints within the optimization problem, thereby limiting the theoretically possible solutions to those that are feasible. In comparison, such constraints may not easily be integrated when defining the compared scenarios a priori.

This research project therefore aims to meet three objectives: the first one is to identify optimal scenarios to manage ELT in Europe using the main available technologies to minimize the overall environmental impacts. The second one is to evaluate the consequences of extending the traditional perspective in LCA of waste management systems by (i) encompassing all the life cycle stages, (ii) addressing material flows and competition across industrial sectors and involved actors, and (iii) taking into account physical and market constraints at a system level (European market). The third one is to illustrate the strengths of linear programming applied to LCA compared to the classical approach of scenario comparison. This analysis is not a long-term one but intends to guide short-term decision-making by capturing a snapshot of the actual European tire waste management system.

To achieve the above objectives, two distinct analyses will be performed to identify optimal scenarios to manage ELT in Europe based on the same dataset. The first one is a traditional comparative LCA of the main existing European EOL routes with a mass-based functional unit, without considering the upstream processes before the EOL stage. The second LCA expands the scope of analysis by including all the life cycle stages of a tire with a distance-based functional unit, which reflects the service provided by the annual quantity of tires used at the European scale. Moreover, instead of pre-defining scenarios to be compared, we apply multi-objective optimization to identify the optimal mix of technologies under given physical and market constraints. The strengths and limitations of these two approaches are further compared.

2 | METHODS

2.1 | A1: Comparison of the European end-of-life tire treatment pathways

2.1.1 | Goal and scope

For the first analysis, the functional unit (FU) is defined as *treating 1 kg of ELT in Europe in 2022*. Tire waste is therefore considered burden free when entering the EOL stage. Each EOL pathway modeled is multifunctional: it provides a valuable energy or material output in addition to treating

TABLE 1 Category, main substitution, and emission hypothesis of the end-of-life unit processes assessed, expressed as difference between the process using tire-based inputs and the traditional one.

EOL unit process	Category	Tire-based input material replacing the traditional ones	Direct emissions from the process using tire-based inputs replacing the traditional ones
P0: Landfill	Disposal	1 kg whole tire is landfilled (no substitution)	Direct emissions from landfill of inert waste (no substitution)
P1: Synthetic turf	Material recovery	1 kg rubber crumb replaces 0.51 kg EPDM	Same emissions
P2: Molded objects	Material recovery	1 kg rubber powder replaces 1 kg EPDM	Same emissions
P3: Recycling in production	Material recovery	1 kg rubber powder replaces 0.41 kg natural rubber, 0.28 kg synthetic rubber (SBR), 0.31 kg carbon black	Same emissions
P4a: Steel works	Material recovery	1 kg shredded tire replaces 0.59 kg coal, 0.18 kg scrap metal	Same emissions
P4b: Steel works	Material recovery	1 kg scrap metal from tire replaces 1 kg scrap metal	Same emissions
P5: Cement kilns	Material and energy recovery	1 kg whole or shredded tire replaces 0.16 kg iron ore, 0.28 kg hard coal, 0.95 kg lignite, 0.11 kg petroleum coke	Direct emissions from fuel mix combustion corrected with CO_2 value calculated from tire composition replace direct emissions from fuel mix combustion
P6: Pyrolysis	Material and energy recovery	1 kg shredded tire produces 0.30 kg carbon black, 0.18 kg steel scrap, 0.41 kg diesel	Direct emissions from pyrolysis
P7: Urban heating	Energy recovery	1kg shredded tire replaces 0.33kg natural gaz, 0.20kg hard coal, 0.18 wood pellets, 0.07kg heavy fuel	Direct emissions from rubber burning in municipal incineration corrected with CO_2 value calculated from tire composition replace direct emissions from fuel mix combustion
P8: Waste to energy	Energy recovery	1 kg shredded tire replaces 2.67 kWh electricity, 0.16 MJ heat from European mix	Direct emissions from rubber burning in municipal incineration corrected with CO_2 value calculated from tire composition replace emissions from average European electricity and heat production
P9: Retaining structures	Civil engineering	1 kg whole tire replaces 1.95 kg concrete blocks	Same emissions
P10: Civil engineering infill	Civil engineering	1 kg shredded tire replaces 6 kg gravel	Same emissions
P11: Thin civil engineering infill	Civil engineering	1 kg rubber powder replaces 13.2 kg sand	Same emissions

tire waste. By applying the system expansion method, environmental credit was accounted where production of the equivalent amount of material, fuel, or energy was avoided. Twelve EOL pathways, which are considered the most common and promising technologies (Clauzade et al., 2010; Sienkiewicz et al., 2012), are assessed in the study. These latter are described in Table 1. Collection and sorting, shredding, granulation, and pulverization are considered for each EOL pathway. The process trees corresponding to each assessed scenario are available in Supporting Information S3. Retreading is out of the scope of this first analysis because it intervenes before the EOL treatment stage.

2.1.2 | Data collection

The data are taken from scientific literature, grey literature, industrial data (provided by Michelin, the European main tire manufacturer), and from the Ecoinvent v3.8 database (Wernet et al., 2016). The dataset is provided in Supporting Information S4. It was built following several steps to ensure coherence: (1) selection according to geographical, time, and technology representativeness of the data sources, (2) scaling and unit conversion, and (3) harmonization. In this process, whenever possible, the same parameters, hypotheses, and calculation methods were used for similar processes.

The tire composition is provided by Michelin and represents the composition of an average passenger car tire calculated from the tire model's composition and the share of the corresponding sales volumes in Europe. Data used for raw material production is mainly provided by Quantis within the Tire Industry Project (TIP) and Michelin.

In material recovery and civil engineering EOL pathways, the tire replaces the production of another virgin material that fulfills the same function (lifespan and quality are parameters for substitution rate calculation). Potential differences between the EOL of the substituted materials and the tire-derived substituting materials were ignored. In other words, we assumed that the ultimate EOL of tire-based outputs is not included in the study, considering that their ultimate EOL treatment is similar to that of the output replaced and that it hence have a similar impact. More difficulty was encountered in energy recovery data collection because the tire combustion induces not only an avoided production of fuel but also a change in emissions that is poorly documented in the literature (Clauzade et al., 2010). For the tire-based energy recovery processes, the quantities of fossil and biogenic carbon dioxide (CO_2) emissions were modeled based on a stoichiometric carbon balance assuming a full oxidation. The carbon content of the tire was estimated based on the tire composition and the chemical formula of the listed components with the carbon content of natural rubber considered as biogenic carbon.

2.1.3 | Impact assessment method

Two midpoint indicators, Climate Change short-term (CC) and Fossil and Nuclear Energy Use (FNEU), and two damage indicators, Ecosystem Quality (EQ) and Human Health (HH) from the ImpactWorld+ version 2.0 impact assessment method (Bulle et al., 2019), were selected to provide a comprehensive environmental impact profile. In this study, HH and EQ do not include the contributions of climate change to ensure that the selected indicators are independent of each other. Water availability contributions are also removed from HH and EQ since the software used does not include default regionalization of water flows, and hence, results could be distorted.

2.1.4 | Mathematical structure

The matrix representation of the model is based on the traditional LCA equation described by Heijungs and Suh (2002):

$$\boldsymbol{s} = \boldsymbol{A}^{-1}\boldsymbol{f}, \tag{1}$$

where $\boldsymbol{s}$ is the scaling vector containing the scaling factor of each process in the system; $\boldsymbol{A}$, also defined as the technology matrix, is a square matrix containing all the exchanges of economic flows (rows) between the processes (columns), and $\boldsymbol{f}$ is the final demand vector that contains the FU. The total environmental impact scores of the system are obtained by multiplying the impact factors per unit of elementary flow that each process produces by the corresponding scaling factor computed to fulfill the functional unit:

$$\boldsymbol{h} = \boldsymbol{QBs} = \boldsymbol{QBA}^{-1}\boldsymbol{f}, \tag{2}$$

where $\boldsymbol{h}$ is a vector containing the final impacts scores of the product system delivering the FU, $\boldsymbol{Q}$ is the characterization matrix that contains the characterization factors linking the elementary flows (columns) to the corresponding impact factors (rows), and $\boldsymbol{B}$ is the elementary flow matrix containing the elementary flows (rows) directly consumed or emitted by each process (columns) before scaling.

In this study, to simplify the calculations, the cradle-to-gate impact scores of background processes and the gate-to-gate impact scores from foreground processes are pre-calculated and directly supplied to the optimization model. Let $\boldsymbol{E}$ be a matrix containing the environmental impact scores (lines) of each process (columns) before scaling. The equations become:

$$\begin{aligned} \boldsymbol{E} &= \boldsymbol{QB}, \\ \boldsymbol{h} &= \boldsymbol{Es} = \boldsymbol{EA}^{-1}\boldsymbol{f}. \end{aligned} \tag{3}$$

All impact assessment calculations were made with Brightway (Mutel, 2017) using the Activity Browser interface (Steubing et al., 2020).

2.2 | A2: Optimization of the European tire waste management system

This second analysis is based on the same dataset as A1, and the same impact assessment method is used.

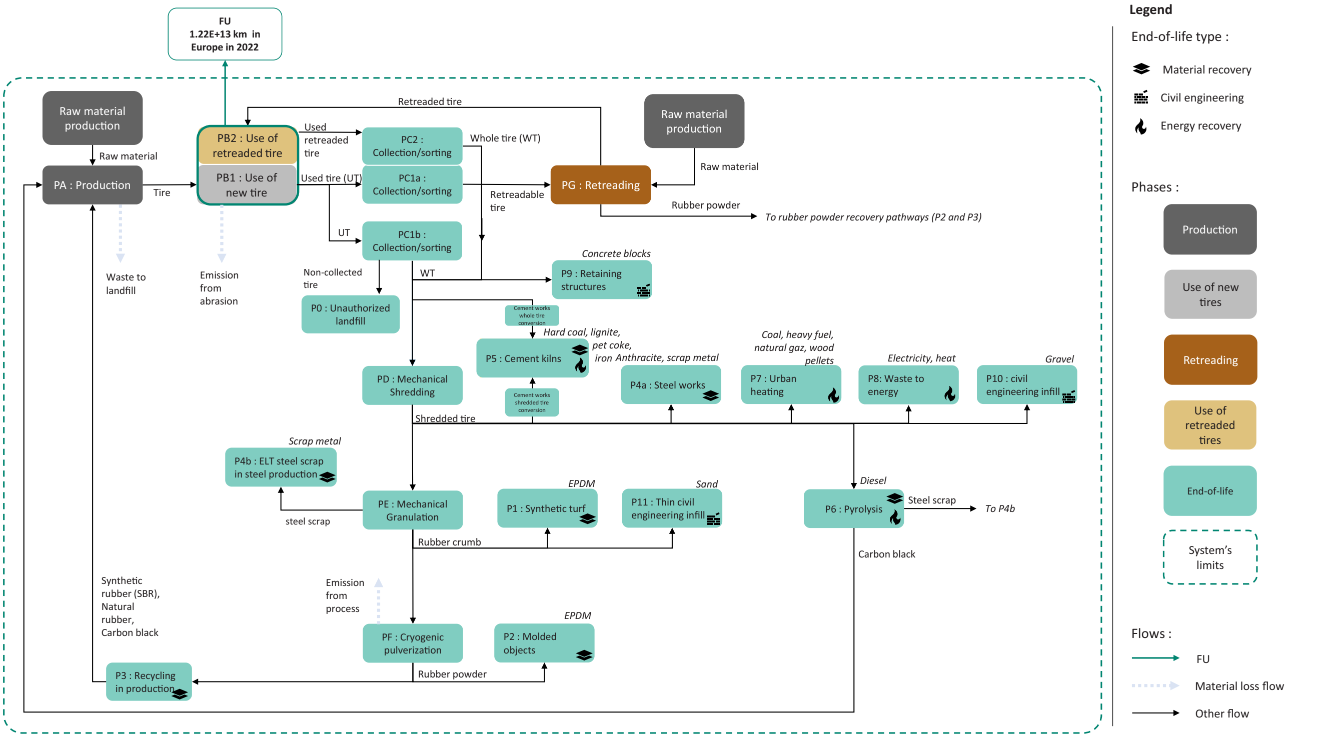

FIGURE 1 Optimization of the end-of-life tires repartition within the European tire waste management system to minimize the environmental impacts of the distance traveled in Europe in 2022 (1.3×10^{13} km) (A2).

2.2.1 | Modification of the scope of the study

The functional unit is modified as follows: 1.3×10^{13} *km traveled in Europe in 2022*, reflecting the total distance traveled in Europe as if it were traveled by one tire. The system boundaries are consequently extended to encompass raw material production, tire production, retreading, and the use stage of both new and retreaded tires. The flow diagram is available in Figure 1 where life cycle stages are represented by different colors. The "Production" stage includes the cradle-to-gate production process, covering in particular the impacts from raw material production. The "Use" stage includes the use of new tires and the use of retreaded tires. The "Retreading" stage encompasses the gate-to-gate impacts from the retreading process and the impacts from the production of raw material added to the tire. All the EOL treatment pathways, including collection and sorting, transformation/separation processes, and their specific EOL processes, are grouped in the "End-of-life" stage. A summary of the main differences and results of A1 and A2 is provided in Supporting Information S2.

2.2.2 | Modification of the mathematical structure

In this second analysis, the EOL treatment technologies are competing to process used tires. The matrix structure of the problem is therefore modified based on the rectangular choice-of-technology (RCOT), which is an input–output model developed by Duchin and Levine (2011) and adapted to LCA by Katelhön et al. (2016). Each technology is represented by a column in the ***A*** technology matrix, which then becomes rectangular and makes the equation system undetermined: there is an infinite range of combinations of EOL treatment technologies that can be chosen to provide the FU. The optimization framework guides the system toward optimal solutions regarding the user's interests by defining the variables, the objective function, and the constraints of the problem to bring out the optimal set of scenarios based on these criteria. The optimization problem is defined as follows:

minimize

$$\Phi(s) = \sum_{i=1}^{4} w_i h_i^{\text{norm}}(s) \tag{4}$$

TABLE 2 Constraint values and calculation hypothesis.

Proces name	ub_i	Calculation method
P1: Synthetic turf	5.2×10^7 kg of tire crumb	Current quantity of synthetic fields in Europe multiplied by the quantity of tire necessary per football field divided by the lifespan
P2: Molded objects	2.8×10^7 kg of rubber powder	Percentage of the molded object annual production
P3: Recycling in production	15% of the production material input	Provided by Michelin
P6: Pyrolysis	0	Supposed not mature enough, from the literature
Retreading	5% of retreadable tires	Amount supposed from numbers from European countries and economic barriers to retread a personal car tire

subject to

$$\begin{cases} \boldsymbol{As} = \boldsymbol{f} \\ lb_p \leq s_p \leq ub_p \quad \text{for p} \in [1, n] \end{cases} \tag{5}$$

such that

$$\begin{cases} w_i > 0 \\ \sum_{i=1}^{4} w_i = 1. \end{cases} \tag{6}$$

The variables are the scaling factors of the system including the quantity of material sent to each EOL route, that is, the coefficients s_p.

This problem would be a multi-objective optimization problem with four objective functions, corresponding to the impact scores in CC, FNEU, EQ, and HH, that are to be minimized, and whose values are the coordinates h_i of the corresponding vector $\boldsymbol{h}$.

In this study, the weighted sum method is chosen to transform the multi-objective optimization problem into a single objective optimization problem by defining the objective function Φ being the weighted sum of the normalized environmental impact scores h_i^{norm} (Equation (4)) (Arora, 2012). All the combinations of weights built with (0, 0.25, 0.5, 0.75, 1) are tested, and the exhaustive list of optimal scenarios found are provided in the results. Functions must be normalized such that the different units and the magnitude of the environmental impacts scores can be harmonized to allow an efficient exploration of the solution space by varying the weight combinations. The normalization formula is defined as follows:

$$h_i^{\text{norm}}(s) = \frac{h_i(s)}{h_i^{\text{max}} - h_i^{\text{min}}}, \tag{7}$$

where h_i^{max} is the maximum value of $h_i(s)$ in the solution space, and h_i^{min} is the minimum value of $h_i(s)$ in the solution space (optimum).

The first set of constraints is the traditional LCA equation (Equation (1)). In addition, constraints linked to the accessibility of the assessed technologies are added to restrain the solution space to the feasible technology mixes. Each coefficient s_p is therefore contained between a lower boundary lb_p and an upper boundary ub_p, chosen by the user to represent the market limitations. The constraints associated to each technology, lb_p and ub_p, are estimated from European average data based on material, economic, and technological barriers. No limitation is supposed for energy recovery processes because of the destructive nature of these technologies and the growing demand for energy. Due to a lack of data, no constraints were defined for tire use in steel works (P4a and P4b) and for civil engineering processes (P9, P10, and P11). However, these options were never preferred. Therefore, adding constraints would not have any influence on the results. More information about the remaining constraints calculations are given in Table 2 and in Supporting Information S6.

The final set of solutions gathers all the available repartition scenarios obtained within the solution space. Each one either minimizes one impact category or is a compromise between two or more impact categories. The combinations of weights used to obtain these optimal scenarios are not provided in the results because they do not represent anything in the physical world. The decision-maker should consider the environmental performances of the scenario rather than the weight combinations used to generate it.

The matrices are contained in an excel file (available in Supporting Information S5). Python is used to code and run the optimization algorithm (code provided in Github, https://github.com/LisaDuval/Optimization-European-end-of-life-tire-system-management) and to generate the graphs.

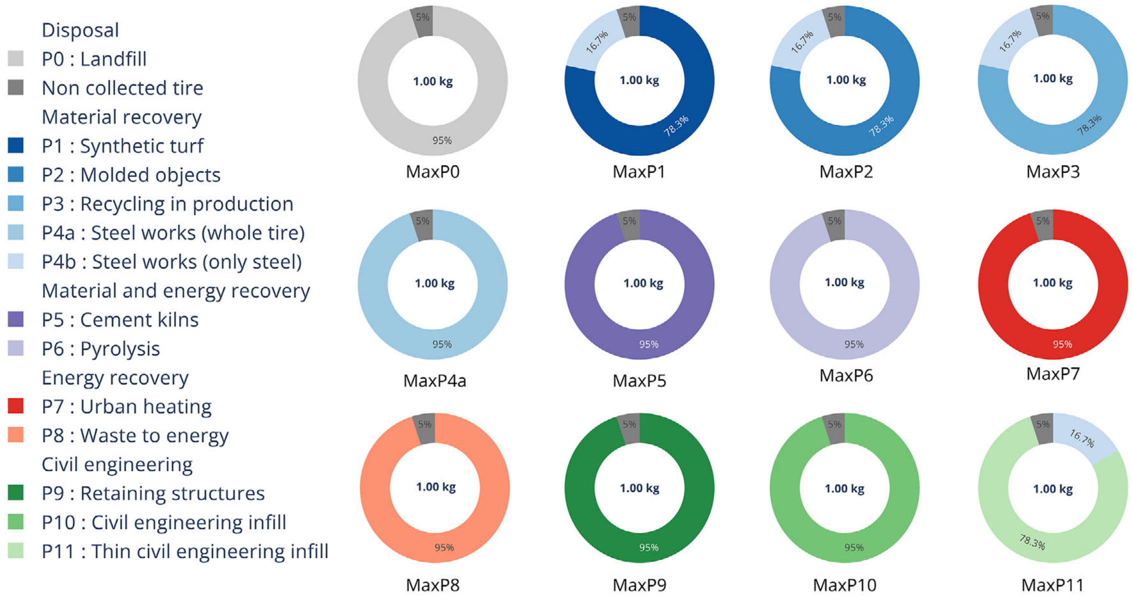

FIGURE 2 Repartition of 1 kg of end-of-life tires maximizing each one of the 12 main European tire waste management technologies (A1).

3 | RESULTS

For both analysis, the results are provided in terms of material repartition and their corresponding impacts in two distinct figures. Data that are used in figures are provided in Supporting Information S1.

3.1 | A1: Comparison of the European end-of-life tire treatment pathways

3.1.1 | Material repartitions

Figure 2 shows the repartitions of ELT in the available pathways of the 12 scenarios assessed in A1, corresponding to each EOL pathway given in Table 1. Each donut chart corresponds to a scenario and shows the total quantity of ELT that arrives in the EOL treatment stage in absolute value and its repartition within the EOL routes in percentage.

In all cases, 5 % of the material is not recovered by the collection/sorting process and appears in dark grey; this quantity is based on the European tire recovery rate (ETRMA, 2021). When a granulation step is required prior to the EOL treatment, the metallic part and the rubber part of the tire are separated and treated by different technologies: the metal part is recycled in steel works (P4b) and the rubber part in the chosen EOL pathway (P1, P2, P3, or P11). Some material is lost during the cryogenic pulverization process due to particulate emissions, but this quantity is too small to appear in the final figure.

3.1.2 | Environmental impacts

Figure 3 shows the impact scores corresponding to the scenarios displayed in Figure 2. They are presented regarding the four chosen impact categories (CC, FNEU, EQ, and HH). The impact scores and avoided impacts (environmental credits) are presented separately by plain or stripped colored bars, whereas the total net impact scores are given by the bars with a black outline.

All the scenarios tested show a negative net impact score, except when tires are landfilled (*MaxP0*). It means that whatever treatment option is chosen, the benefit of energetic, material, or physical properties recovery of tires offsets the environmental impacts coming from the EOL treatment itself. To landfill the tires appears to be a waste of valuable resources.

Overall, in all impact categories, the rubber material recovery pathways (*MaxP1*, *MaxP2*, and *MaxP3*) have the best performances, and the civil engineering pathways (*MaxP9*, *MaxP10*, and *MaxP11*) present the least environmental benefits. This tendency is directly linked to the type and quantity of the avoided material: virgin polymer production has a higher impact in all categories than sand, gravel, or concrete production.

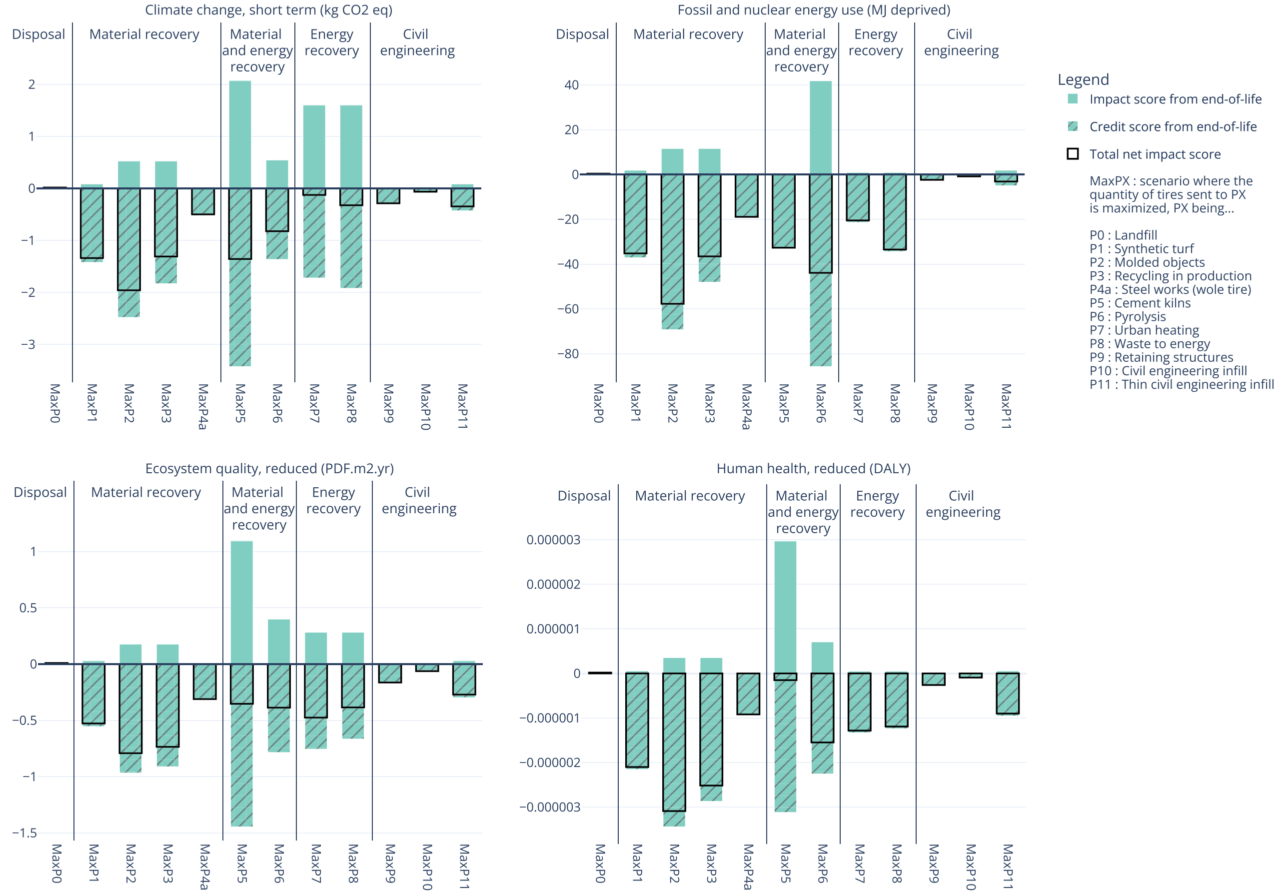

FIGURE 3 Tire life cycle stages and their contribution to the total net environmental impact scores, given in repartitions of 1 kg of end-of-life tires; each of the 12 main European tire waste management technologies is maximized (A1).

Energy recovery pathways have mixed environmental performances depending on the impact category observed. For CC, treatment in cement kilns (*MaxP5*) is the second best alternative overall, while for FNEU, it is pyrolysis (*MaxP6*).

The best environmental scores for all the assessed impact categories are reached when the rubber from ELT displaces virgin ethylene propylene diene monomer rubber (EPDM) in molded objects production (*MaxP2*). Sending all the discarded tires toward the molded object industry would be the best choice to reduce all the environmental impacts.

3.2 | A2: Optimization of the ELT repartition within the European tire waste treatment system

For the second analysis (A2), three sets of results are produced (Figure 4): two of them are obtained from an a priori defined simulation and used as a baseline to compare optimal solutions. The *AllToLandfill* simulation consists in sending all the ELT to landfill, which would represent a “linear economy” reference scenario, or the situation that would hypothetically exist without any European waste policy. The *ActualDistrib* simulation represents the actual repartition of ELT in Europe extrapolated from ADEME (2020). All other scenarios are obtained by optimization without and with constraints, respectively, in order to highlight the difference between a system where all treatment pathways are considered equally accessible and the same system where some options are limited. The constrained scenarios are identified by “-c” at the end of their name.

3.2.1 | Material repartitions

Without constraint, the optimizer sends the maximum quantity of tires into molded object production (P2), which is the option with the least impact for all impact categories, as shown by A1 (Figure 3). However, while in A1 it was not possible to assess retreading, due to the FU and related system boundaries being defined in too narrow a scope, it becomes possible in A2 because of its different FU and more broadly defined scope. A second

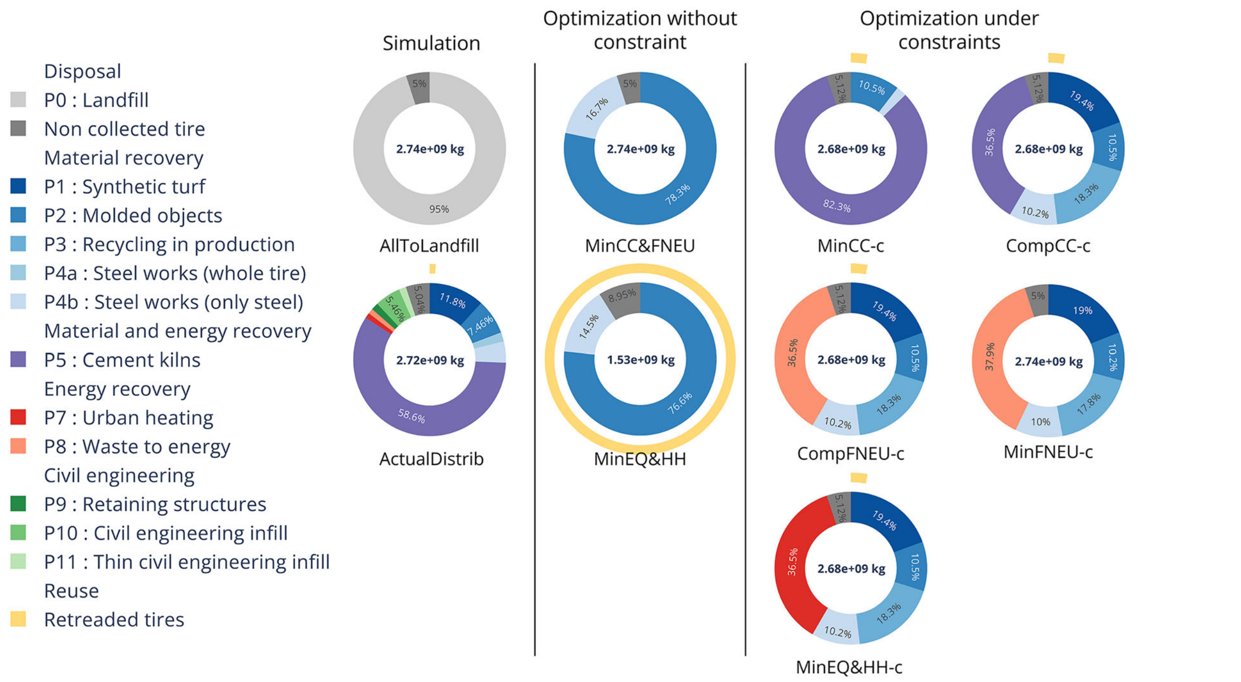

FIGURE 4 Simulated and optimal repartitions of end-of-life tires (ELT) within the European tire waste management pathways to minimize the environmental impacts (A2). The masses inside the rings represent the quantity of ELT arriving at the end-of-life treatment stage. Two scenarios are simulated (*AllToLandfill* and *ActualDistrib*), two scenarios are obtained by optimization without constraint (*MinCC&FNEU* and *MinEQ&HH*), and five scenarios are obtained by optimization under constraints (*MinCC-c*, *MinFNEU-c*, *MinEQ&HH-c*, *CompCC-c*, and *CompFNEU-c*).

scenario with a similar repartition of ELT emerges from the optimization without constraints, but here 100% of tires are retreaded. This leads to a significantly lower amount of tires to fulfill the same FU: 1.53 instead of 2.74 million tons of tires.

The optimization of the constrained scenario leads to significantly diverse solutions with an increased number of EOL pathways involved. The optimizer will favor the pathways with less impact over those with more impact, until their limits to distribute the total quantity of ELT are reached. Overall, the privileged technologies are the material recovery processes that were identified to have good environmental performances in A1 (P1, P2, and P3) followed by energy or mixed energy/material recovery processes. Civil engineering pathways are not chosen by the optimization because of their lower environmental credit in all impact categories.

3.2.2 | Environmental impacts

The environmental performances of the three sets of assessed scenarios are presented in two figures. Figure 5 displays the total net impact scores of each scenario in a parallel coordinate graph, and Figure 6 shows the relative life cycle stage contribution using the worst-case scenario *AllToLandfill* as a reference.

Unlike the scenarios assessed in A1 (except *MaxP0*) (Figure 3), A2 reports positive (i.e., detrimental) instead of negative (i.e., beneficial) impact scores, thereby highlighting the adverse environmental net impact of the tire's life cycle as a whole (Figure 5). The broader scope of analysis unambiguously clarifies that maximizing the credit from EOL by increasing the quantity of tire treated would result in an overall impact augmentation because of the increase of the quantity of tires produced and used.

A change in contributions from other stages appears since system boundaries are extended such that they now include the production, use, and retreading stages (Figure 6). The maximum environmental performances for CC, FNEU, EQ, and HH reach a 7.6%, 14.8%, 12.6%, and 17.3% improvement, respectively, compared to the scenario *AllToLandfill*. The gap between the best unconstrained and the best constrained scenario scores in each impact category represents the potential for improvement induced by the relaxation of constraints, that is 2%, 5.1%, 4.9%, and 8.3%, respectively, for CC, FNEU, EQ, and HH (Figure 6).

Since tires go to the same EOL pathway, the comparison between the unconstrained scenarios *MinCC&FNEU* (0 % of tires are retreaded) and *MinEQ&HH* (100 % of tires are retreaded) helps to identify the consequences that retreading has on several stages of the tire's life cycle. Less material flows in the system of the scenario with retreading (*MinEQ&HH*). This reduces the impacts and credits from the production and EOL treatment that are directly proportional to the quantity produced and treated. However, it adds the impacts from the retreading process itself and rises the

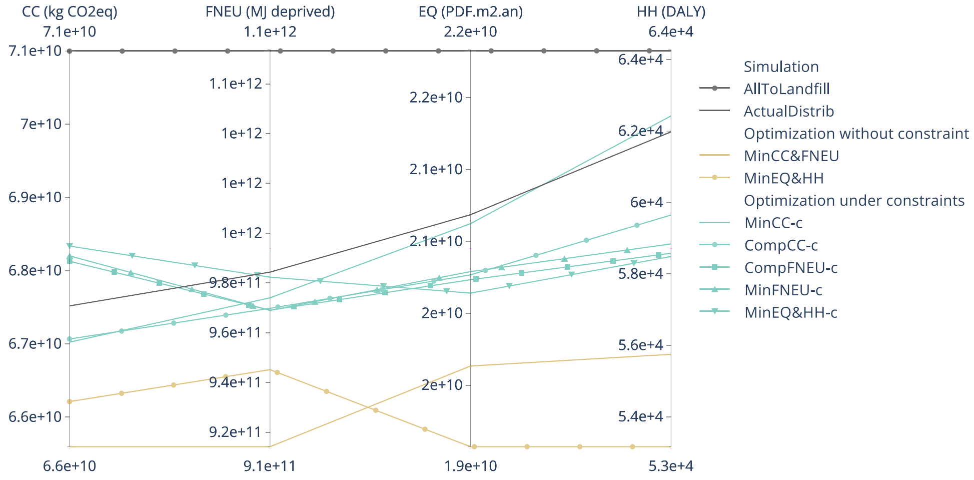

FIGURE 5 Net environmental impacts of the simulated and optimal repartitions of end-of-life tires (ELT) within the European tire waste management pathways minimizing the environmental impacts (A2). Each scenario is represented by a polygonal line intersecting the axes at their corresponding impact values. Intersections between polygonal lines depict trade-offs between the adjacent environmental impact categories. Grey lines represent the two simulated scenarios (*AllToLandfill* and *ActualDistrib*), yellow lines the two scenarios obtained by optimization without constraint (*MinCC&FNEU* and *MinEQ&HH*), and blue lines the five scenarios obtained by optimization under constraints (*MinCC-c*, *MinFNEU-c*, *MinEQ&HH-c*, *CompCC-c*, and *CompFNEU-c*).

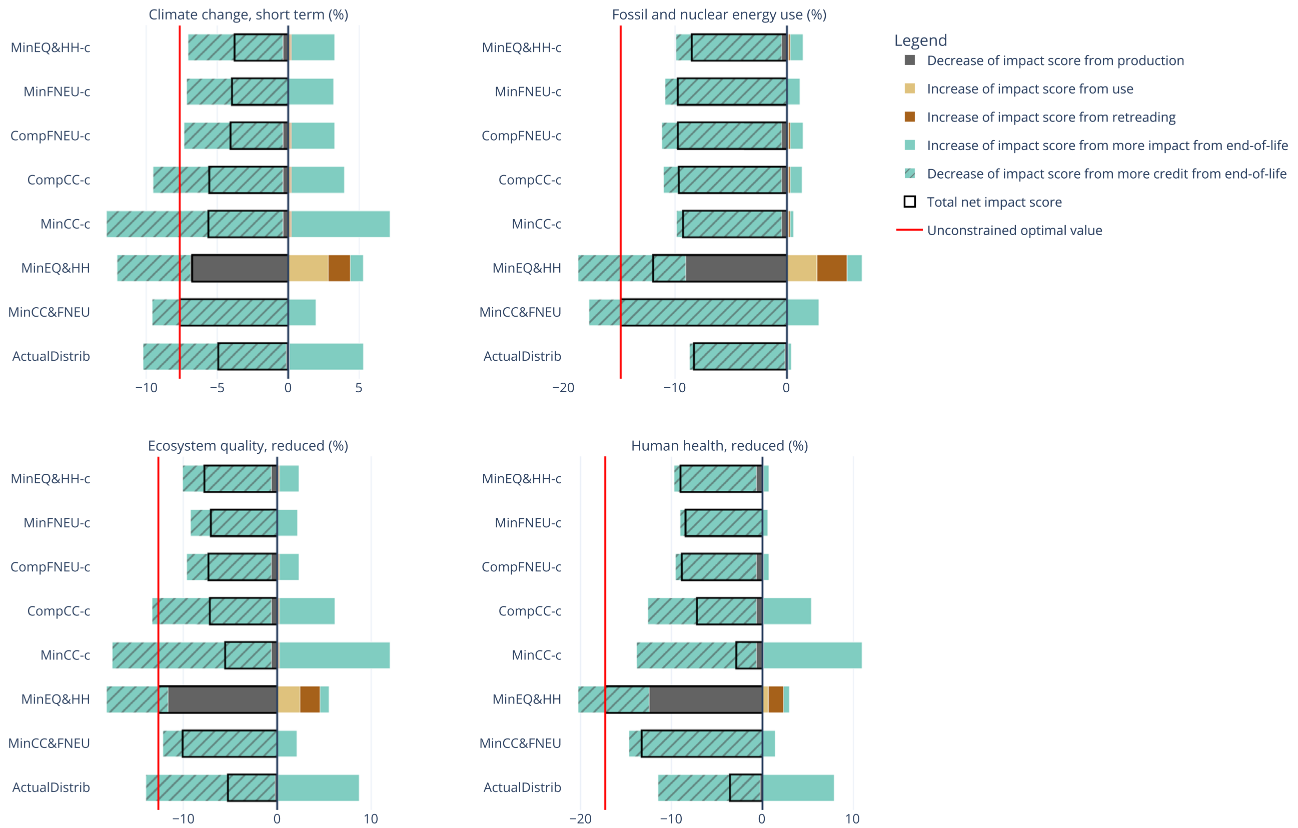

FIGURE 6 Relative contribution to the total net environmental impact scores of the tire life cycle stages of the simulated and optimal repartition scenarios (A2). Values are given in percentage relatively to the simulated scenario *AllToLandfill*. One scenario is simulated (*ActualDistrib*), two scenarios are obtained by optimization without constraint (*MinCC&FNEU* and *MinEQ&HH*), and five scenarios are obtained by optimization under constraints (*MinCC-c*, *MinFNEU-c*, *MinEQ&HH-c*, *CompCC-c*, and *CompFNEU-c*). The red line shows the best impact score obtained for each impact category.

impacts from the use stage because a retreaded tire consumes more fuel per kilometer traveled due to its higher rolling resistance. Ultimately, for the EQ and HH categories, the gain in environmental performances from less tires produced compensates the impact increase due to the use stage, the retreading process and the loss of credit from the EOL treatment stage. The situation is inverted for the categories CC and FNEU where the scenario *MinCC&FNEU* has better environmental performances than *MinEQ&HH*. These conclusions hold when tires are sent to the molded object production (P2) pathway afterward.

Regarding the impact scores of the constrained scenarios, it is more visible in Figure 5 that there are three scenarios that minimize one or two impact categories: CC is minimized by the scenario *MinCC-c*, FNEU by *MinFNEU-c*, and *MinEQ&HH-c* minimizes EQ and HH. The optimization also selected *CompCC-c* and *CompFNEU-c*, which are compromise scenarios. The first one has a little more impact in CC, but is performing much better in the other impact categories than the *MinCC-c* due to a proportion of tire going to rubber material EOL processes (P1, P2, and P3) that has high reduction potential in all impact categories instead of cement factories (P5), process more impacting in FNEU, EQ, and HH. Similarly, the scenario *CompFNEU-c* is less efficient to minimize FNEU but presents better scores in the other impact categories compared to *MinFNEU-c* due to the use of retreading.

This constrained optimization shows a scenario where retreading is favored when the category CC is minimized (*MinCC-c*), which was not the case in an unconstrained system. The net benefit or impact from retreading lies in its influence on four life cycle stages (production, retreading, use, and EOL) as presented before. When retreading is favored, the reduction of the tire quantity flowing through the system lowers in particular the amount of environmental credit given by the EOL stage. The amount of credit per kilogram of tire treated depends on the pathways chosen: there is a tipping point where the loss of credits in the EOL stage is too important to be compensated by the environmental impact reduction from production and therefore disfavors retreading. The scenario *MinCC-c* illustrates this effect for the CC impact category when compared to the scenario *MinCC&FNEU*: the credits from an EOL mix sending 82.3% of ELT to cement kilns (P5) and 10.5% into molded objects production (P2) are less important than the credits from an EOL mix sending 76.6% of ELT into molded object production. Therefore, the loss in credit from the EOL stage is not important enough anymore to condemn retreading. This means that the environmental benefits of retreading depend on the EOL repartition and that retreading could be artificially disfavored in unconstrained systems.

Even though the scenario *AllToLandfill* is confirmed to be the worst in all impact categories, there is only one scenario that is better than the *ActualDistrib* within the constrained scenarios regarding all the impact categories. Three scenarios, *MinFNEU-c*, *MinEQ&HH-c*, and *CompFNEU-c* are more impacting regarding CC whereas *MinCC-c* has more impact in HH. The trade-offs between impact categories preclude an environmental impact reduction in all impact categories simultaneously.

4 | DISCUSSION

The contrast between the two analyses highlights the challenges associated with upscaling results in LCA. What may appear valid at a small scale may not necessarily hold true at a larger scale: in this study, the routing of all European tires toward the single best EOL pathway is unfeasible due to constraints that exist on a European scale. This necessitates the allocation of this material across multiple EOL pathways instead of relying on a single one. This conclusion underscores that, in general, adapting an LCA to a larger scale cannot be reduced to a mere multiplication of the functional unit but rather requires a more intricate adjustment of the model to accommodate this new scale.

The systemic approach in A2 allows to put the results in a circular economy perspective. For example, the promotion of material loops is a fundamental principle of circular economy. At the product scale, reusing old tires to produce new ones would contribute to keep the material within the life cycle of the tire. However, tire reuse competes with the replacement of different materials or energy sources in other sectors of the industry that could lead to more interesting environmental benefits. Circular economy should be applied in a cross-sectoral way to maximize the environmental benefits for the whole economy, and not for a single product chain or industrial sector. This scaling effect of circular economy is also investigated in a PET plastic bottle case study conducted by Lonca et al. (2020) that shares the same conclusion.

The results obtained largely validate the current European waste hierarchy, and help refine its broad recommendations for ELT management. “Prevention,” which corresponds to a diminution of the number of kilometers driven by light vehicles, would indeed be the best way to lower the impacts of the whole system. Then, retreading, which corresponds to a “Reuse” process, simultaneously reduces environmental impacts at the production stage and augments them in three other stages: in the retreading stage itself, in the use stage due to additional fuel consumption, and in the EOL stage where environmental credit is lost to a varying extent, depending on the chosen EOL pathway. The overall performance of retreading depends on all these life cycle stages, which must be included in the analysis to be assessed properly. The results even show that if LCAs ignore constraints, they may artificially disfavor reuse and bias the final decision taken. This emphasizes the importance of including these constraints in the analysis. As conservative limitations, assuming significant economic barriers, have been imposed on retreading, relaxing these constraints could result in even greater environmental benefits in scenarios where retreading is favored.Then, “recycling” in the hierarchy would include material recovery and civil engineering applications for ELT. The results show that recycling is to be favored if the properties of the recovered rubber/material are of functional relevance in its second life, such as in material recovery and contrary to civil engineering where only the structural properties are retained. Energy recovery pathways, which correspond to the “recovery” category, are even to be preferred over civil engineering applications in the particular case of tire under the current energy system contrary to what is recommended. In a future where the energy system becomes decarbonized, energy recovery might become less preferable. Nevertheless,“disposal” remains the last resort for the treatment of waste tire. The tire disposal ban by the European Union and the implementation of the European waste hierarchy have already ensured great progress both in environmental impact mitigation and circular economy compared to a linear scenario where tires would be landfilled.

By extending the system boundaries, this analysis makes links between all the actors of the value chain that can influence several steps of the life cycle of the tire. For example, a change in the tire's composition made by tire producers could change the environmental impacts of raw material production, the fuel consumption in the use stage and the EOL treatment stage and therefore involve the raw material suppliers, the consumers, and the EOL actors. Such a broader scope of analysis also identifies actors outside the value chain that might contribute to the whole EOL treatment system by facilitating the integration of tires in their industrial sector to obtain the best environmental performances. All these actors should work together rather than separately to enhance the environmental performances of the whole life cycle of the tire, and studies to guide large-scale decisions must include them to highlight their influence.

5 | LIMITATIONS

First, the study demonstrates that the results are sensitive to the constraints imposed on the most environmentally preferable EOL pathways, with tighter constraints leading to a tire allocation shift between pathways and, in turn, resulting in an increase in overall environmental impact. Estimating the maximum potential sizes of markets for EOL byproducts with precision constitutes a major challenge. Notably, the current list of constraints is not comprehensive, and substantial enhancement would entail both improving their calculation through expert consultation and considering additional factors such as regulations or social acceptance. Nevertheless, by contrasting conservatively constrained scenarios with completely unconstrained models, our results demonstrate the strategic influence of these market dynamics for circular economy initiatives. The identification of the most binding constraints and the study of the most effective and easy-to-implement means to relax them is a promising direction for further research to efficiently guide the implementation of sustainable policies.

More broadly, the accuracy of the results is reliant on the quality of the collected data. The multitude of sources used to construct the dataset contributes to its richness but has also presented a harmonization challenge. Collaborating with stakeholders involved in the life cycle of the tire (industry, consumers, governmental entities, etc.) would help refine the data quality, not only for modeling constraints but also for modeling processes, and represents a highly relevant avenue for further work.

Second, the data used represents the ELT processing technologies in Europe, and the number of tires produced and discarded is based on the amount of tires actually used in Europe (ETRMA, 2019). Potential differences in the cradle-to-gate impacts of the 30% share of tires produced abroad and imported (ETRMA, 2019; ADEME, 2020) were neglected. This assumption only affects the life cycle benefits of retreading, leaving the life cycle performances of all other EOL treatments unaffected. Nevertheless, examining the import–export dynamics of tires presents an opportunity to explore the trade-offs associated with factors such as the distances tires travel to access EOL treatment pathways, potential variations in parameters within these pathways linked to their geographic context, and the constraints that may arise in expanding treatment options.

Ultimately, the study is conducted in a short-term context, that is, all the data used to model the technologies and their constraints only represent the current situation in Europe. The scenarios that appear to be optimal today could be very different in the future due to the evolution of the EOL technologies available, of the energy mix, and more broadly of the automotive industry. The results of this analysis are valid only to make short-term and European-level decisions, but constitute a first step to build a prospective optimization model with dynamic background data to make proactive decisions about the future to guide the EU's decarbonization and energy transition.

6 | CONCLUSION

The quantity and complexity of tires have made ELT management a technological, economic, and environmental challenge.

This paper contrasts two different approaches to assess the environmental impacts of the European tire waste treatment system. The first one is the traditional LCA where the scope is restricted to the EOL system boundary and scenarios are defined a priori and compared. The results enable the decision-maker to rank the pre-defined EOL pathways individually: rubber recovery pathways are the best alternatives, followed by energy recovery and civil engineering. Landfilling does not bring any environmental benefit and should be avoided as it is the case under the current European legislation. The second analysis is an optimization with an extended system boundary that encompasses the tire's full life cycle and considers the EOL treatment system as a whole including its competing technologies and the constraints they face. The emerging EOL technology mixes depend on the environmental impact that the decision-maker wishes to minimize and on the constraints the system faces. In addition to how the ELT is repartitioned within the EOL pathways, relaxing constraints can become an additional lever to mitigate the environmental impacts. From a methodological perspective, the use of multi-objective optimization is a way to explore the whole solution space and does not give a final answer, but a set of optimized scenarios that may be relevant to consider for the decision.

The purpose of this study is not to show that one approach is superior to the other, but that both types of analysis are suitable depending on the question asked and the scale of decision-making. LCA analyses done with a restricted scope are particularly adapted to guide small-scale choices when a limited number of options need to be analyzed in detail. By contrast, in order to guide large-scale transition choices, an optimization-based LCA approach is necessary. Thus, the entire spectrum of the alternatives available within their respective system can be considered while taking into account the competition and complementarity between these options and their constraints.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article https://doi.org/10.1007/s11367-016-1087-8.

ORCID

Lisa Duval https://orcid.org/0009-0007-1146-6243
Manuele Margni https://orcid.org/0000-0002-2475-0768

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Duval, L., Majeau-Bettez, G., Saunier, F., Maréchal, F., & Margni, M. (2024). Optimization of the end-of-life tire repartition within the European treatment system to minimize its environmental impacts. *Journal of Industrial Ecology*, 1–15. https://doi.org/10.1111/jiec.13474