A reverse logistics network optimization model for residual OTR tires from the mining industry: A Colombian case study

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Abstract
Around a billion new tires are generated every year around the world as a result of the global growth of the tire industry, but only a small percentage are reused as in closed-loop supply systems. The mining industry is one of the world's massive scrap off-the-road (OTR) tire generators considering their uninterrupted high-scale activity fueling faster OTR tire life cycles. The handling of massive OTR tires discarded from the mining industry represents an economic, environmental and social challenge. As a solution to this problem, reverse logistics plays an important role enabling the cost-effective management of residual items while affecting the service and product recovery value, adequate final disposition and the development of environmentally friendly practices. This research proposes a solution approach to the problem of the reverse logistics network for residual OTR tires from the mining industry, illustrating with a Colombian case study. An optimization model is proposed to determine the final OTR tires disposition at a minimum cost. Results showed that opening a power generation plant might be a potentially cost-effective solution that could help mines to comply with the country's regulations and turn this waste into a positive value good.

Keywords
Reverse logistics network; scrap tire; mining industry; optimization model; Colombian case study.

1. Introduction
The tire industry is a global and growing industry, in which around a billion new tires are generated every year around the world (Kumar & Saravanan, 2014), with only a small percentage of these being properly disposed for reuse in closed-loop supply systems. This research develops in the context of the mining industry, a significant market segment for the tire industry, but even more significant with regards to the share of scrap tires by weight that is generated as an externality of the mining operations (Sheerin, 2017). In the world, the handling of massive OTR (Off the Road) tires discarded from the mining activity, oftentimes simply disposed as a whole and piled up near the operation, has represented an economic, environmental and social challenge.

As for the economical adversities advised, are due to the logistical difficulties in transporting OTR tires from remote places to any given location due to its huge dimensions: the diameters of these tires oscillate between 2 and 3 meters, but they can reach up to 4 meters with weights of more than 3 tons (Goodyear, 2017). Downsizing these tires as an initial step for reusing and/or recycling also poses both significant technical and economic challenges, due to its gigantic dimensions that requires important investments in heavy duty large-sized shears for tires to be chopped up into pieces small enough to fit into a large shredder and then into mechanical grinding pulverization systems. Most usual ecology conversion alternatives into by-products start from tire triturate, directly used as raw materials in road construction, parks and sports surfaces (Ferrão, Ribeiro & Silva, 2008). Tire triturate is as well input of a variety of energy recovering techniques used as fuels (Amari, Themelis & Wernick, 1999; Jang, Yoo, Oh & Iwasaki, 1998) and incineration processes available including dedicated incineration, incineration in utility and industrial boilers, incineration in cement kilns and pyrolysis (Galvagno, Casu, Casabianca, Calabrese, & Cornacchia, 2002).

As cited in Evans (1997), scrap tire accumulation can also potentially create adverse environmental effects and threats to public health and safety. Problems associated with scrap tires include solid waste management in landfills

(Beckman, Crane, Kay & Laman, 1974; Hall, 1990; Miner and Warfield Consultants, 1987), tires as breeding grounds for mosquitoes and rodents (Malcolm Pirnie Inc., 1991), tire fires (Best & Brookes, 1981), air emissions from tires as a fuel source (Malcolm Pirnie Inc., 1991), waste tire legislation (Scrap Tire News, 1991), and leach-ability (Envirologic Inc., 1990; Environmental Consulting Laboratory, 1987; John et al., 1984; Radian Corporation, 1989; Twin City Testing Corp., 1990; Wisconsin Department of Natural Resources, 1990). The solid waste management problematic is also influenced by regulations enacted by governments.

The objective of this paper is to formulate and develop an optimization model to minimize the logistics costs associated with the handling of the residual tires used in mining activity, exploring most viable approaches to have them properly disposed once their life cycle ends. The fundamentals of reverse logistics, closed-loop supply chain and regulations for residual tires disposal are discussed in the literature review section. We defined the problem of residual OTR tires disposal in the mining sector and proposed a MILP model in order to determine amounts of tires per year to be disposed, as well as the design of a reverse logistics network for OTR tires recycling. We considered capacity constraints and the sequencing and transportation of a single set of shredding machines allocated between four mining sites, placed within a region of approximately a hundred thousand square meters. Finally, the obtained results are discussed.

2. Literature Review

2.1. Reverse logistics

Reverse logistics (RL) as cited in Agarwal, Govindan, Darbari, & Jha (2016) over the years has been defined by many authors, referring to this as the process of planning, implementing, and controlling the efficient, 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 (Fleischmann, Beullens, Bloemhof-Ruwaard, & Van Wassenhove, 2001; Mutha & Pokharel, 2009; Rogers & Tibben-Lembke, 1999; Srivastava, 2006; Thierry, Salomon, Van Nunen, & Van Wassenhove, 1995). That means RL is a process within the supply chain management that allows for managing the returns from the clients, while altogether impacts on the service and the product recovery value, its adequate final disposition and the development of environmentally friendly practices. Barker & Zabinsky (2008) consider reverse logistics as a set of processes in charge of receiving, evaluating, registering and transforming or treating the products returned by customers, to reuse them in the industrial environment or to properly dispose them to reduce the impacts on the environment, the community and generate economic benefits. Chiou, Chen, Yu, & Yeh (2012) claim that reverse logistics has become an important source of opportunity for companies to improve visibility and profitability and lower costs across supply chain.

More companies are now regarding reverse logistics as a strategic activity because it can create value out of waste. Mollenkopf & Closs (2005) proved the point that companies can well manage the flow of goods back through their supply chain and will have many more benefits, such as creating additional revenue, reducing operating costs, and minimizing the opportunity costs of defective or out-of-date products. Govindan et al. (2012) agree with this, stating that companies hiring reverse logistics assistance from third party providers could reduce up to 10% of their company's annual logistics costs.

2.2. Scrap tires disposal

In the words of Beckman et al. (1974), scrap tire disposal has been with the rubber industry since the use of tires became significant. Initially, the rubber industry reclaimed the scrap tire. However, as the industry developed synthetic elastomers, the reclaim processes became more complex and expensive. Malcolm Pirnie Inc. (1991) concluded that scrap tires should be considered a resource rather than a waste material; scrap tires in either a shredded, chipped, or whole condition can be combusted in an environmentally sound manner; and scrap tires have a significant heat content, and under controlled conditions this heat can be extracted for a beneficial use. Despite this, they also claim that several other issues must be addressed concerning the use of scrap tires for heat recovery, such as the issues of chipping or shredding technology reliability, regulatory review, uniformity of air emissions data and test methodologies, and ash characteristics. De Souza & D'Agosto (2013) concluded that despite scrap tires are usually considered to be negative value goods that do not generate revenue when reintroduced into the production cycle, by taking advantage of cross applications, it is possible to use scrap tires as a substitute for petroleum coke for co-processing in cement plants. This method remunerates the chain elements, except in extreme situations in which petroleum coke reaches minimum value. In addition, the proper use of scrap tires reduces public health costs by minimizing potential breeding grounds for insects and rodents, which often lead to the development of diseases, such as dengue fever, yellow fever, leptospirosis, and malaria (De Souza & D'Agosto, 2013).

The handling given to final disposal of scrap tires has been widely explored in the literature. However, there are two types of scrap tires: regular tires used in automobiles and off-the-road tires, also known as OTR tires. Sheerin (2017) claims that OTR tires represent just 1% of the U.S. tire industry in unit volume, but 15 to 20% in total weight. Only the mining segment, with 8% of the OTR tires in quantity, represents 45% of the overall OTR scrap tires by weight (Moore, 2018). Seemingly, OTR scrap tires from the mining segments constitutes an interesting target for the tire recycling industry which addresses the challenge to recover and recycle the significant volume of high quality rubber and high carbon steel from these type of tires. The ecological conversion alternatives of OTR tires begin with the crushing of the tires, and later they pass on to different processes, which constitute a reverse supply chain with different routes, but which is finally part of the large closed-loop supply chain of the tires.

2.3. Closed-loop supply chains (CLSC) of scrap tires

If we consider forward and reverse supply chains simultaneously, the result network will construct a closed-loop supply chain (Govindan, Soleimani, & Kannan, 2015). According to Krapp, Nebel, & Sahamie (2013), the closed-loop supply chains (CLSC) are economic systems in which returned products or components are recycled. "CLSC focus on taking back products from customers and recovering added value by reusing the entire product, and/or some of its modules, components, and parts" (Guide & Van Wassenhove, 2009). Figure 1 illustrates a generic supply chain for both forward and reverse logistics. In this figure, the classical (forward), and reverse supply chains are presented by solid lines and dashes, respectively. In the reverse logistics chain, used products are taken back from customers and are assessed to determine if they are good to be distributed again, or they need to pass through a recovery process, or they are considered waste that needs to be disposed.

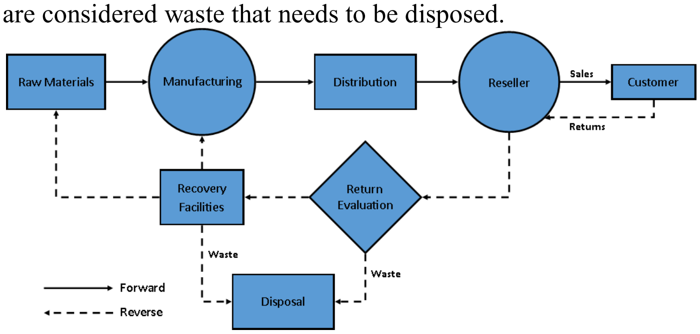

Figure 1. A generic form of forward/reverse logistics. Adapted from Govindan et al. (2015).

Subulan, Taşan, & Baykasoğlu (2015) made a representation of the closed-loop supply chain for end-of-life tires (scrap tires) considering multiple recovery options. They explain that scrap tires can be used in five alternative ways: direct reuse, retreading, recycling, energy recovery, and disposal (land filling or incineration). Analyzing each alternative, direct reuse is the most environmentally friendly but only a small fraction of the used tires can be resold in secondary markets (Martinez-Alvaro & Herrero-Del-Barrio, 2009; Panagiotidou & Tagaras, 2005). With regard to retreading, this can be done by replacing the worn rubber and the outer layer of a tire with a new rubber layer. The retreading process saves up to 80% of the material cost of a tire (Debo & Van Wassenhove, 2005), also contributing to the conservation of material resources and reducing CO_2 emissions during production processes (Bridgestone, 2010). Retreaded tires have almost the same performance as new tires, but are sold for 30-50% discounts in secondary markets (Lebreton & Tuma, 2006; Sasikumar, Kannan, & Haq, 2010). Panagiotidou & Tagaras (2005) describe that materials recovered from recycling are rubber powder, steel wires and fibers. These are separated during the recycling phase, and along with the tire granulate, they can be reused in the upper asphalt layer of roads, as well as in several other applications. Although, according to Waste Management World (2003), the reuse of tire rubber or granulate for its original intended (or related) purposes is the preferred alternative because of its environmental and economic benefits. Also, Ferrão et al. (2008) emphasized that tire recycling has an environmental benefit because it avoids the production of materials from their primary sources.

Subulan et al. (2015) also claims that tires have a high-energy content compared with other types of solid waste and fossil fuel, so they can be used for electricity generation by incineration and as a fuel substitute in thermoelectric plants, cement kilns, and paper mills. Since this fuel has a low cost compared with classical fuels (Bridgestone, 2013; Lebreton, 2007), energy may be recovered using this recovery option, as explained in Panagiotidou & Tagaras (2005), Lebreton & Tuma (2006) and Sasikumar et al. (2010). Land filling is the least preferred option for the waste management of scrap tires because when this option is used, tires must first be quartered, split, or shredded to reduce the potential for the tires to resurface (New Hampshire Department of Environmental Services, 2011) and it incurs in high processing costs. Moreover, scrap tires occupy large amounts of landfill space and they remain intact for decades (Ferrão et al., 2008). The incineration of whole tires in industrial furnaces is environmentally safe compared with uncontrolled tire fires, which create air and ground pollution (Waste Management World, 2003).

2.4. Scrap tire management regulations

In solid waste management, one of the great barriers in its implementation is the decision making for the collection of waste from the generation points to the final disposal point. In particular, the problem of waste tire management requires extensive use of reverse logistics in order to have a network that allows for an environmentally friendly use of these wastes. Even though they are not considered hazardous waste in Colombia, they do need to be returned to the producers to favor recycling, use as asphalt aggregate or retreading, as well as avoid being burned in open spaces and as fuel in informal activities, as stated by the Ministry of Environment and Sustainable Development (2017b). Kannan, Diabat, & Shankar (2014) reviewed the literature and identified factors that influence the construction of a reverse logistics model for the end-of-life tires. Some of the factors identified were extended producer responsibility (EPR), stakeholder pressure, value recovery, environmental conservation, reverse logistics and cost benefits. According to Rueda Verde (2013), consumers in Colombia tend to keep used tires in case there is any flaw in the new ones, and eventually the old tires are abandoned along with other solid wastes. This situation differs from developed countries where the end-users pay eco-fees or taxes on the EPR products (Uruburu, Ponce-Cueto, Cobo-Benita, & Ordieres-Meré, 2013).

Hickle (2014) states that while consumers are generally not subject to specific legal requirement under EPR, they are instrumental to the effectiveness of the program. In Colombia, Resolution 1457 of 2010 requires producers (those who produce more than two hundred tire units per year, manufacturers of tires and vehicles) and importers (those who import more than fifty units per year, importers of tires and vehicles) to collect certain target percentage of used tires out of the total that they sell in two years. However, tires covered by this resolution only include those from automobiles, SUVs, large vans, buses, and trucks, or noncompliant ones (less than 22.5-inch rim diameter), excluding tires from bicycles, motorcycles, airplanes, forklifts, or other similar vehicles used for agriculture, mining, or engineering purposes. The collection target in 2012 was 20%, which meant at least 20% of the tires on the market during the previous two years should be collected, and the target increases by 5% per year until it reaches 65% (Ministry of Environment Housing and Territorial Development, 2010).

Last year, the Ministry of Environment and Sustainable Development (2017) enacted Resolution 1326 of 2017, by which the Selective Collection and Environmental Management Systems of Used Tires is established and other provisions are dictated. In this resolution, the concept of 'mining vehicle tire' is defined as tires manufactured or imported for the development of mining activities with inner diameter greater than 24 inches. This resolution now includes used tires from bicycles, motorcycles, mopeds and off-the-road vehicles. Park, Díaz-Posada, & Mejía-Dugand (2018) depicts the stakeholders in the Colombian tire extended producer responsibility (EPR) system as well as material and monetary flows between them. The end-of-life management receive monetary flows from Producer Responsibility Organizations (producers and importers grouped under a collective scheme), and individual actors with or without approved EPR. The end-users do not provide a monetary flow but only a material flow to collectors because they do not pay for the collection and disposal of their waste tires, since they are not obligated to do it. This contributes to the lack of environmental awareness in end-users that leads some of them to improperly dispose their tires and causes that part of this material flow becomes illegally managed end-of-life tires.

2.5. Facility Location Problems (FLPs)

Facility location problems (FLPs) constitute a major area of interest for researchers and practitioners in operations research (OR), as explained by Ortiz-Astorquiza, Contreras, & Laporte (2018), since the mathematical structure of some FLPs has proven fruitful to the development of OR solution methodologies broadly used today, as well as their applicability to real-life problems. Before a facility can be purchased or constructed, suitable locations must be identified, appropriate facility capacity specifications must be determined, and large amounts of capital must be allocated (Owen & Daskin, 1998). According to Terouhid, Ries, & Fard (2012), traditionally decision makers have focused the decision of choosing a site on the economic aspects of locating facilities. But given the growing interest in sustainable development, location decisions frequently also include environmental and social consequences. Farahani & Hekmatfar (2009) claim that many factors have an impact on location decisions, however the importance of these factors depends on the scope of the location problem (international, national, statewide, or communitywide).

Badri (1999) states that in many location-allocation problems, cost minimization may not be the most important factor; and other factors or criteria may be considered, such as availability of transportation facilities, cost of transportation, availability of labor, cost of living, availability and nearness to raw materials, proximity to markets, size of markets, attainment of favorable competitive position, anticipated growth of markets, income and population trends, cost and availability of industrial lands, closeness to other industries, cost and availability of utilities, government attitudes, tax structure, community related factors, environmental considerations, assessment of risk, and return on assets.

3. Case Study

This investigation consists of a reverse logistics network design for the OTR scrap tires discarded from open pit mines, focusing on the 4 principal mining sites of the Colombian Caribbean region. Flórez, Toro, & Granada (2012) reviewed the solution techniques literature on the design of reverse logistics networks, including a waste tires management case in two Colombian cities. However, such study centers on the tires handling in urban environment. Barraza, Fuentes, Guarin, Silvera, & Amaya (2016) dealt with the incorrect disposal of tires used in the mining industry, proposing a linear programming model to minimize the costs of collection and final disposal of the tires collected in Colombia's principal mines. These previous works precede and serve as a base for Llaín et al., (2017), who designed a logistics strategy for the collection, downsize and transportation of scrap tires from the mining sector to a reconversion plant that generates electricity out of the rubber from shredded tires, through mathematical modeling to define a reverse network including decisions of plant location, storage and distribution of the raw material. They also used a weighted factor scoring model for the selection of the reconversion plant location alternatives as a complement to the mathematical model. The present investigation takes on the contributions from Barraza et al. (2016) and Llaín et al., (2017), thus location alternatives considered for the power plant are Barranquilla (Atlántico), El Paso (Cesar), Santa Marta (Magdalena) and Mine G (La Guajira), which in recent years implemented a shredding solution in place but this is currently idle.

4. Proposed Model

A mixed integer linear programming (MILP) model is proposed to address the problem presented earlier.

4.1. Assumptions

1. Only one power generating plant will be opened, and once opened remains operating until the end of the model time horizon. The rest of the mines will supply the generating plant with their tires.
2. The generating plant will cover the cost of shredding.
3. Everything that is sent to the power generation plant is processed.
4. Available units of tires to be sent from each mine to the generating plant at any time is the outcome of the current initial inventory of the mines plus the waste generation rate minus the net tire disposal rate during the model time horizon.
5. The time horizon considered for the model is twenty years, with semesters as time units
6. There is only one (1) set of shredding machines available and it can be assigned only to one mine at any time period t with a fixed operating cost FA_h. Additionally, at t=1 all sites will incur in an FA_h initial set up cost of adapting the shredding resource set.
7. Transportation is in full container loads

4.2. Subscripts

In table 1, all subscripts used in the proposed model are explained:

Table 1. Model subscripts with possible values and descriptions

Subscript	Possible values	Description
i = Set of mines	$i = 1,2,3,4$	1 – Mine C, 2 – Mine P, 3 – Mine D, 4 – Mine G
j = Generating plant location	$j = 1,2,3,4$	1 – Mine G, 2 – El Paso, 3 – Barranquilla, 4 – Santa Marta
m = Mode of transport used for tire shipment	$m = 1,2,3$	1 – Rail, 2 – Road, 3 – Fluvial
t = Time period (semesters)	$t = 1,2,3,\dots,40$	
h = indicates the shredding machines set location	$h = 1,2,3,4$	1 – Mine C, 2 – Mine P, 3 – Mine D, 4 – Mine G

4.3. Parameters

Parameters for the model are listed in table 2.

Table 2. Model parameters and descriptions

Parameter	Description
C_{ijmt}	Cost of collection and transportation per trip from mine i to plant j in time period t by mode of transportation m
Tt_{im}^{+}	Maximum tire carrying capacity of mode of transport m from mine i
$I(0)_i$	Initial scrap tire inventory of mine i at the model outset
T_{it}	Rate of scrap tires from mine i (in tons / semester)
CS_{iht}	Transport cost of the shredding resource from mine i to mine h in the time period t
FA_h	Fixed operating cost of the shredding resource set in mine h
S_h	Capacity of shredding resource set at h
PS_{jt}	Set up costs of a generating plant j at time period t
FO_{jt}	Fixed operating costs of the generating plant j at period t
VO_{jt}	Variable operating costs of the generating plant j at period t
D_{jt}	Demand for tires required by the generating plant j at period t
D_{jt}^{-}	Lower limit of demand of the generating plant j in time period t
D_{jt}^{+}	Upper limit of demand of the generating plant j in time period t

4.4. Variables

The decision and auxiliary variables for the model are depicted on table 3. Results obtained from the mathematical solution to the model will serve as guidelines for the decision maker.

Table 3. Decision and auxiliary variables for the model and descriptions

Variable	Type	Description
X_{ijmt}	Decision	Tons of tires sent from mine i to plant j by mode of transportation m in time period t
Y_{ht}	Decision	1 if the set of shredding resource at h is enabled at the time t and 0 otherwise. They can be enabled and disabled at any time period t
Z_{jt}	Decision	Binary variable that takes the value of 1 if the generating plant j is opened in the time period t and 0 otherwise. Once opened it remains open
I_{it}	Auxiliary	Inventory of mine i in time period t (in tons of tires)
TS_{ht}	Auxiliary	Total costs of the shredding resource set at h at period t

4.5. Objective Function

The objective function minimizes the total logistic cost of what is defined in the scope. This includes the costs of relocating the group of shredders between the mines depending on the new allocations defined, the opening costs, fixed and variable costs of the generating plant.

Total Cost = Shredder Cost + Plant Opening Cost + Plant Fixed Cost + Plant Variable Cost + Transportation Cost

$$\boldsymbol{Z(min)} = \sum_{h=1}^{4}\sum_{t=1}^{40} TS_{ht} + \sum_{j=1}^{4} PS_{j1} * Z_{j1} + \sum_{j=1}^{4}\sum_{t=1}^{40} FO_{jt} * Z_{jt} +$$
$$\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t=1}^{40} VO_{jt} * X_{ijmt} + \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t=1}^{40} C_{ijmt} * \frac{X_{ijtmt}}{Tt_{im}^{+}}$$

These costs will largely depend on the location of the plant and the amount of tons of tires processed, the costs of collecting and transporting the tires to the generating plant by the possible modes of transportation as well as the transportation costs of moving the shredding resource set between mines.

4.6. Constraints

The decision variables are subject to the following constraints:

Table 4. Model Constraints

No.	Constraint	Description
1	$\sum_{i=1}^{4}\sum_{m=1}^{3} X_{ijtm} \geq D_{jt}^{-} * Z_{jt} \;\; \forall\, j,t$	The number of tons of shredded tires to be collected and sent in a time period t from all mines to the generating plant must be at least 5000 tons for it to be able to operate.
2	$\sum_{i=1}^{4}\sum_{m=1}^{3} X_{ijtm} \leq D_{jt}^{+} * Z_{jt} \;\; \forall\, j,t$	The number of tons of shredded tires to be collected and sent in a time period t from all mines to the chosen generating plant, must be maximum 14000 tons for it to be able to operate.
3	$\sum_{m=1}^{3}\sum_{j=1}^{4} X_{ijtm} \leq \; S_h * Y_{ht} \;\; \forall\, h,t;\; i = h$	The capacity of the shredding machine h set must not be exceeded by the amount of tons of tires to be sent from the mine i to where the shredders are located at time t.
4	$\sum_{h=1}^{4} Y_{ht} = \; 1 \;\; \forall\, t$	There is only 1 set of shredding machines available and this must be assigned only to one mine at any given time period t.
5.1	$\sum_{j=1}^{4} Z_{j1} = 1$	Only one generating plant must be opened and this must occur in the first time period, considering assumption 1.
5.2	$Z_{jt} = \; Z_{j1} \;\; \forall\, j, t > 1$	Once the generating plant is opened, it never closes, considering assumption 1.
6	$I_{it} = \; I_{i,t-1} - \sum_{j=1}^{4}\sum_{m=1}^{3} X_{ijtm} + T_{it} \;\; \forall\, i,t$	The final inventory of tons of tires in the mine i in the time period t is equal to the final inventory from the previous period minus the tons of tires that leave the mine i plus the waste rate generated in the mine i in the current time period.
7	$I_{i0} = I(0)_i \;\; \forall\, i$	The inventory level for each mine i at time 0 is equal to its corresponding parameter of initial scrap tires inventory.
8	$I_{it} \leq 0{,}80 * I(0)_i \;\; \forall\, i, t \geq 10$ $I_{it} \leq 0{,}60 * I(0)_i \;\; \forall\, i, t \geq 20$ $I_{it} \leq 0{,}40 * I(0)_i \;\; \forall\, i, t \geq 30$ $I_{it} \leq 0{,}20 * I(0)_i \;\; \forall\, i, t \geq 40$	The target percentage of collection and recovery of tires must comply with those stated in Resolutions 1457 of 2010 and 1326 of 2017.
9.1	When $t = 1$: $TS_{h1} = \sum_{h=1}^{4} FA_h \;\; \forall h$	Indicates the fixed cost of adapting the shredder, which includes the infrastructure of the space where machines and public services will serve the operation in mine h at time period $t = 1$. This cost is incurred by all mines, as stated in assumptions.
9.2	When $t > 1$: $TS_{ht} = FA_h * Y_{ht} + \sum_{\substack{i=1 \\ i \neq h}}^{4} Y_{i,t-1} * CS_{iht} \;\; \forall\, h$	Indicates the cost of opening the set of shredding machines at h for a time period $t > 1$, taking into account the fixed cost of operating the shredder in the current period and the transportation costs of the machinery from the predecessor mines available in earlier periods to the current mine.
10	$X_{i1t1} = 0 \;\; \forall\, i,t$ $X_{i1t3} = 0 \;\; \forall\, i,t$ $X_{i2t1} = 0 \;\; \forall\, i,t$ $X_{i2t3} = 0 \;\; \forall\, i,t$	It is not feasible to transport shredded tires by fluvial nor rail modes of transportation from any mine to the plants located in Mine G and El Paso. Also, mine C. Thus, the tons transported under these conditions are set to zero.
11	$Z_{jt} \in \{0,1\} \;\; \forall\, j,t$	The decision variable for opening the generating plant j in time period t is binary
12	$Y_{ht} \in \{0,1\} \;\; \forall\, j,t$	The decision variable for opening a set of shredding machines h in time period t is binary
13	$X_{ijtm} \geq 0 \;\; \forall\, i,j,t,m$	The number of tons of tires to be sent from mine i to plant j in time period t by mode of transportation m is real and nonnegative. (Non-negativity)
14	$I_{it} \geq 0 \;\; \forall\, i,t$	The auxiliary variable for inventory of mine i in time period t is real and nonnegative.

5. Results

The model was solved using the CPLEX solver included in the software AMPL, yielding that the generating plant must be open in the first time period in El Paso ($Z_{21} = 1$) and it will permanently remain open. Such location choice relates to the proximity of this location with the mines that have higher initial inventory of tires and higher waste rates (Mine D, Mine G and Mine P). The shredders will eventually be traveling every six months between the mines to be able to reduce the tires dimensions, supposing a semester as the minimal period of stay to offset fixed set up costs. According to the results shown in table 5, an illustration of the programming for the group of shredders during the first 7 semesters is as follows: during the first semester, the shredding machines will be located in the Mine D. Later the machines will be moved by truck to the Mine G for 1 semester. Then they will operate in mine P for 2 semesters. The next semester they must be available for 1 semester at Mine G, at time t = 5. Then, the shredders will be moved to the Mine C where they will remain for 1 semester and will come back to mine G to complete the first 7 time periods, and so on. The table 5 shows the entire programming of the shredders during the 40 periods considered in the model time horizon.

Table 5. Assignment of shredders between mines

Time	**Shredder**				**Time**	**Shredder**				**Time**	**Shredder**				**Time**	**Shredder**			
$\boldsymbol{Y(h,t)}$	**1**	**2**	**3**	**4**	$\boldsymbol{Y(h,t)}$	**1**	**2**	**3**	**4**	$\boldsymbol{Y(h,t)}$	**1**	**2**	**3**	**4**	$\boldsymbol{Y(h,t)}$	**1**	**2**	**3**	**4**
1	0	0	1	0	11	0	0	0	1	21	0	0	0	1	31	0	1	0	0
2	0	0	0	1	12	0	1	0	0	22	0	1	0	0	32	0	1	0	0
3	0	1	0	0	13	0	0	0	1	23	0	0	0	1	33	0	0	1	0
4	0	1	0	0	14	0	0	1	0	24	0	1	0	0	34	0	1	0	0
5	0	0	0	1	15	0	1	0	0	25	1	0	0	0	35	0	0	0	1
6	1	0	0	0	16	0	0	1	0	26	0	1	0	0	36	0	1	0	0
7	0	0	0	1	17	0	0	1	0	27	0	0	0	1	37	0	1	0	0
8	0	1	0	0	18	0	1	0	0	28	0	1	0	0	38	0	1	0	0
9	0	0	1	0	19	0	1	0	0	29	0	1	0	0	39	0	1	0	0
10	0	1	0	0	20	0	0	0	1	30	0	0	0	1	40	0	0	0	1

As for the mode of transport of the shredded tires to be sent from each mine, results show that trucks were chosen as the most economical way to carry out these moves. The point of origin of shredded tires movement is determined by the shredding machines location at any given time (shown in table 5), and the destination will depend on the location of the power generation plant, as previously stated, assigned in El Paso. The amount of shredded tires will depend on the lowermost among the allowance of shredded tons to be shipped, transport capacity, shredders capacity, capacity of the generating plant, and the final inventory of whole tires held by the mines at the previous period. Table 6 shows the origin and amount of tons of shredded tires available to be sent to the plant by truck using the land transportation mode.

Table 6. Tons of tires to be sent from the mines to the power plant by land transportation mode

Time	**Tons of tires**	**Sent from**	**Time**	**Tons of tires**	**Sent from**	**Time**	**Tons of tires**	**Sent from**	**Time**	**Tons of tires**	**Sent from**
1	7,372	Mine D	11	14,000	Mine G	21	14,000	Mine G	31	14,000	Mine P
2	13,807	Mine G	12	14,000	Mine P	22	5,000	Mine P	32	5,000	Mine P
3	14,000	Mine P	13	13,807	Mine G	23	13,614	Mine G	33	14,000	Mine D
4	13,861	Mine P	14	13,271	Mine D	24	5,000	Mine P	34	5,000	Mine P
5	14,000	Mine G	15	11,607	Mine P	25	5,002	Mine C	35	14,000	Mine G
6	5,838	Mine C	16	14,000	Mine D	26	13,353	Mine P	36	5,000	Mine P
7	14,000	Mine G	17	14,000	Mine D	27	14,000	Mine G	37	5,000	Mine P
8	14,000	Mine P	18	14,000	Mine P	28	14,000	Mine P	38	5,607	Mine P
9	14,000	Mine D	19	14,000	Mine P	29	14,000	Mine P	39	14,000	Mine P
10	14,000	Mine P	20	14,000	Mine G	30	14,000	Mine G	40	14,000	Mine G

The inventory level in each time period depends on the initial inventory of tires that each mine has, the number of shredded tires removed out and the arriving new scrap tire created at the given time period. They also must comply with the recollection rates enforced in the Colombian law, mentioned in the literature review. Below in figure 2, the inventory levels are shown for each mine at each period, represented by the continuous series. The associated dotted lines in this figure represent the dynamic inventory reduction targets for the mines to comply with the legal requirements stated in constraint #8. As shown, there is an effective inventory reduction during the modeling horizon.

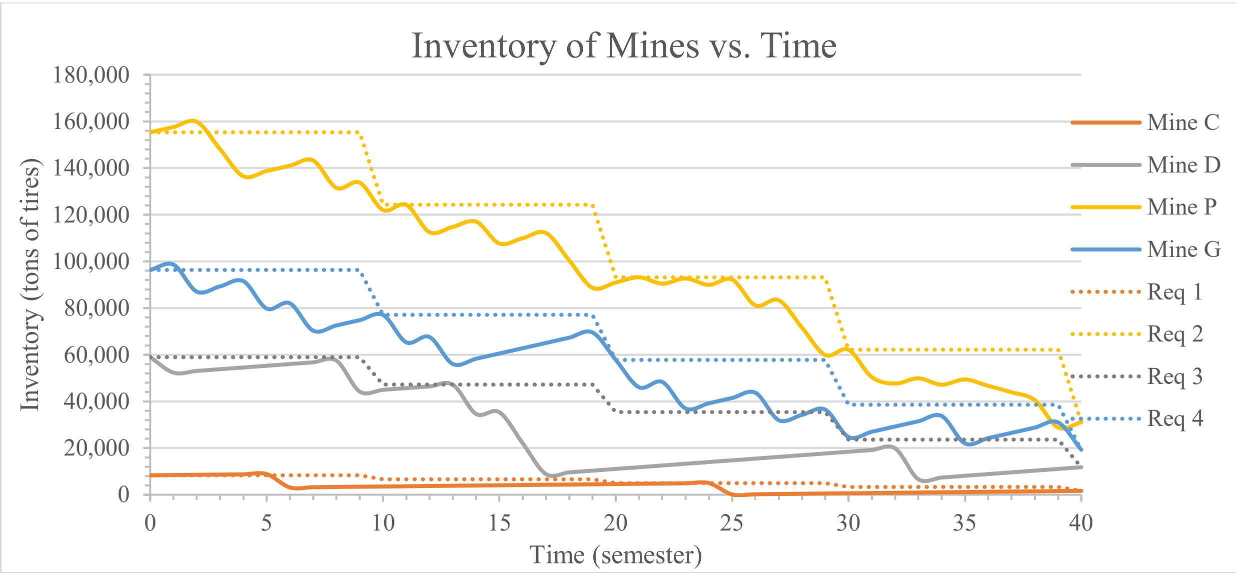

Figure 2. Inventory of Mines (tons of tires) vs. Time (semester)

Finally, the minimum value in current prices obtained for the objective function is USD $ 10,344,396 and it is broken down in table 7. The table shows that the highest component of the total cost is the plant fixed cost, followed by the transportation cost and the plant opening cost. The shredders set-up cost and the plant variable cost have the lowest contribution, which proves the complexity of the OTR tires problem explained earlier: in order to implement a feasible solution, a higher-order investment must be made to meet the fixed and opening cost of the plant. The shredder set-up cost is relatively high but unavoidable, given the absence of an in-site reconversion alternative at the mines. The shredded tires movement and processing represent a partial solution to the problem, future research should address its market and explore income sources in order to better predict the viability of such a significant investment and to determine a sustainable business option for transforming waste into a positive value good.

Table 7. Breakdown of the total cost of the objective function

Cost Type	**Value**	**%**
Shredder Cost	$ 1,198,233	12%
Plant Opening Cost	$ 1,692,393	16%
Plant Fixed Cost	$ 4,000,000	39%
Plant Variable Cost	$ 312,760	3%
Transportation Cost	$ 3,141,010	30%
Total Cost ($Zmin$)	**$ 10,344,396**	**100%**

6. Conclusions

This paper proposes a reverse logistics network optimization model for the residual OTR tires discarded from the mining industry. This problem has been present throughout the last decades in this economic sector, given the complexity of the tires structure and the logistics difficulties in the handling and management of this waste. These residual tires have always been perceived as a negative value goods since they do not generate revenue when reintroduced into the production cycle. However, through a case study it was possible to illustrate a potential cost-effective solution that can be achieved in the Colombian mining industry. The optimization model proposed is useful for decision makers in the principal mines as it provides a set of strategic decisions that can help these mines to comply with the current Colombian regulations of tires collection and final disposition. In the results yielded by the model, the total logistic cost was minimized and the analysis showed that a considerable investment shall be made in order to offset the high fixed costs and to accomplish the implementation of the reverse logistics network. The generating plant variable costs and the shredder set-up costs were also considered and found to be relatively low in comparison to the other costs mentioned earlier. Because of the already high initial investment, the scope of this work only considers the incorporation of a single (1) set of shredders, which must be shared and sequenced between mines. It does not incorporate, as well, the flow of smaller tires coming from the surrounding cities. This should be taken into account for future research, given that urban settings exhibit a similar problem as to the one from the mining industry. Nevertheless, the urban issue is expected to require less investment for the implementation of the solution, given that the dimensions of urban tires are relatively easy to handle, but a greater deal in transport due to the sparsity of locations and lesser amount of cargo.

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