THE ECONOMICS OF TIRE REMANUFACTURING

by

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96/58/TM
(Revised version of 96/39/TM)

This working paper was published in the context of INSEAD's Centre for the Management of Environmental Resources, an R&D partnership sponsored by Ciba-Geigy, Danfoss, Otto Group and Royal Dutch/Shell and Sandoz AG.

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The Economics of Tire Remanufacturing

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Abstract

The world market for tires is described to identify the current material flow from raw materials to tires and the used tire disposal problem. Then, I describe the value-adding operations in the tire production process and in the tire retreading process. Once retreading is identified as the only recovery alternative that maximizes tire utilization, I explain why heat generation is the only recovery alternative, when retreading is not technically feasible. The economic values of heat generation in electric plants and in cement kilns are discussed. The paper culminates with the case of retreading, the tire remanufacturing process, and the recommendation of a simple decision rule for selecting the number of times a tire should be retreaded to maximize its utilization.

Keywords: *remanufacturing, recycling, retreading, incineration, material recovery, product recovery, tire industry, waste reduction, resource conservation, pollution prevention, environmental economics.*

1. Introduction

With a world production of 800 million units in 1992, tires are among the industrial products with largest generation of solid waste. Each passenger car leaves the assembly line with the equivalent of 30-40 kg of rubber and steel wire material as tires that are used for two or three years before being dumped. On average, automobiles last about 11-12 years using 3 sets of tires. Hence, if used tires are not reused somehow, each car dumps 10 kg of used tires in the waste stream each year. In a larger scale, the amount of tires disposed in a country such as France is equivalent to 250,000 tons per year. Fortunately, used tires are not necessarily useless. When they are replaced, many used tires retain some of the key characteristics required from a new tire, such as shape, rigidity, impermeability and lateral strength. Rubber reclaimers and tire retreaders have explored some of these properties. In many cases, surface adhesion is the only physical property lost by the tire during its first life. While the lack of adhesion renders the tire inappropriate for its original use, its remanufacture – I shall call it retreading – is still viable. Moreover, if a specific tire does not satisfy the technical and economical conditions for retreading, the cycle may be closed with one of the many methods of rubber reclaim.

1.1 Used tires in the literature

There are several works about the impact of the increasing number of used tires in the waste stream. Guelorget (1993) analyses the life-cycle of used tires in France, emphasizing the materials and energy consumption in tire production [1]. The report by US EPA (1991) focuses on the used tires applications in the United States. In particular, it considers used tires as substitutes of traditional fuels in several industries, and the use of ground rubber in civil engineering [2]. From this work, used tires can efficiently substitute coal and other fuels in the generation of energy. The same work clarifies that the technology for recycling tires into its original raw materials (pyrolysis) is not economically competitive. The report by Clark et al. (1991) focuses on the environmental impact of the tire incineration processes [3]. It includes an industry-wide study of thermoelectric and cement plants that burn used tires as some or all of their need for heat. They observe how

Table 1: Rubber consumption in tire and tire products by polymer type in 1992
Source: EIU Rubber Trends, September 1991.

		Europe	North America	Asia
SBR	Styrene-Butadiene (solid)	441,000 ton	565,000 ton	432,000 ton
SBR	Styrene-Butadiene (latex)		3,000 ton	3,000 ton
BR	Polybutadiene	193,000 ton	323,000 ton	201,000 ton
EPDM	Ethylene-Propylene		8,000 ton	16,000 ton
NBR	Acrylonitrile-Butadiene		1,000 ton	
IIR	Butyl	128,000 ton	197,000 ton	128,000 ton
SR	synthetic rubber	762,000 ton	1,097,000 ton	780,000 ton
NR	natural rubber	713,000 ton	772,000 ton	1,327,000 ton
Total		1,474,000 ton	1,869,000 ton	2,107,000 ton

the emissions of several pollutants change with the proportion of tire in the fuel mix. That report concludes that burning used tires in thermoelectric or cement plants can reduce the emissions of several of the usual pollutants in this industry. The report by EcoPlan International (1992) focuses on the technology changes and customer preference in the tire industry, and how these may affect investment decisions in the industry [4]. Its major concern is not on used tire recovery but on the new technologies that render tires more durable and fuel efficient.

The first contribution of this paper is the identification of the recovery processes that can absorb a large quantity of used tires regularly. Priority is given to the technologies available today, or those that will be available in a foreseeable future. The second contribution is the determination of a simple policy that maximizes the tire utilization through retreading, before the used tire is recovered by one of the dissipative technologies.

2. The market for tires

Over three-fourths of the tire market in the world is held by six companies: Michelin (F), Bridgestone (J), Goodyear (US), Continental (D), Sumitomo (J) and Pirelli (I). Each of these firms has several manufacturing plants in the United States and Europe but, as with other products, the non-Japanese manufacturers have low penetration in Japan. These firms have made significant efforts in R&D, building proprietary technology for tire-making, with different choices of processes and compounds. Given the exclusive nature of product development, and the difficulty in determining the product content through reverse engineering, tire development and production has the same secretive characteristic found in other segments of the chemical industry. Similar tires produced by different companies are made by different processes with an exclusive mix.

2.1 Geographic distribution of tires for passenger cars

Each tire manufacturer has made enormous progress towards the development of proprietary production processes. They have developed proprietary machinery and skills that are not immediately transferred from one company to the next, as observed in other segments of the chemical industry. Moreover, although the production process tends to be the same within a firm, the rubber compound mix varies with the geographic destination. Table 1 illustrates. The quality requirements in each market, the technology used by the market

Table 2: Market segmentation of tires in the OEM and replacement markets.
Source: EcoPlan (1992).

		Europe		USA		Japan	
		OEM	replacement	OEM	replacement	OEM	replacement
Aspect ratio	75 or 78	3%	5%	46%	68%	23%	25%
	70	40%	60%	46%	31%	30%	40%
	65	47%	29%	5%	1%	38%	30%
	60 or less	10%	6%	3%	marginal	9%	5%
Speed rating	low (S)	30%	38%	71%	68%	70%	75%
	medium (T)	35%	33%	21%	22%	23%	20%
	high (H, V, Z)	35%	29%	8%	10%	7%	5%

leader and the availability and cost of raw materials are some of the reasons that explain the different material choices. The product quality must suit the roads and the driving styles. Table 2 corroborates this idea. It identifies the share of different tire types and sizes in the OEM and in the replacement market in Europe, United States and Japan. The market is segmented according to two characteristics: the *aspect ratio* and the *speed rating* of the tire.

The *aspect ratio* is one of the three measures that define the tire geometry or shape[1]. The other dimensions are *rim diameter* and *tire width*. A fast driving style in winding roads, typical of Europe, demands tires with low aspect ratio. The low ratio is a consequence of wider wheel and larger rim radius, which increases the area of contact between the tire and the road surface, decreases sidewall flexing and increases vehicle stability.

The *speed rating* defines the highest speed that the tire can run without compromising its integrity. For example, a speed rating of S suffices for driving at the speed limit – or recommended speed – in any country. To merit a speed rating of V, a tire must be able to sustain speeds of at least 240 km/h. This rating is obtained by selecting compounds that can resist the temperature and traction requirements associated with very high speed.

Each geographic region has a different demand profile, reflecting the road conditions and speed limits in each area. The difference in the segmentation of the OEM and the replacement market regarding speed ratings is probably related to the difference in preferred aspect ratios in the two markets. Tires consumed in Europe have lower aspect ratios and higher speed rating than the ones consumed in Japan or in the United States. This reflects the difference in driving style, road design, traffic intensity and speed limits in each region. This table suggests that the one cannot discuss tire production or remanufacturing costs without designating the market of destination. The choices made in each market affect the technology adopted and production cost. Comparing the OEM with the replacement market in any region, the OEM market favors lower aspect ratios. One of the following reasons may cause this behavior:

1. Today, automobile designers select tires with smaller aspect ratios than they used to select in the past. Hence, replacement market reflects the preferred design of many years ago, while the OEM market reflects newer designs. This reasoning describes a market in transition, where the replacement market

1 Aspect ratio = 100 x (tire radius - rim radius)/tire width.

Table 3: Replacement market in selected European countries
Source: OECD 1994; EIU Rubber Trends, September 1991.

Country	Passenger cars units	PC replacement tires/year	Commercial vehicles units	CV replacement tires/year
Benelux	9,530,000	6,000,000	920,000	1,200,000
France	23,550,000	24,400,000	4,740,000	3,000,000
Germany	35,520,000	23,100,000	2,250,000	2,200,000
Italy	24,800,000	16,200,000	2,430,000	1,500,000
UK	19,740,000	20,000,000	2,860,000	3,200,000
Total	113,140,000	89,700,000	13,200,000	11,100,000

eventually has the same market segmentation as the OEM market. It assumes that customers do not have the flexibility to switch from one tire geometry to a different one.

2. Buyers of replacement tires are very price sensitive. If price decreases with the aspect ratio (which tends to be true), they would prefer to buy tires of aspect ratio higher than in the tires supplied by the OEM. If this reasoning is correct, it describes a stable situation where the OEM and the replacement markets have different segmentation, given the customers' ability to choose tires with different aspect ratios.

3. The replacements of tires of different aspect ratio and speed rating occur with different frequency. The usage profile is a function of the tire type.

At this point, it is difficult to identify the best explanation for the different segmentation in the OEM and the replacement markets. Whether one justification or the other dominates, the different distribution between the tires returned for retreading and the demand profile in the replacement market affects the execution of a tire remanufacturing program. The speed rating of the retreaded tire can be equal to or lower than the speed rating of the used tire entering the process. The tire geometry does not have the same flexibility: retreaded tires must have the same shape as the used tires entering the retreading process.

2.2 The replacement market

The replacement market accounts for 85% of the demand for truck and bus tires; OEM absorbs the remaining 15% of the market. The use of retreaded tires is generally limited to trailer tires; many operators do not use retreads for steer or drive axle, because of the different wear pattern. The trailer tire tends to wear faster, because of the multiple trailer axle: when the truck turns, the axles remain parallel to the truck, forcing the tire to slide against the pavement. The more often the truck has to make sharp turns (driving in the city, maneuvering, etc.), the faster it consumes the trailer tires. Notice that a large convoy made of a truck and a trailer has 2 steering wheels, 4 driving wheels and 6 to 12 trailer wheels. With the fast usage of trailer tires, they represent more than half of the replacement market. This justifies developing a tire management plan favoring the use of retreads for the trailer axles. Indeed, there are few incentives for using retreaded tires at steering and driving axles in small fleets.

When buying a new vehicle, fleet operators often have the choice of the tire type in the vehicle. The retreading molds available with their preferred retreaders constrain their decision. Table 3 shows the size of the vehicle park and the tire replacement markets in five regions, representing more than 85% of the Western European market (1990 figures). In all countries, the share of retreaded tires in the replacement market of passenger cars is small and decreasing. The table indicates that the ratio between the replacement market and the passenger car fleet in these countries average to 0.79. Since each car has a life expectancy of 11-12 years, it is reasonable to estimate that each car consumes on average 11.5*0.79 = 9.1 replacement tires during its useful life.

3. The value-added in tire production

In this section, the value-added in each stage of tire production is evaluated, from raw material to finished tire. I give emphasis to the elastomer production since it represents nearly 80% by weight of the materials in a tire. First, I identify the materials contained in the tire, their production flow and the value increase with the sequence of transformations. The Appendix contains the detailed calculation.

3.1 Tire components and rubber compounds

At a first look, a tire is a one-piece product made of a mix of rubber, steel and cords. A typical tire in a passenger car weighs between 6kg and 10kg. Henceforth, unless otherwise specified, I analyze a generic steel belted tire, typical of a European passenger car weighing 8kg. Table 4 shows its breakdown by weight of raw material. The material cost to make a tire amounts to $17.37. Approximately one half of this cost is represented by the rubber content. The steel cord is the second most expensive component.

Table 4: Cost breakdown of an European tire

Source: EcoPlan (1992), adjusted.

Inputs	kg/tire	$/kg	cost/tire
Rubber compounds	6.3	$ 1.41	$ 8.87
Steel cord	1.0	$ 3.60	$ 3.60
Bead wire	0.3	$ 2.00	$ 0.60
Rayon cord	0.4	$ 7.00	$ 2.80
Solvents			$ 0.50
Energy			$ 1.00
Total	8.0		$ 17.37

The final inspection rejects about 3% of the tires produced, increasing the cost to $17.89. Considering the rejected tire worthless, and the good tire worth $40, the aggregate value added in the production process equals ($40.00 - $17.89) / 8kg = $2.76/kg. However, one should notice that the tire is a complex product built from the assembly of 6 components: *tread, bead, sidewall, breakers, carcass and inner liner*. It is important to know the amounts of compounds present in each of the 6 tire components, to identify the proportion of a tire's value consumed during its life.

A typical tire loses up to 10% of its weight until it is disposed of. Most of the dissipated material comes from the tread. Now, notice that the tread does not contain any of the cords in a tire, it is made of rubber only. The assembly of the five remaining components makes up the casing, which may last much longer than the tread. Usually the entire casing is in good state once the tread is finished. Nonetheless, the physical stress or fatigue accumulated limits the number of retreads that the tire may receive. Table 5 shows the breakdown of the rubber compounds per tire component, for each kilogram of rubber in a typical European tire. The tread

Table 5: Breakdown of rubber compounds per tire component

Source: Aggregate values from several sources; partial values estimated by author.

Inputs	Tread	Bead	Sidewall	Breakers	Carcass	Inner liner	Compound proportion	Cost/kg
NR Natural rubber	0.146	0.001	0.031	0.003	0.091	0.001	27%	$ 1.20
SBR Styrene-butadiene	0.091	0.001	0.031	0.005	0.040	0.001	17%	$ 1.20
BR Butadiene	0.050	0.002	0.030	0.002	0.001	0	9%	$ 1.65
IIR Butyl	0	0	0	0	0	0.034	3%	$ 2.80
Elastomers	0.287	0.004	0.092	0.010	0.132	0.036	56.00%	$ 1.37
Carbon black	0.107	0.079	0.005	0.088	0.005	0.005	29%	$ 1.29
Rubber chemicals	0.004	0.003	0.030	0.005	0.030	0.079	15%	$ 1.80
Component proportion	40%	9%	13%	10%	17%	12%	1	$ 1.41
Cost/kg	$ 1.29	$ 1.32	$ 1.45	$ 1.31	$ 1.31	$ 2.05	$ 1.41	

contains 40% of the rubber in a tire, with a material cost of about $1.29/kg. The other components make up the tire casing, absorbing 60% of the rubber material in the tire, at an average cost of $1.52/kg.

If a passenger car's tire contains 6.3 kg of rubber, the value of materials dissipated during its first useful life is given by the following:

$$\begin{aligned} \text{Value of Dissipated Materials} &= \text{Total Rubber} \times \text{Rubber in Tread} \times \text{Value of Tread Rubber} \\ \text{VDM} &= 6.3\text{kg} \times 40\% \times \$1.29\,/\,\text{kg} \\ \text{VDM} &= \$3.25 \end{aligned} \tag{1}$$

Compare the result of equation (1) with the material cost in a tire (table 4). During the tire's first useful life, less than 20% of the raw material value is consumed. Even considering the tire a consumable good, 80% of the original material value is still available for reuse at the end of its life.

3.2 Material flow

Natural rubber and synthetic rubber appear in equal proportion in the European tire. Synthetic elastomers are some of the many subproducts of petroleum and coal, taking several stages to be produced. A first refining stage separates the many substances in crude oil to obtain the simplest forms of hydrocarbons (alkanes). A catalytic refining stage converts the alkanes into monomers. Butadiene and styrene, followed by isobutyl and isoprene, are the monomers most used in tire production. They are the basis for the synthetic rubber compounds in the tire. The polymerization of the butadiene gives BR (polybutadiene rubber). The co-polymerization of the butadiene and the styrene give the SBR (styrene-butadiene rubber). Similar processes give the other elastomers used in tire fabrication, such as IIR (butyl rubber) which ensures the impermeability of the tire at a wide range of temperatures. Natural rubber, carbon black, steel and a variety of rubber chemicals make up the remaining ingredients used in the tire industry. The value added in each of these production steps, from petroleum to finished tire, appears in the tables in the Appendix.

Strictly speaking, the elastomer is the finished material used in tire manufacturing while the crude oil or natural gas is the raw material. Figure 1 shows a stylized material flow in the production of synthetic elastomers. It starts with the basic raw materials (coal, natural gas and petroleum), and concludes with the two prevalent elastomers used in the production of a European tire. Different facilities, specialized on a certain

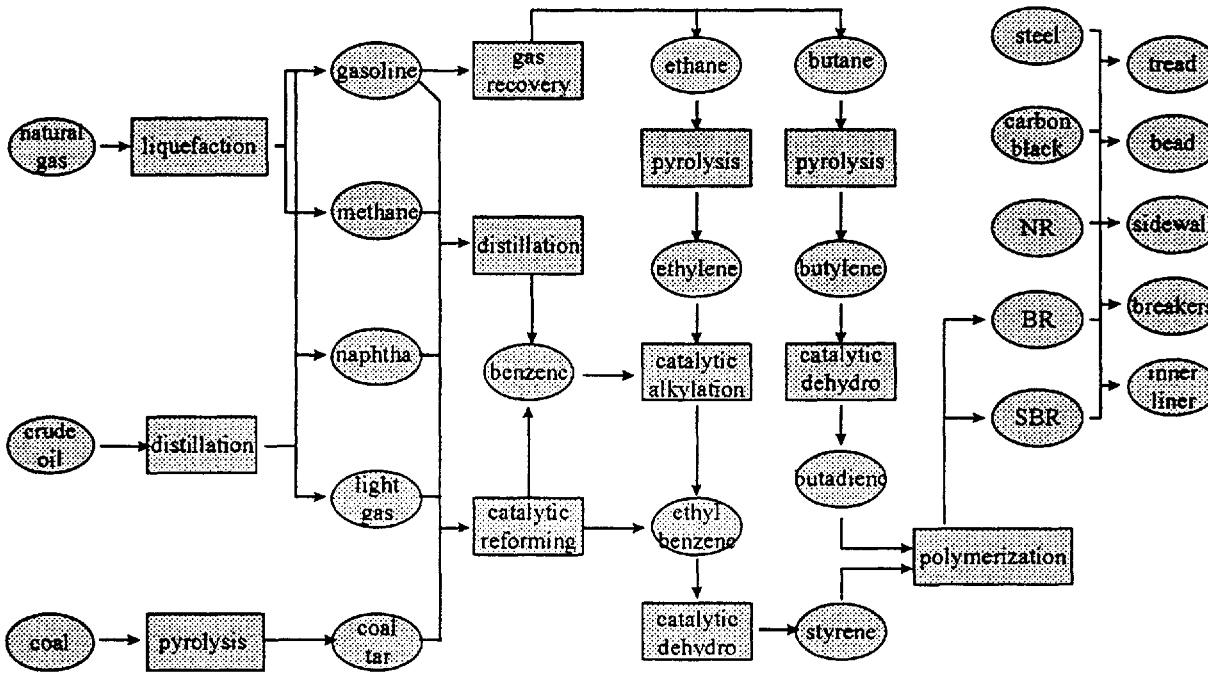

Figure 1 - Raw materials in tire production

compound such as ethylene or benzene, execute each process in the picture. The production scale is a key cost determinant. The production of the intermediate compounds comes from several industries but some of the tire makers are backward integrated to the elastomer polymerization business.

Our value-added analysis takes care of the successive transformations, from crude oil to the synthetic elastomers in the tire -- SBR, BR and IIR -- and from these to the finished tire. Table A-12 shows that these operations add $26.64 to the value of the inputs, that is approximately 2/3 of the value of the finished tire. The successive operations add more value to the casing than to the tread – certainly because the casing contains most of the tire material. The value adding operations that generated the other finished materials – natural rubber, carbon black and steel wires – are not considered in this analysis. This simplification is acceptable since these processes contribute with a small fraction of the value added in the final product.

4. Retreading used tires

Much of the research about the commercial vehicle tires concerns the development of casings that can live longer through a large number of retreads. A well-managed tire may be retreaded at least twice, lasting 500,000 km under US conditions. However, tire makers are working on the development of a tire whose carcass can live up to one million km (600,000 miles), with the help of two or three retreads.

Retreading is the only tire reclaim process that attempts to take full advantage of the value remaining in the used product. Table A-12 shows that 60% of the value-added in the tire is in the casing, which hardly deteriorates during its first life. Hence, tire retreading brings the opportunity to recover all of this value-added, at a certain recovery cost. It is this large value-added still available that "finances" the retreading process.

4.1 The retreading process

There are two competing technologies in tire retreading: the *mold cure process* and the *pre-cure process*. They differ in the sequence of operations, whether the tread application occurs before or after its curing. One advantage of the pre-cure process is that the vulcanization is outsourced, allowing the development of specialized small shops retreading a limited variety of tread types. This fits well with the existing market where fleet managers simplify their tire management task by choosing a small variety of tire shapes and sizes for its fleet. Then, they can place contracts with a single retreader specialized on the same tire geometry.

In contrast, high volume retreaders and tire makers involved in the retread business prefer the mold cure process. Here, the whole tire is heated while the heated chamber applies and vulcanizes the tread design. This process mimics the new tire production process. The retreading process takes seven steps, described below:

4.1.1 Pre-inspection

The used tires enter the process with an initial inspection that chooses the ones with better retreading potential. It is a labor intensive task, where the inspector uses his experience selecting the tires that demand the simplest repair process. His objective is to select the tires with lowest retread cost and longest expected casing life. It is a process where standardization of procedures is difficult, and with direct effect on the firm's profitability.

The market for used tires is a buyer's one. Hence, the retreaders can afford to be very selective with the used tires that arrive in the process. They discard a considerable number of tires that could be retreaded, if there were a larger demand for the final product.

4.1.2 Buffing (or shaving)

Here, the tread is removed from the worn tire in a lathe-like machine, the *buffer*. It is a batch process requiring the predetermination of the buffer settings for each tire model and size, removing the correct amount of rubber from the casing without compromising its resistance. It requires an experienced operator because each tire geometry requires a different buffer setup. Buffing a passenger tire generates about 0.8 kg of ground rubber, which is then sold to the rubber industry.

4.1.3 Casing preparation

The casing is repaired from all injuries remaining after buffing. An operator may reject a tire because its structure has been severely degraded and repairing it would be too costly. Just like the pre-inspection, it is important to define standards such that the operator can make fast and sound decisions. The casing repair specialist is trained to understand these standards and how it affects the quality of the final product. With a fairly high population of used tires and a strict inspection process, accepted casing should not have severe injuries so that retreading remains profitable.

4.1.4 Tread application

This is where the two processes differ:

1. In the *mold cure process*, the tread is applied to the tire in the same way as in the primary tire manufacture. Uncured tread rubber is applied on the buffed casing up to the correct tire diameter. The jargon says that a simply *retreaded tire* receives the rubber only in its outer diameter. Contrarily, the

remanufactured tire receives a new rubber coating on its sidewall as well, a process knows as bead-to-bead retreading. The difference lies on the physical appearance, which is very important in the passenger car market as well as in some of the commercial market. However, both types of reused tires are expected to satisfy precisely the same performance and safety standards as the new tires.

2. In the *pre-cure process*, the tread is molded and cured before it is applied to the tire. A layer of cushion gum is applied on the casing's outer surface to bond the pre-cured tread. Different tires require pre-cured tread of specified width and thickness, adding to the operations complexity. The retreaded tire moves to the curing chamber to complete the vulcanization process.

4.1.5 Curing

The curing – or vulcanization – is the process that ensures the bonding between the case and the new tread. It gives the hardness and abrasion resistance required in the tread.

1. In the *mold cure process*, this stage is responsible for forming the tread design and vulcanizing the rubber tread. The prepared casing is placed into a full-circle mold where it is inflated. Swelling the tire against the mold's inner wall conforms the uncured rubber to the tread design in the mold. Then, the mold is heated to the temperature and time for ideal curing. One of the challenges in this operation is to define the correct heat parameters for each variation of tire size.
2. In the *pre-cure process*, the cured tread is applied with its final design. Hence, the curing process just has to ensure the correct vulcanization of the gum layer between the tread and the casing for appropriate bonding. Instead of a whole mold, a simple ring is assembled onto the tire casing to receive the curing pressure. Then, the assembly enters a chamber for a certain time and temperature for vulcanization.

4.1.6 Inspection and finishing

The inspector in this station is looking for defects occurred in the retread process, because the casing itself has already been inspected. If the tire meets the safety requirements, it may go on to the finishing process. The excess rubber is trimmed and the sidewall is painted and labeled for a like-new appearance. (The finishing operation may be unnecessary for bead-to-bead retreaded tires.) Now, the retreaded tire is ready to return to market for a new life.

4.1.7 External testing

Specialized laboratories support the retreading industry, performing exploratory tests to increase the understanding about the whole production process. One of the main targets is to improve the vulcanization settings. Some of these tests are:

- adhesion pull tests
- cure rate determination
- tire failure analysis
- tread rubber analysis
- section repair analysis

Most of all, they certify the retreader, reassuring the customers against questions about product quality.

4.2 The economics of retreading

For each remanufactured tire, one casing is reused. However, there are several stages in the retreading process where some material is lost. The current technology cannot eliminate these losses: the first one is the tire usage, when roughly 10% of the tire's weight is dissipated. The second loss occurs during pre-inspection process, because some of the incoming casings have been worn beyond repair. Then, some 10% of the weight of the tire is buffed away. The final inspection is responsible for eliminating the tires not successfully retreaded, for instance, because of vulcanization problems. The amount of virgin materials required for each retreaded casing, by weight, equals:

$$\begin{aligned} \text{Virgin Material Requirement} &= (\text{Fraction Dissipated} + \text{Fraction Buffed})\ \text{Tire Weight} \\ \text{VMR} &= (\text{FD} + \text{FB})\ \text{TW} \end{aligned}$$

The virgin material cost should equal the price of a new tread, adjusted for the different weights. That is

$$\begin{aligned} \text{Virgin Material Cost} &= \text{VMR} * \text{Tread Cost} \ / \ \text{Tread Weight} \\ \text{VMC} &= \text{VMR} * \text{TrC} \ / \ \text{TrW} \end{aligned} \quad (2)$$

Hence, when a casing is retreaded, its attributed value can be identified as the difference between the market price of the retreaded tire and the sum of two costs: the virgin materials required in the process and the retreading operating cost. Notice that not all casings entering the system is sold, and some of the virgin material is lost with the retreaded tires that do not pass final inspection. Hence, to calculate the used casing value, it is necessary to adjust for these losses, attributing a production yield for the retreaded tires that are not salable and for the virgin material that is lost in their production.

$$\begin{aligned} \text{Used Casing Value} &= \text{Market Value of Retreaded Tire} * \text{Yield} - (\text{VMC} + \text{Retreading Cost}) \ / \ \text{Partial Yield} \\ \text{UCV} &= \text{MVRT} * \text{Y} - (\text{VMC} + \text{RC}) \ / \ \text{Y}_\text{p} \end{aligned} \quad (3)$$

The expression assumes that the type of material needed to retread a tire is the same as to make the tread of a new tire. Once equation (3) is solved, the unit value of any retreaded casing is calculated.

4.2.1 The market for retreaded tires

Retreaded tires have suffered from a credibility problem that poses difficulty in its expansion. Most of its market is from knowledgeable customers who can evaluate the product quality. These customers are the large fleet operators and frequent buyers of replacement tires. For them, tire replacement is usually the third largest item in the operating budget, right after personnel and fuel. Hence, using retreaded tires is a natural choice for profit improvement through cost reduction. Retreaded tires deliver the same mileage as comparable new tires, although they are sold with discounts between 30% and 50%. They are supplied with the same warranty as standard tires. Moreover, tire retreading consumes fewer energy: it takes 26 liters of oil to make a new passenger car tire, but just 9 liters to retread it. Likewise, retreading a single heavy duty tire may save up to 40 liters of oil. Table 6 shows the retread market in the United States in 1995, and the respective oil savings.

Retreaded tires hold an 80% share of the replacement market for aircraft landing gears, since nearly all air carriers procure retreads when available. Off-road machines, such as earth excavators are other big users of retreads. All tire types can be retreaded, including steel belt radial, mud and snow tires. Size is not a

Table 6: Petroleum savings attributed to the retread business
Source: American Retreaders Association (1996).

United States 1995	Retreaded tires (units)	oil saved per tire (liters)	total oil saved (liters)
passenger cars	5,300,000	17	90,000,000
light trucks	7,200,000	36	259,000,000
medium and heavy trucks	15,900,000	63	1,000,000,000
specialty	870,000	140	121,000,000
Total	29,270,000	50	1,470,000,000

constraint either: for example, the front tires of the CAT 994 Loader, each tire weighing 4.5 metric tons can be retreaded for an additional life expectancy of 5000 hours. Among retreaded tire customers, there are civil and military fleets of many governments. In response to the US Environmental Protection Agency support to retreaded tires through its Federal Tire Program, the US Executive Order 12873 mandates commodity managers to take affirmative steps to procure retreaded tires.

Knowledgeable customers of retreaded tires include the US Post Office (20% of its replacement tires), France's La Poste, other express courier companies (FedEx, UPS, etc.) and bus fleet operators. In all of these cases, tire procurement is an important management decision that may impact the company's profit. The very large fleets manage their tire consumption with regular retreading of a fixed pool of tires by a selected retreader. In this case, the retreader becomes a service provider and the tire is a valuable asset, carefully managed by fleet operators. In these instances, the casing is expected to live through at least two retreads; six retreads is not entirely uncommon. Similar policies are practiced by the users of specialty tires, such as for aircrafts or off-road vehicles. Among many criteria, fleet managers choose their retreaders based on their deadlines, which may vary between 2-3 days and 7-10 days for regular commercial tires. The outcome is that retreads command 41% of the replacement market of tires for commercial vehicles in the United States and 50% in Europe.

There are 1385 retreading plants in the United States. About 70 of these plants belong to tire manufacturers and the others belong to independent owners, sometimes associated with a large franchiser. Retreading plants can vary in size from 20 tires/day to more than 2600 tires/day. Some plants are specialized on a few segments (air, off-road), while others serve the long-haul trucking market as well as the light truck market. Only one market faces decline, that of passenger cars. This decline reflects the increased competition from inexpensive new tires, whose price differential from retreaded tires has been significantly reduced, and the common misconception that retreaded tires are unsafe.

4.3 Tire leasing

If large fleet operators prefer to manage their own tires with sophisticated programs suited for their requirements, smaller fleets may find more convenient to lease their tires. Tire manufacturers offer to some customers the possibility to lease tires and be charged by the mileage. The customer is expected to return the tires for replacement after running a pre-specified distance to have them retreaded. This system poses some difficulties because the supplier may not have the necessary means to enforce the correct operating parameters. Likewise, there are some difficulties ensuring correct tire identification.

4.3.1 Smart tires

One of the recent changes in the tire operating management will come with the development of the so-called *smart tire*. The smart tire brings a large number of benefits to the fleet operator and the tire owner. Two kinds of chips have been developed: A *passive* chip embedded in the tire transmits information such as an identification number, tire type and manufacturing date. The *active* chip can provide real-time information from temperature and air pressure sensors, and it may be reprogrammed at each retreading event.

The chip is an electronic device patched to the tire, ensuring unique identification. The device contains a transducer which transmits information about the tire usage to the fleet operator and, in case of leasing, to the tire owner. Some of these measures include:

- **Distance run**: It is an important way to collect information regarding wear patterns. The operating manager is able to schedule and control the time before retreading, ensuring maximal mileage without compromising safety. For the tire owner, it is a useful accessory in the enforcement of tire leasing contracts.
- **Tire pressure**: The operator has regular readings of the pressure on all tires, including the internal tires on trailer axles, usually inaccessible. Having regular pressure readings helps ensuring maximum tire life.
- **Tire temperature history**: It is an accessory information, identifying instances where the tire operated in suboptimal conditions. Having a history of the tire temperature, the retreader is able to identify the most appropriate tread for a given casing.

The chip allows improved efficiency in tire usage, continuously reviewing the operating conditions, informing the operator when abnormal tire pressure or temperature occurs. This information can be used in the continual improvement of the operating parameters, helping defining the distance between retreads and the optimal casing conditions. An efficient monitoring system assures that a higher percentage of used tires is suitable for retreading. Furthermore, it helps in the development of fair tire leasing contracts with efficient consumption measures, keeping track of the distance ran for correct invoicing, reducing the conflicts between supplier and buyer.

5. Applications for used tires

Used tires can have many destinations. Out of 283 million tires used in the United States in 1995, only 30 million were retreaded. The remainder had the destinations shown in table 7. The table shows that 39% of all used tires are landfilled, while less than 11% of them are retreaded[2]. Each application seeks a different property in the tire: the rubber's energy content, different physical characteristics (chock absorption, elasticity, impermeability, resistance to abrasion) or the chemical properties. However, these reclaim processes only use a small fraction of the value in the used tire. Only a small part of the physical, chemical and structural properties still remaining in the used tire are exploited in each of them.

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[2] Formerly, the US EPA (1991) estimated that 66% of all used tires is landfilled, but the same 11% is retreaded. Some of the difference is justified by the increased number of tires that incinerated or used as asphalt additive. Nonetheless, both estimations should be read with caution.

Table 7: Used tires applications in the United States

Source: American Retreaders Association (1996).

Application	Quantity (thousands)	Weight (metric tons)
heat generation	101,000	1,087,500
civil engineering applications	13,500	145,500
export	12,500	134,500
direct material use (punch, cut, stamp)	8,000	86,000
ground rubber applications	3,373	36,500
agriculture	2,500	27,000
pyrolysis (thermal distillation)	500	5,500
miscellaneous	1,000	11,000
Reclaim (non-retread)	142,373	1,533,500
Landfilled	110,626	1,191,500
All Used Tires	253,000	2,724,000

5.1 Heat generation

More than 57% of a used tire weight is made of rubber and other organic materials. On average, the heat value of a used tire is around 33 MJ/kg. If a used passenger car tire weighs 7.2 kg, it contains at least 238 MJ of thermal energy, which can be useful in some dedicated facilities. The market value of coal with specific heat of 27 MJ/kg is about $45/ton, that is $1.60 for 1000 MJ. Assuming that the operating cost (other than fuel) of a heat generating facility using coal is the same as using whole tires, the incineration implies a valuation of $0.38 per used passenger tire. This section discusses two industries where used tires can be used as a coal substitute: thermoelectric plants and cement plants.

5.1.1 Thermoelectric plants

This application has some interesting aspects: The tires are fed into the hearth without any pre-treatment or slicing. Once the system is operating little additional investment is required, as long as it receives a constant supply of used tires.

This opportunity has been exploited by several thermoelectric plants. The Wolverhampton plant in the UK burns 94,000 tons of scrap tire to produce 144,000 MWh of electricity. Considering a (conservative) market price of $50 per MWh, each ton of scrap tire fed into this facility can generate $76 worth of electricity. Assuming an average of 138 passenger car tires per ton, this operation values them as no more than $0.55/unit. This process is an economically viable alternative for used tires that cannot be effectively retreaded, generating a large amount of by-products. Each ton of input (as tires) generates 287 kg of solid residue made of zinc oxide, ferrous slag and gypsum, each with a well-defined market.

In 1991 there was one 14-megawatt thermoelectric plant in California, burning used tires. Three other plants, totaling 86 MW were planned or under construction in the United States in the same year.[3] As a rule-of-thumb, these facilities produce 20 kWh of electric energy for each tire consumed. The energy generated is

[3] Source: US EPA (1991)

sold to the local utility company for rates ranging from 6 to 8.3 cents/kWh. Under this valuation, an average used tire (commercial and passenger car sizes alike) contributes with a revenue of about $1.20 - $1.66. Adjusting for the respective weights, this implies in contribution of $0.80 - $1.10 per passenger car tire.

5.1.2 Portland cement plant

This process has the advantage that it does not generate any waste beyond what is usually generated by a standard cement production process. Sliced tires are fed into the kiln with the other raw materials. The energy in the rubber provides the heat while the combustion residues are incorporated in the cement without compromising the product's quality. The ferrous material from the steel wire partially substitutes the large quantities of iron ore used in cement production. Several fuels are used in a cement plant, including coal, natural gas and oil. The rubber may provide roughly 20% of the heat required in the kiln, generally at a lower cost than the other fuels. The high temperature of combustion, around 1400°C, under appropriate supply of oxygen, ensures complete burnout of the organic material.

Several European cement plants have been burning used tires since the 1970's. The Heidelberg Zement plant in Germany consumes 50,000 tons/year, representing 20% of its need for fuel. A small number of North American plants consume used tires as fuel substitute. The Genstar Cement plant in California substitutes 25% of its energy needs with 20,000 tons/year of tire chips. Other plants have been operating successfully in the United States, Canada, Europe and Japan.

The Lafarge plant in France is the first experience in this country. It started with the capacity to burn 20,000 tons of used tires per year but this figure is not always reached, creating some difficulties in adjusting the process parameters to changes in the input composition. Moreover, the firm has difficulty obtaining a continuous stream of used tires, which underscores the importance of locating the plant at a location where used tires are easily available, such as near tire piles.

5.1.3 The economics of heat generation

In order to be successful, the facilities incinerating used tires have to be located close to the locations of large tire dumps, as it is the case with the dedicated thermoelectric facilities in the United States. Otherwise, one such operation may have significant transportation cost. Under strict tire disposal legislation, these facilities may charge a fee for taking in used tires, greatly increasing the operation profitability. The US EPA (1991) report proposes the following expression for analyzing heat generation with used tires:

$$\begin{aligned} \text{Profit} &= \text{Tipping Fee} + \text{Revenue} - \text{Process Cost} - \text{Transport} - \text{Disposal} \\ P &= TF + R - PC - TR - D \end{aligned} \tag{4}$$

If the tire must be obtained from distant locations, it might be worth to shred it, to allow full truck loading. This reduces transportation cost by increasing shredding costs. Disposal might occur when the ashes produced in the facility have no commercial value. Clearly, this problem only affects thermoelectric plants, since cement production does not produce solid waste.

5.2 Ground rubber applications

Granular rubber can be obtained from three sources: from scrap tires, from reject tires and from retread buffings. When a used tire is buffed in the retread plant, a large amount of granular rubber is generated. Buffing is responsible for 2/3 of all granular rubber available in the United States. Granular rubber is also obtained by grinding whole scrap or reject tires at room temperature or by a cryogenic method. Not all physical properties of the virgin rubber are preserved in the ground rubber, hence its utilization in the tire industry has been quite limited. So, there has been some research toward the development of a recycling process that allows reusing more of the rubber qualities still present in the used tires.

5.2.1 Processes for grinding

Cryogenic grinding is one of the processes of grinding rubber – or any other polymer – without changing the polymer structure or the hydrocarbon content. The term "cryogenic" indicates that the rubber is vitrified in liquid nitrogen to about -200°C and pulverized with a hammer mill at an operating cost of $40/ton of scrap tire. Approximately 70% of the tire content is yielded as rubber, 10% is steel and 15% is fiber. All products can be sold. The process is more advantageous for recycling scrap rubber and plastic before any mixture occurs; the polymer coming out of the grinding process reflects the variety of raw materials in the mix. Users of cryogenic granulated rubber include

- Contractors who make running tracks, tennis courts and other sport surfaces
- Landscapers who use rubber as a soil amendment
- Manufacturers of rubber products who use recycled material as a filler
- Asphalt plants who use rubber as a modifying additive
- Rubber devulcanization facilities

Used tires can be ground at room temperature as well. The used tires are fed into a shredder that reduces then into 3/4 inch chips before a magnet separates the steel wires. The chips are further reduced by a granulator down to 600-800 μm crumbs. The finely ground rubber is reused as filler in applications where the superior qualities of virgin rubber are not required. The advantage over cryogenic grinding is in the lower cost.

5.2.2 Upgrade with *Bioreaction*

Because the used rubber has already been vulcanized, the utilization of ground rubber presents a number of technical difficulties with degradation of the physical properties. A number of companies worldwide have developed methods to turn recycled rubber particles (crumb rubber) into a material that has physical properties and a processing behavior comparable to that of virgin rubber. This new trend has the potential of revolutionizing the rubber industry because crumb rubber will no longer be limited to applications in low-tech products. Romine et al. (1995) report significant progress in the development of bioreaction, which reduces this handicap and might allow the reuse of rubber into the tire industry (5). Bioreaction is a process that has the potential to improve the quality of the ground rubber, perhaps giving it the opportunity to return to the beginning of the production cycle as a new material. The objective of this technology is to avoid that ground rubber is forced into *cascade recycling* but that it is allowed into a *like-for-like recycling* process.

Granular rubber is introduced in a bioreactor containing microorganisms that metabolizes its sulfur content, neutralizing its first vulcanization process. After the reaction is complete, the output is ready to be incorporated in a new rubber matrix to produce high grade rubber for tires. However, the process is still in laboratory scale, with batch sizes of 45 kg. Primary figures say that the process may generate a profit margin of

$10/ton of tire rubber. It is hoped that once the continuous process is fully developed, it may substitute some of the demand for virgin rubber materials.

5.2.3 Asphalt enrichment

One of the preferred applications for granular rubber is as filler in asphalt mix, absorbing 50,000 tons/year of ground rubber in the United States. The report by US EPA (1991) tell us that the rubber is expected to increase durability and traction of highway pavement. If the technology is appropriately developed, there would be enough demand to absorb the totality of scrap tires generated in any country. There are two competing technologies: the rubber-modified asphalt concrete (RUMAC) includes about 3% by weight of ground rubber, replacing some of the aggregate in the original asphalt. The rubber is graded to specifications and uniformly dispersed throughout the mixture. The final asphalt is applied by conventional equipment. It was originated in the 1960's and has been tested in the Department of Transport of New York State since 1989. A complete analysis comparing the material costs with the expected life of the road surface for both the RUMAC and the standard asphalt is not available yet.

The alternative technology is the asphalt-rubber (A-R). It has been extensively used in some areas of the United States. In this process, conventional asphalt is blended with up to 25% of ground rubber, after complete separation of the steel and fibers, at 200°C. The outcome is a product of higher viscosity requiring special equipment to apply it on the road surface. Some of the problems faced by A-R is the absence of standardization in application and mixture methods. Because of the high viscosity, asphalt rubber does not lay thinly so, the final cost per paved length may be higher than with conventional asphalt. On the other hand, asphalt-rubber present significant advantages such as better permeability and, apparently, longer life. Tests with A-R in three American states report a life extension of up to 3 times.

5.3 Direct material reuse

A small fraction of the scrap tires is consumed through direct reuse. The tire is cut, stamped or sliced to form welcome mats, muffler hangers, traffic cone weights, dock bumpers, as well as to secure covering for silos and outdoor storage. Some car manufacturers have included in their designs rubber components made of used tires, such as brake pads. It is a very limited market that takes advantage of part of the physical properties remaining in the rubber.

5.3.1 Other civil engineering applications

Some of the used tire physical properties, such as sound and impact absorption, suggest its use in construction. Whole tires have been used in reef and breakwater construction, stabilizing embankments, as highway crash barriers and attenuating highway noise in urban areas. However, these applications can only absorb a small fraction of the used tires available each year. Other widely available recycled materials , such as used plastic bottles have been suggested for the same uses, thus reducing the opportunity to use recycled tire materials.

5.4 Pyrolysis

Pyrolysis is the process of separating materials in the presence of heat and without air, avoiding oxidation. Strictly speaking, pyrolysis is the recycling process for used tires, re-generating the basic chemicals used to make a tire. It generates carbon black, zinc, sulfur, steel and oils; the polymeric structure is lost. The process has been researched since mid-70's. The pyrolysis of 1 ton of tires produces 350-420kg of oil, 130-160kg of char, 190-220kg of steel, 150-180kg of fiber glass. The char can be reprocessed into low-grade carbon black, which cannot be used in tire production. This technical difficulty is the major drawback against the implementation of a successful pyrolysis process.

All the products from the pyrolysis have a stable demand, however its operating cost is still not competitive. Nonetheless, a few small commercial plants have operated in the United States and in the UK. Eventually, if the supply of some of its output becomes restricted, pyrolysis may become an economical use for scrap tires, but this is not expected to happen in the near future.

6. Static analysis of tire recovery processes

Figure 2 shows the material flow, considering the main alternatives for tire reuse today. Landfill is included for completeness, although the material is not reused. I indicate bioreaction and pyrolysis with dashed lines, to remind that these technologies are not fully developed. However these processes are worth considering because they might consume large amounts of used tires in the future. Some of the output ratios in this graph are:

- Of all tires produced in a new-tire manufacturing process, about 3% is rejected.
- About 10% of a tire's original weight is dissipated in the road.
- About 10% of the used casings arriving at a retreading plant is rejected at one of the three inspection points (before buffing, at case repair, or after retreading).
- About 10% of a tire's original weight is removed during the buffing process.
- The pyrolysis of 1 ton of tires should produce 350-420kg of oil, 130-160kg of char, 190-220kg of steel, 150-180kg of fiber glass.

The diagram shows that tire retreading reduces the demand for casing material. Each tire coming out of a retreading plant is reusing a casing that would have to be manufactured otherwise. However, tire retreading increases the consumption of tread material. First, because the retreading procedure has higher reject ratio. Second because optimal retreading requires a reduction in tire life: the time between retreads is shorter than the single-usage tire life. Also, the production of significant amounts of ground rubber is unavoidable. Hence, an integrated tire reuse program should identify economical uses for ground rubber. In what follows I identify the value attributed to the casing whenever either alternative is adopted. Only the alternatives that can potentially absorb a significant amount of the used tires available today are considered.

6.1 The value of the casing in retreading

Section 4.2 provided an approach for analyzing the value of a used casing entering the retreading plant:

$$\text{Used Casing Value} = \text{Market Value of Retreaded Tire} * \text{Yield} - (VMC + \text{Retreading Cost}) / \text{Partial Yield}$$
$$\text{UCV} = \text{MVRT} * \text{Y} - (\text{VMC} + \text{RC}) / \text{Y}_p \qquad (3)$$

The new tire in our calculations weighs 8kg and is worth \$40. The retreaded tire is worth \$24. Figure 3 shows the material flow (in terms of weight) assuming that the tire is retreaded just once, it has a second life and is finally disposed of. A fraction α of the used tires arriving at the retreading process is rejected during

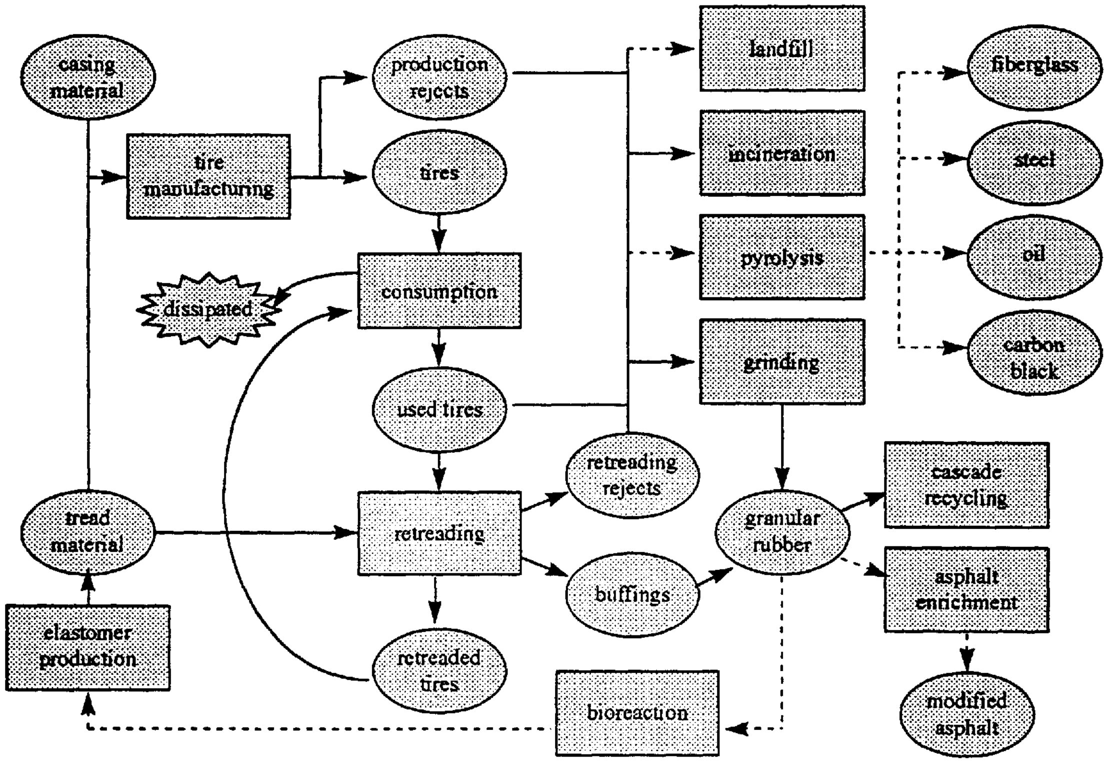

Figure 2 - Material reclaim alternatives for used tires (today)

pre-inspection. Once the tread is applied and vulcanized, all retreaded tires are inspected and a fraction β is rejected. Hence, $Y = (1-\alpha)(1-\beta)$ and $Y_p = (1-\beta)$.

A used casing returning to the retreading facility provides an opportunity value that is exploited when it is effectively retreaded. The virgin material cost is given by equation (2), that is $VMC = VMR * TrC / TrW$. In a new tire, a tread weighs 2.5 kg. Appendix A estimates that it is worth $3.63. The tread material required for retreading a used tire weighs $VMR = 0.2 * (1-\alpha) * 8$ kg = 1.52 kg. Adjusting for the different weights, VMC = $2.20. Assuming that α and β equal 5%, the yield is 0.9025. Apparently, the energy cost to vulcanize the tread-casing assembly is approximately the same, whether the tire is produced new or retreaded. In Appendix A, it is estimated as a mere $0.10/tire. The retreading process includes other costly operations such as pre-inspection, casing preparation and buffing, nonexistent in the tire production process. These are labor intensive operations. Based on interviews with professionals in the field, I estimate that these operations process on average 10-15 tires/man-hour, that is no more than $7.00/tire. Applying these values in equation (3), it becomes:

$$UCV = MVRT * Y - (VMC + RC) / Y_p$$
$$UCV = \$24 * 0.9025 - (\$2.20 + 7.10)/0.95$$
$$UCV = \$11.87$$

Hence, the retreading operation generates a contribution of $11.87 per casing. Alternatively, one may say that the opportunity value of each retreaded casing is $11.87.

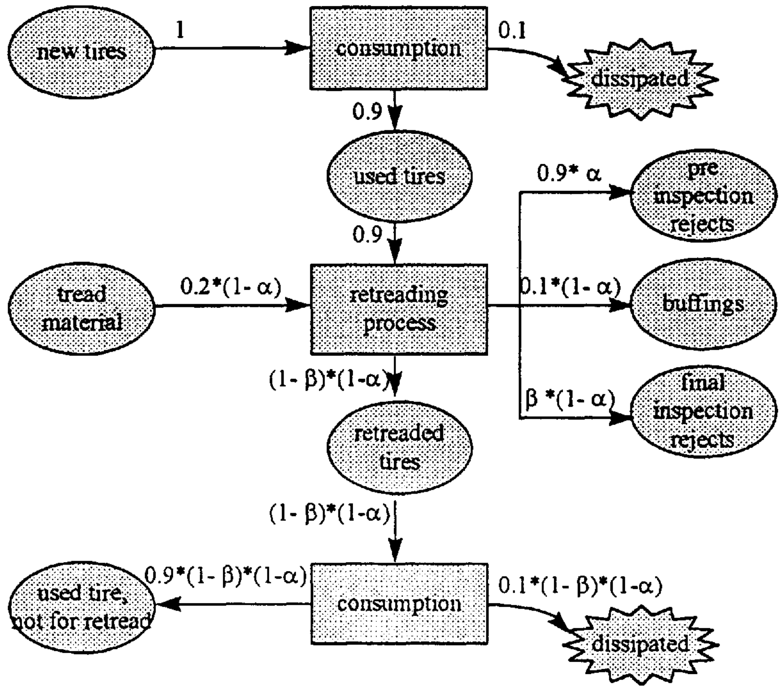

Figure 3 - Material flow, single retreading

This value should be read with caution, because of a number of estimates that directly affect the result. As warned, it overlooks the transportation cost that the retreader might incur to collect used tires and the revenue from the sale of rubber crumbs or from tipping fees. More important, though, the operating yields are sensitive both to exogenous and endogenous causes. There is not much one can do about the exogenous changes in the yield. However, as the retreading technology progresses, the yield in the final inspection is expected to improve.

6.2 The value of the casing in heat generation

The report by US EPA (1991) evaluates the profitability of several ventures where used tires are burned as fuel. Let's use the result in Section 5.1 to identify the intrinsic value of the used tire received at these facilities, drawing from some of the information available in that report:

$$P = TF + R - PC - TR - D \tag{4}$$

In what follows, I use some of the numeric values estimated in that report to evaluate the material value of the used tire at the time of disposal, as a function of its application. Many of the incinerating operations benefit from tipping fees of up to $1.00 paid by tire dealers disposing of the used tires that it is forced to collect from their customers. In some locations, a tire disposal fee is charged at the sale of each new tire, part of this resource is given as subsidy to the ventures that consume or recycle used tire, just as a tipping fee. In practice, power plants locate themselves close to large piles of tires landfilled in the past. The Filbin tire pile, outside the Oxford Energy's Modesto plant in California, guarantees a continuous operation for more than 10 years, along with the additional tires that the plant can collect during this period. Contrarily, the Lafarge cement plant in France depends on the incoming tires to fuel its operation. The difficulty in maintaining a continuous

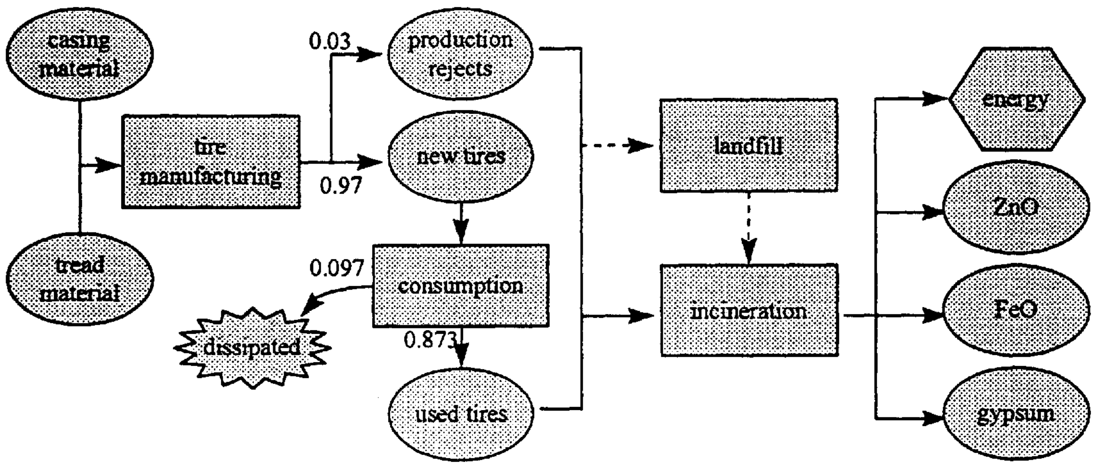

Figure 4 - Material flow leading to used tire incineration

stream has made it difficult to tune the operation for a varying fuel mix. Hence, the income from tipping fee is not considered, since it may not be sustainable in the long run. For the same reason, transportation costs are overlooked, which is correct if regulation is strict and the tire owner is forced to dispose of the tires at approved locations.

Figure 4 shows the material flow leading to the incineration of used tires. The mineral by-products only occur in thermoelectric plants, since the cement production would entirely absorb them. Clearly, incineration is an indirect recycling process: it treats the tires the same way as it treats the petroleum that originated it. Our analysis in section 5.1 showed that each used passenger car tire may generate a revenue of \$0.80 - \$1.10 in a thermoelectric plant. Since the solid waste from this process can be commercialized, I assume that there is no disposal cost. The report by US EPA (1991) estimates that the operating cost of a thermoelectric plant equals \$0.50 per average tire. Assuming activity-based costing (ABC), this figure is adjusted for the smaller size of the passenger car tire. Then, the operating cost of a thermoelectric plant becomes \$0.33/tire. Substituting these values in equation (4) it becomes

$$P = TF + R - PC - TR - D$$
$$P = 0 + \$0.95 - \$0.33 - 0 - 0$$
$$P = \$0.62$$

In a cement plant, the revenue must be measured by the amount of traditional fuel that is diverted from the plant when tires are added to the mix. Section 5.1 indicates that the energy value of the tire, when compared to the price of coal, is \$0.38/tire. Cement plants require that the tire is shredded before fed into the kiln. According to the US EPA (1991), this implies in an additional cost of \$0.18 - \$0.24 per average tire. Adjusted for the size of the passenger car tire, this cost equals \$0.12 - \$0.16 per passenger car tire. Considering that there are no disposal costs, and assuming no transport or tipping fee, the used tire valuation in a cement plant is given by

$$P = TF + R - PC - TR - D$$
$$P = 0 + \$0.38 - \$0.14 - 0 - 0$$
$$P = \$0.24$$

The analysis shows that when a used tire is incinerated, its intrinsic valuation is very low, which does not have to be true, if the casing can be reused in a retreading process. Nonetheless, incinerating tires is the only commercial alternative to tire retreading today, especially for those tires that have been disposed and are sitting in the huge landfills in Europe and the United States or for those significantly damaged that cannot be retreaded. Next, I propose a "wiser" material flow for the tire industry: one that maximizes the recovery of the value-added still available in used tires at the time of disposal.

7. Dynamic analysis of tire recovery processes

Our vision of an optimal tire utilization is to retread it a limited number of times until, eventually, it is shredded in the production of rubber crumbs or incinerated in a thermoelectric plant. If the bioreaction technology is fully developed, and the process can be implemented in an industrial scale, the rubber crumbs can be recycled into high-grade synthetic rubber in the production of new tires. Otherwise, the rubber crumbs can be added in the composition of asphalt, a process for which the technology still have to be perfected. At this date, none of these reuse methods can be fully evaluated because their respective technologies are not completely dominated. Meanwhile, heat generation is the best final use for tires.

Figure 5 balances the material flow of each consumed tire, assuming that each tire can be retreaded indefinitely, without loss in the length of tire life. In steady state, for 100 tires demanded in the market, 10% of the total weight is dissipated during consumption. Assuming that both the pre-inspection reject and the final inspection reject equal to 5%, the system is in equilibrium if, for each 100 tires demanded in the market, 90.25 are retreaded and 9.75 are new. If each tire is allowed to be retreaded an unlimited number of times, the expected number of retreads per tire equals 90.25/9.75 Hence, on average, each tire is retreaded approximately 9 times before eventually rejected. (The graph does not consider that each tire can resist just a limited number of retreading operations.)

Table A-11 indicates that when the tire is originally produced, \$25.36 is spent for an output worth \$40. This represents a return on investment of 58%. If all tires follow the retreading cycle once – subject to being rejected at one of the inspection points – the expected revenue obtained from each casing equals

$$\$40 + 0.9025 * \$24 = \$61.66$$

The expected cost of manufacturing and retreading once each casing equals

$$\$25.36 + (\$2.20 + \$7.10) / 0.95 = \$35.15$$

Hence, the return on investment increases to 75%. Allowing unlimited retreading, the expected revenue from each casing from the time it is first manufactured until it is eventually rejected equals

$$\$40 + \frac{90.25 * \$24}{9.75} = \$262.15$$

Likewise, the expected cost of manufacturing and retreading each casing an unlimited number of times, until eventually rejected, equals

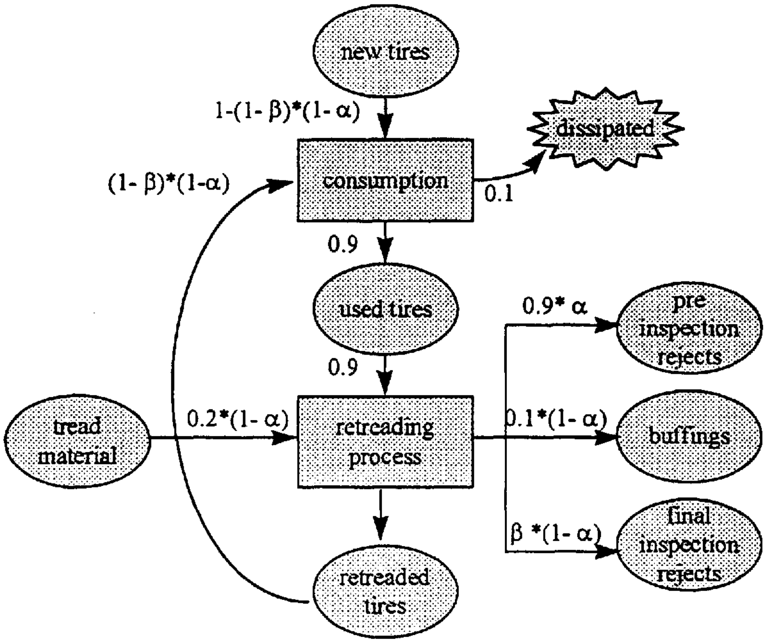

Figure 5 - Material flow, unlimited retreading per casing

$$\$25.36 + \frac{90.25 * (\$2.20 + \$7.10)/0.95}{9.75} = \$115.98$$

This represents an expected return on investment of 126%. If n is the maximum number of retreads that a casing is allowed to receive, it is simple to show that the expected revenue and the expected cost per casing is given by the expressions

$$\text{Expected Revenue}(n) = \text{New Tire Revenue} + \text{Retread Revenue} * \text{Expected Number Retreads}(n)$$

$$ER(n) = NTR + RR * \frac{Y - Y^{n+1}}{1 - Y} \tag{5}$$

$$\text{Expected Cost}(n) = \text{New Tire Cost} + \text{Retread Cost} * \text{Expected Number Retreads}(n)$$

$$EC(n) = NTC + RC * \frac{Y - Y^{n+1}}{1 - Y} \tag{6}$$

where $Y = (1-\alpha)*(1-\beta)$ is the expected total yield. Substituting different values of n in the expressions with the values of new tire revenue and cost and retreaded tire revenue and cost, the graph in Figure 6 is generated.

In practice, the tire cannot be retreaded more than a limited number of times. The pre-inspection rejection rate tends to increase with the number of times that the tire is retreaded, because of the fatigue of the casing structure. In order to ensure that a large number of tires pass the pre-inspection process, practitioners reduce the time between retreading as the number of retreads increase. Suppose that a tire is retreaded three times before it is finally disposed of. Some in the industry use the rule-of-thumb that the length of the three tire lives should be in the proportion 1 : 0.8 : 0.7. If the retread life length is reduced, one should expect that its value is reduced in the same proportion. Hence, for analytical convenience, I propose a recursive rule for estimating the life length of a retread such that the rejection rate is not altered:

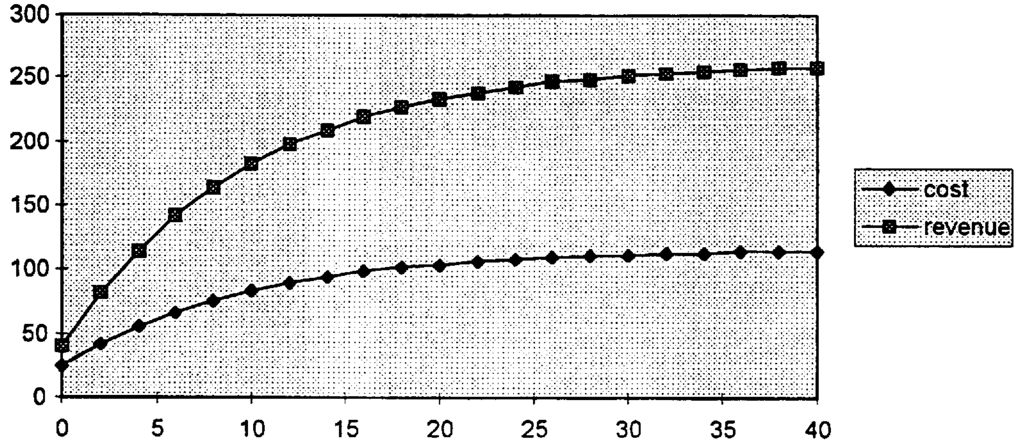

Figure 6 - Expected revenue and cost when the casing is allowed to be retreaded n times, assuming that durability is not affected by the number of retreads.

$$RR_n = Z * RR_{n-1}$$

$$RR_0 = NTR \quad .$$

where Z is the rate of life reduction at each retread event. Under this assumption, equation (5) becomes:

$$ER(n) = RR_0 + Y * RR_1 + \ldots + Y^n * RR_n$$

$$= \sum_{i=0}^{n} Y^i RR_i = NTR * \sum_{i=0}^{n} Z^i Y^i$$

$$ER(n) = NTR * \frac{1 - Y^{n+1} Z^{n+1}}{1 - YZ} \qquad (7)$$

Notice that for each additional retread, one should compare the expected additional revenue with the expected additional cost. The optimal policy allows retreading up to n times if and only if the expected additional cost of retreading n times is less than the expected additional revenue. Moreover, the expected additional cost of retreading n+1 times is greater than the expected additional revenue. This translates to

$$\begin{cases} Y^n Z^n NTR > Y^n RC \\ Y^{n+1} Z^{n+1} NTR < Y^{n+1} RC \end{cases}$$

The solution to this problem is given by the integer n satisfying

$$n = \left\lfloor \frac{\log(RC/NTR)}{\log(Z)} \right\rfloor \qquad (8)$$

where $\lfloor X \rfloor$ equals the largest integer less than or equal to X. Applying the value of retread cost (RC = \$9.79) and the new tire revenue (NTR = \$40) with several values of Z in equation 8, the recommended number of retreads for each tire is about four or five times, depending on the rate of reduction of the time between retreads (Z) required for maintaining the yield rate at a constant level (Y). The results are in the grid below:

Z	0.7	0.71	0.72	0.73	0.74	0.75	0.76	0.77	0.78	0.79	0.8
n	3	4	4	4	4	4	5	5	5	5	6

Notice the simplicity of equation (8). The information it requires is easily available to the fleet manager or to the tire lessor. For the sake of illustration, let Z = 0.78. Then, the tire is retreaded 5 times with respective life lengths in the proportion

$$1 : 0.78 : 0.60 : 0.48 : 0.37 : 0.29$$

Using equations (6) and (7), the expected revenue is $118.67, and the expected cost is $61.74, which represents a return on investment of 92%.

8. Discussion

This paper is concerned with the large amount of tires disposed in landfills each day, and proposes alternative ways to recover the value still remaining in the used tire. It describes the international market of tires, some of the used tire recovery practices and a decision rule which identifies the number of times the tire should be retreaded and reused before facing a final recovery process. The Appendix identifies the value-added in each step of the tire production, necessary as a benchmark to compare the profitability of tire retreading with the primary manufacture. I describe the retreading process, identifying value-adding steps as well as inspection steps where some material is forced out of the recovery cycle.

Section 5 described four recovery processes suitable as final applications for used tires: (1) heat generation in thermoelectric plants or in cement kilns, (2) ground rubber applications, as asphalt additive or recycled into high-grade rubber by means of bioreaction, (3) direct reuse in civil engineering works, or (4) recycling through pyrolysis. Heat generation is the only alternative entirely available today: it is economically viable, the technology is satisfactory and the demand is constant. The other alternatives have technological, economical or demand limitations that justify being overlooked at this point. Bioreaction and asphalt enrichment are technologies of the future that might complement the existing alternatives, in the development of an integrated tire life-cycle. They should be closely followed.

I maintain that retreading is the sole alternative for maximizing tire utilization. A single retreading event attributes the value of $11.87 to the used tire, without precluding some further incineration when the tire becomes not suitable for retreading. I have compared it with the economic value of incinerating used tires in power plants or in cement kilns. I propose that, as long as the bioreaction technology or the asphalt enrichment techniques are not fully developed, tires that can no longer be retreaded should be incinerated in power plants or in cement kilns with appropriate pollution abatement equipment. When a tire is incinerated in a power plant, it is attributed the value of $0.62; in a cement kiln, just $0.24. It should be observed that transportation cost and tipping fee was not considered in the analysis. However, the results should not change significantly.

Finally, I considered the reduction in the time between retreads caused by the material fatigue. Assuming that the value of the tire, retreaded or not, is proportional to the time between retreads, I proposed a closed-form expression based on the rate of reduction of the time between retreads, the value of the new tire and on the retreading cost. The expression recommends the number of retreads for each tire that maximizes tire utilization.

9. Appendix

Tables A-1 through A-13 contain the evaluation of the value-added in the elastomer content of a typical 8kg European tire, from crude oil refining until the last vulcanization step:

Table A - 1: Petroleum refining

INPUT	quantity	unit price	cost		
crude oil	26.412 kg	$ 0.10	$ 2.64		
OUTPUT	**quantity**	**unit price**	**sold for**	**value-added**	**VA/kg**
naphtha	26.187 kg	$ 0.20	$ 5.21	$ 2.63	
butene-1	0.002 kg	$ 0.79	$ 0.00	$ 0.00	
benzene	0.224 kg	$ 0.34	$ 0.08	$ 0.02	
total	26.412 kg		$ 5.29	$ 2.65	$ 0.10

Table A - 2: Value-added from petroleum refining

	naphtha		butene-1		benzene		process VA	VA/kg
in tread	0.080	2.099 kg	0.564	0.001 kg	0.527	0.118 kg	$ 0.22	$ 0.10
in casing	0.068	1.791 kg	0.436	0.001 kg	0.473	0.106 kg	$ 0.19	$ 0.10
excess	0.851	22.297 kg	0.000	0.000 kg	0.000	0.000 kg	$ 2.24	$ 0.10
total	1	26.187 kg	1	0.002 kg	1	0.224 kg	$ 2.65	$ 0.10

Table A - 3: Cracking processes (partial)

INPUT	ratio	quantity	unit price	cost		
utilities	1.000	7.296	$ 6.56	$ 47.86		
naphtha	3.589 kg	26.187 kg	$ 0.20	$ 5.21		
total		26.187 kg		$ 53.08		
OUTPUT	**ratio**	**quantity**	**unit price**	**sold for**	**value-added**	**VA/kg**
propylene	0.5731	4.182 kg	$ 0.51	$ 2.12	$ 1.97	
gasoline	1.017	7.420 kg	$ 0.25	$ 1.86	$ 3.50	
fuel oil	0.0649	0.474 kg	$ 0.12	$ 0.05	$ 0.22	
energy				$ 54.07		
C4 fractions	0.451	3.291 kg	$ 0.21	$ 0.69	$ 1.55	
ethylene	1	7.296 kg	$ 0.68	$ 4.98	$ 3.45	
total		22.662 kg		$ 63.78	$ 10.70	$ 0.47

Table A - 4: Value-added from the cracking processes

	ethylene		C4 fractions		process VA	cum VA	cum VA/kg
in tread	0.52	0.040 kg	0.54	1.777 kg	$ 0.86	$ 1.08	$ 0.59
in casing	0.48	0.036 kg	0.46	1.514 kg	$ 0.73	$ 0.92	$ 0.60
total	1	0.076 kg	1	3.291 kg	$ 1.59	$ 2.00	$ 0.59

Table A - 5: Alkylation processes

INPUT	ratio	quantity	unit price	cost		
utilities				$ 0.05		
ethylene	0.2997	0.076 kg	$ 0.68	$ 0.05		
benzene	0.799	0.201 kg	$ 0.34	$ 0.07		
C4 fractions	2.34	3.291 kg	$ 0.21	$ 0.69		
total		3.560 kg		$ 0.86		
OUTPUT	**ratio**	**quantity**	**unit price**	**sold for**	**value-added**	**VA/kg**
styrene tread	0.52	0.132 kg	$ 0.777	$ 0.102	$ 0.035	
styrene casing	0.48	0.120 kg	$ 0.777	$ 0.093	$ 0.032	
styrene	1	0.252 kg	$ 0.777	$ 0.196	$ 0.066	$ 0.26
mix butylenes	1.282	1.803 kg	$ 0.260	$ 0.469	$ 0.177	
butadiene tread	0.54	0.759 kg	$ 0.408	$ 0.310	$ 0.074	
butadiene casing	0.46	0.647 kg	$ 0.408	$ 0.264	$ 0.063	
butadiene	1	1.406 kg	$ 0.408	$ 0.574	$ 0.138	$ 0.10

Table A - 6: Value-added from the alkylation processes

	styrene		butadiene		process VA	cum VA	cum VA/kg
in tread	0.52	0.132 kg	0.54	0.759 kg	$ 0.11	$ 1.19	$ 1.33
in casing	0.48	0.120 kg	0.46	0.647 kg	$ 0.10	$ 1.02	$ 1.33
total	1	0.252 kg	1	1.406 kg	$ 0.20	$ 2.21	$ 1.33

Table A - 7: Polymerization processes

INPUT	ratio	quantity	unit price	cost		
utilities				$ 0.134		
rubber chemicals				$ 0.077		
styrene	0.223	0.252 kg	$ 0.78	$ 0.196		
butadiene	0.728	0.823 kg	$ 0.41	$ 0.336		
butadiene	1.021	0.584 kg	$ 0.41	$ 0.238		
butene-1	0.003	0.002 kg	$ 0.79	$ 0.001		
benzene	0.0398	0.023 kg	$ 0.34	$ 0.008		
methanol	0.001	0.001 kg	$ 0.16	$ 0.000		
isobutyl	0.973	0.209 kg	$ 0.50	$ 0.104		
isoprene	0.027	0.006 kg	$ 1.50	$ 0.009		
total		1.898 kg		$ 1.103		
OUTPUT	ratio	quantity	unit price	sold for	value-added	VA/kg
SBR tread	0.52	0.591 kg			$ 0.371	
SBR casing	0.48	0.539 kg			$ 0.338	
SBR	1	1.130 kg	$ 1.20	$ 1.356	$ 0.709	$ 0.628
Poly BR tread	0.56	0.322 kg			$ 0.350	
Poly BR casing	0.44	0.249 kg			$ 0.271	
Poly BR	1	0.572 kg	$ 1.65	$ 0.943	$ 0.621	$ 1.087
IIR tread	-	0.000 kg			$ -	
IIR casing	1.00	0.214 kg			$ 0.466	
IIR	1	0.214 kg	$ 2.80	$ 0.600	$ 0.466	$ 2.173

Table A - 8: Value-added from polymerization

	SBR		Poly BR		IIR		process VA	cum VA	cum VA/kg
in tread	0.52	0.591 kg	0.56	0.322 kg			$ 0.72	$ 1.91	$ 2.09
in casing	0.48	0.539 kg	0.44	0.249 kg	1.00	0.214 kg	$ 1.08	$ 2.09	$ 2.09
total	1	1.130 kg	1	0.572 kg	1	0.214 kg	$ 1.80	$ 4.00	$ 2.09

Table A - 9: Tread and casing production

		Tread production		
INPUT	ratio	quantity	unit price	cost
energy		6 kWh	$ 0.05	$ 0.30
NR	0.367	0.948 kg	$ 1.20	$ 1.14
SBR	0.229	0.591 kg	$ 1.20	$ 0.71
BR	0.125	0.322 kg	$ 1.65	$ 0.53
carbon black	0.270	0.698 kg	$ 1.29	$ 0.90
rubber chemicals	0.010	0.026 kg	$ 1.80	$ 0.05
total		2.586 kg		$ 3.63

		Casing production		
INPUT	ratio	quantity	unit price	cost
energy		12 kWh	$ 0.05	$ 0.60
NR	0.136	0.773 kg	$ 1.20	$ 0.93
SBR	0.095	0.539 kg	$ 1.20	$ 0.65
BR	0.044	0.249 kg	$ 1.65	$ 0.41
IIR	0.038	0.214 kg	$ 2.80	$ 0.60
steel	0.182	1.031 kg	$ 3.60	$ 3.71
carbon black	0.209	1.182 kg	$ 1.29	$ 1.52
rubber chemicals	0.168	0.951 kg	$ 1.80	$ 1.71
bead wire	0.055	0.309 kg	$ 2.00	$ 0.62
rayon cord	0.073	0.412 kg	$ 7.00	$ 2.89
total		5.662 kg		$ 13.64

OUTPUT		quantity	unit price	sold for
tread	1	2.586 kg	$ 3.20	$ 8.27
casing	1	5.662 kg	$ 3.00	$ 16.98

Table A - 10: Value-added from tread and casing production

	process VA	cum VA	cum VA/kg
in tread	$ 4.65	$ 6.56	$ 7.18
in casing	$ 3.35	$ 5.44	$ 5.42
total	$ 7.99	$ 12.00	$ 6.26

Table A - 11: Tire production

INPUT	quantity	unit price	cost
energy	2 kWh	$ 0.05	$ 0.10
tread	2.586 kg	$ 3.20	$ 8.27
casing	5.662 kg	$ 3.00	$ 16.98
total	8.247 kg		$ 25.36
OUTPUT	**quantity**	**unit price**	**sold for**
tire	8.000 kg	$ 5.00	$ 40.00

Table A - 12: Value-added from final production

	process VA	cum VA	cum VA/kg
in tread	$ 4.59	$ 11.15	$ 12.58
in casing	$ 10.05	$ 15.49	$ 15.92
total	$ 14.64	$ 26.64	$ 14.33

Table A - 13: Cumulative value-added per kilogram of elastomer

	Oil fractions	Alkylene	Monomers	Elastomers	Component	Tire
tread	$ 0.10	$ 0.59	$ 1.33	$ 2.09	$ 7.18	$ 12.58
casing	$ 0.10	$ 0.60	$ 1.33	$ 2.09	$ 5.42	$ 15.92
tire	$ 0.10	$ 0.59	$ 1.33	$ 2.09	$ 6.26	$ 14.33

References

[1] Guelorget, Y., V. Jullien, P.M. Weaver, A Life-Cycle Analysis of Automobile Tires in France, working paper 93/67/EPS, Center for the Management of Environmental Resources, INSEAD, Fontainebleau, France, 1993.

[2] US Environmental Protection Agency, *Markets for Scrap Tires*, October 1991, in Scrap Tires Technology and Markets, published by Noyes Data Corporation, Park Ridge, NJ-USA, 1993.

[3] Clark, Charlotte, K. Meardon, D. Russell, *Burning Tires for Fuel and Pyrolysis*, December 1991, in Scrap Tires Technology and Markets, published by Noyes Data Corporation, Park Ridge, NJ-USA, 1993.

[4] EcoPlan International, *New Developments in Tire Technology*, Paris, France, 1992.

[5] Romine, Robert A., M. F. Romine and L. Snowden-Swan, *Microbial Processing of Waste Tire Rubber*, presented at the meeting of the American Chemical Society on October 17-20, 1995.