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**Fausto Freire**
University of Coimbra

**Paulo Ferrão, Cristina Reis and Sten Thore**
Instituto Superior Técnico

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## ABSTRACT

A mathematical programming decision model — Life Cycle Activity Analysis (LCAA), integrating economics and environment in the optimization of the life cycle of products is presented. LCAA is based on the integration of *"activity analysis"* with the "*life cycle assessment"* framework. An illustrative application taken from the Portuguese used tire market is described. The model features two scenarios for tire end-of-life recovery technologies, where the environmental consequences of the prohibition of tire landfill are analyzed, namely in terms of energy use. Alternative end of life strategies such as tire remanufacture (retreading), recycling, heat generation in cement plants is considered in the model. The model shows that, provided the Portuguese constraints on the capacity of the alternative solutions, the prohibition of tire landfill result in a 5% decrease of energy consumption over the total tire life cycle.

## INTRODUCTION

Environmental burdens are typically associated with physical flows, which are mainly due to energy processing, manufacture of goods, their use and disposal.

In particular, the environmental stresses caused by industry stem primarily from the use of strictly linear process fluxes with almost no recovery or reuse of products, materials and energy. As a consequence, new scientific and technological challenges are arising from the need to redesign industrial infrastructures and products in such a way that product environmental impacts are reduced over its entire life cycle.

Industrial ecology takes the pattern of ecological systems as a model for solving environmental problems and thus promoting the view of industrial infrastructures as a series of interlocking man-made ecosystems interfacing with the natural global ecosystem. This is an important shift from the previous focus, which is restricted to the analysis of specific parts of the product-material chain. Analysis within a life cycle system perspective is fundamental, namely because, in many cases, reduction or change in one part of a system typically results in shifting the burden to other system component.

Several methods have been developed to model physical flows and, in particular, to assess the associated environmental impacts, e.g. Life Cycle Assessment (LCA), Materials Flows Analysis (MFA), Environmental Impact Assessment (EIA). However valuable, these methods generally do not include the description of economic mechanisms (allocation, optimization, substitution) or costs and benefits. Traditional economic models, on the other hand, have mainly focused on the general notion of externalities and do not explicitly describe the flows and transformation of materials.

In this context, a new analytic format: Life Cycle Activity Analysis (LCAA) is proposed, which ties mathematical programming formulations of activity analysis to their environmental impacts. LCAA is based on the integration of *Activity Analysis,* a well-known procedure in economics, solving for optimal levels of production and for the optimal allocation of resources, with environmental *Life Cycle Assessment*, which aims to quantify the environmental impacts of a product or a service from the “cradle” to the “grave”.

Tjalling Koopmans (1957) developed the basic concepts of activity analysis — Koopmans shared (with L. Kantorovitch) the 1975 Nobel Prize in economics. Charnes and Cooper (1961) have extended activity analysis, as a linear program, to allow for any number of activities and any number of commodities.

The classical formulation of *Activity Analysis* distinguishes three classes of goods: primary goods (natural resources or materials), intermediate goods and final goods (outputs). LCAA extends the concept of linear activities to embrace mass and energy fluxes over the entire life cycle of products. In particular, the proposed LCCA model includes one additional category of goods: *"environmental goods",* which represent the emissions of pollutants, energy consumption and the dumping of waste. These environmental outputs can be further aggregated into a number of environmental impact categories, such as global warming, ozone depletion, etc. This approach links up with the development of *Life Cycle Assessment* methodology and its aim is twofold. Firstly, it interprets the environmental burdens included in the output table in terms of environmental problems or hazards. Secondly, it aggregates the data for practical reasons, particularly for decision-making.

LCAA integrates engineering, environmental and economical sciences, including operations research as LCAA solves for optimal solutions of multi-variable complex systems, and can be interpreted as a new Industrial Ecology tool.

This paper presents an application of Life Cycle Activity Analysis (LCAA) to an illustrative example brought from the Portuguese used tire market.

The motivations for this paper derives from the current work at the European Union level, where a working group was set, with the purpose of developing a strategic proposal for management of the used tire flux. According to their conclusions, there are a few goals that must be achieved in the year 2000:

- Selective recover must be implemented to 100% of the total production;
- Prevention strategies must be implemented in a way that the waste flux should equal the production levels of 1990;
- Retreading must be the end of life for, at least, 25% of the produced used tires;
- For energy recover should be sent, at least, 65% of the used tires;
- Landfill deposition must be forbidden.

In addition, a hierarchy of uses for scrap tires and their derivatives can be established, Snyder (1998). At the top of the hierarchy is retreading and at bottom is landfilling (with a negative value). The lowest positive value is the use of scrap tires as fuel. Snyder (1998) estimates the energy recovery from an economical point of view at approximately $40/ton of tire. The use of tires as asphalt extender —assigning it the same value as the asphalt that it replaces— worth more than $100/ton. Alternatively, if the tire is comminuted to fine particles and incorporated it into virgin rubber compounds, or blend it to certain plastics, the value can rise to $250 or $500/ton.

Therefore, one of the goals of this paper consists on the identification of the recovery processes alternative to landfill, taking into consideration the Portuguese industrial capacity for each technology. As a consequence, two scenarios are analyzed, the conventional situation, corresponding to 1995, and a prospective scenario for 2000, considering the prohibition of landfilling. Here the analysis of the environmental impacts is focused on the energy use, over the tire life cycle.

The paper is organized in five sections, including this introduction. Section 2 summarizes the main processing alternatives for used tires. Section 3 provides the mathematical background and gives an overall view of the LCAA methodology and section 4 describes the model of the tire life cycle. Section 5 offers some concluding remarks.

## TIRE LIFE CYCLE: RECOVERY PROCESSING ALTERNATIVES

Tires are among the industrial products with the largest generation of solid waste. In 1998, the weight of used tires disposed of in Portugal was more than 25 thousand tons (2.5 kg/year per capita). Used tires are can have several destinations and a significant part of them can be reused after being retreaded, gaining similar quality standards as new ones. Others reprocessing include several technological possibilities for material recycling and energy recovering by using tires as fuels.

According to Snyder (1998), the decline of the rubber reclaiming industry was the major cause of today's scrap tire problem. The reasons for this decline included (i) the advantages of synthetic rubber supplanting natural rubber and its unstable market availability (ii), modern plastics have replaced reclaimed rubber in many large-volume uses and many articles that could also use reclaim are no longer manufactured from rubber today, (iii) the level use of reclaimed rubber in tire manufacture has been dramatically reduced. Therefore, the corresponding markets for reclaim have disappeared.

An important secondary cause of the scrap tire problem is the recent and continuing decline in the passenger retreading industry.

In this model, economy is represented as a system, including activities and physical and monetary flows between these activities. The referred activities represent the processes necessary to provide the product being analyzed and cover the entire product life cycle. In specific nodes of the material-product chain there are alternative activities capable of supplying and demanding the same intermediate product.

The model calculates the least-cost system configuration. Process activities, financial flows and material-product flows characterize the system configuration. Special attention is given to include alternative end-of-life recovery technologies (reusing, recycling,...), which contribute to close loops in the production chain, so that downstream outputs are returned as inputs upstream.

TIRE MANUFACTURE – Here, it is assumed that a tire is a one-piece product made of a mix of the following materials: compound rubber, steel and textile (cords). Rubber compound is a mixture of synthetic, natural, and occasionally reclaimed rubber, with various chemical additives. The proportions of natural and synthetic rubber in tires depends of the use to which tires will be put and the balance of needs in terms of factors such us flexibility, grip and durability. In addition, the proportions of rubber, steel and textile vary with tire type. Material proportions for several types of tires can be found in Pentreath (1998). Car tires have about 50% natural rubber and 50% synthetic rubber.

A typical passenger car tire weighs between 6 and 10 kg. In this study, and for simplification, it will be only considered one type of tires: a typical European passenger car tire weighing 8 kg. The material's weights per tire are shown in table 1.

Table 1. Main constitutes of a typical passenger car tire by weight, typical percentages

| Inputs | kg/tire | % |
|---|---|---|
| Natural Rubber | 3.2 | 40% |
| Synthetic Ruber | 3.2 | 40% |
| Steel (cord and bead wire) | 1.2 | 15% |
| textile (rayon cords) | 0.4 | 5% |
| Total | 8.0 | 100% |

Adapted from Ferrer (1997) and Pentreath (1998)

TIRE UTILIZATION – In this study, environmental impacts during tire use, namely associated with energy and rubber losses are not considered, since the focus is on the analysis of alternative disposal strategies, enabling valorization of used tires and not on the ranking of different types of tires.

A typical tire loses up to 10% of its weight during utilization, before being disposed of. Most of the dissipated material comes from the tread, which is only made with rubber. Tires that have reached the end of their lives are usually replaced by garages or specialist tire retailers, and the used tires are then known as ‘casings’ to those in the industry.

RETREADING WORN-OUT TIRES – Retreading is the general term for a process that gives a worn tire another life or, in the case of truck tires, possibly several lives. The retreaders collect tires from dealers, and transport them to the retreading plant where they are sorted to identify those that are reusable. Those tires that are accepted have the old tread removed and the surface prepared for the new tread.

Environmental impacts from retreading – Retreading reuses the majority of the tire’s resources, which results in considerable savings in terms of energy and materials. Table 2 presents a comparison between the resource savings from retreading car and truck tires

Table 2. Resource savings from retreading car and truck tires

| | oil use | rubber use |
|---|---|---|
| | liters | kg |
| Making new car tyre | 32 | 7 |
| Retreading a car tyre | 11 | 3 |
| Car tire resource saving | 21 | 4 |
| Truck tire resource saving | 68 | 44 |

The retreading potential in Portugal, particularly for passenger car tires, is not being met for a number of reasons. The most important is the high competition arising from the new tires market, as the prices of retreaded tire are similar to the cost of new tires.

MATERIAL RECYCLING – There are several ways of reclaiming materials. One way to recycle materials is to reuse the rubber in the form of granulate. Other processes aim to recover both energy and materials from tires, the energy generated often being used to fuel the recovery processes. Some of these processes are described below. Vulcanization process has been developed and patented but is not yet being used commercially. Tire rubber can be reused as granulate for playground surfaces or roads. In the USA, for example, certain states have legislation requiring using recycled rubber or other materials in road building. By 1997, 20 per cent of federally funded roads were required to contain used tire rubber. Roads incorporating granulate last about twice as long as conventional road surfaces, but they cost about twice as much to produce.

ENERGY RECOVERY – The main methods for converting tires to energy are incineration with energy recovered as electricity, heating in cement kilns, and pyrolysis. Tires have a high energy content compared with other wastes and fossil fuels. They have an average calorific value of 32GJ per ton, which is greater than coal. Their size and shape makes them easy to handle when compared with many other types of waste. In Portugal, the main energy recovery process has been using tires as fuels in cement kilns. Cement manufacture is an energy-intensive process, where typically, 30 to 40 per cent of the production cost is spent on energy. In addition, the majority of the inorganic constituents combines with the raw materials in the kiln and leaves the process as part of the cement clinker. Heavy metals remain bound in the cement and in its subsequent use. Tires can be used, either chipped or whole, to replace part of the conventional fuel. They are treated in a different way depending on the type of cement kiln. At "wet" kilns, whole tires are dropped into the kiln about halfway along its length, and shredded tires are added at the fuel end of the kiln. The tires are subject to the very high temperatures inside the kiln and any residues left after burning combine with the final product. In ‘dry’ kilns, the tires are added either to the precalciner or into the kiln at the same end as the feed. Because tires contain iron, using them as a fuel reduces the amount of iron oxide added to the process. An additional benefit is that no residual ash is produced from the cement process, Pentreath, R. (1998).

## METHODOLOGY: LIFE CYCLE ACTIVITY ANALYSIS

Life Cycle Activity Analysis uses an input-output format, and the model considers three demand categories:

- $\mathbf{d_1}$ is a column vector of consumer demand of final products,
- $\mathbf{d_2}$ is a column vector of demand of final products outside the sectors currently analysed
- $\mathbf{d_3}$ is a column vector of demand of intermediate products outside the sectors currently analysed

The demand curve for $d_1$ is vertical; $\mathbf{d_1}$ is a known parameter. The demand curve for $\mathbf{d_2}$ is horizontal, with a given and known price, $\mathbf{P^F}$; $d_2$ is unknown. The demand curve for $\mathbf{d_3}$ is also horizontal with given and fixed price, $\mathbf{P^I}$. In addition to $\mathbf{d_2}$ and $\mathbf{d_3}$, the following decision variables, are determined by the model:

- **x** is a column vector of levels of production activities *(pr)*,
- **t** is a column vector of levels of transportation activities *(tr)*,
- **w** is a column vector of supply levels of primary resources.

The list of goods is partitioned into four classes: inputs of primary goods *(P)*, intermediate goods *(I)*, final goods *(F)*, and environmental goods *(E)*. The basic mathematical format of Life Cycle Activity Analysis can be written as the following linear program:

$$\min c_{pr} \cdot \mathbf{x} + c_{tr} \cdot \mathbf{t} + c_{rs} \cdot \mathbf{w} - P^F \cdot \mathbf{d_2} - P^I \cdot \mathbf{d_3} \qquad (1)$$

subject to:

$$-A^P_{pr} \cdot x - A^P_{tr} \cdot t + w \geq 0 \qquad (2)$$

$$B^F_{pr} \cdot x - d_2 \geq d_1 \qquad (3)$$

$$(-A^I_{pr} + B^I_{pr}) \cdot x - d_3 = 0 \qquad (4)$$

$$(-B^E_{pr} + A^E_{pr}) \cdot x - B^E_{tr} \cdot t \geq -g \qquad (5)$$

$$x, t, w \geq 0 \qquad (6)$$

To assure that, for each intermediate commodity in each link, there is conservation of the quantities for the goods being produced, transported and used in the subsequent activities, additional equations have to be included. In short, one equation is needed for balancing the quantity of each intermediate good leaving a region and another equation should be added for balancing each intermediate good entering a region.

In addition, the x, t and s vectors, may be bounded from above, to reflect the presence of capacity constraints of production and transportation activities and on the availability of primary resources. Vectors $d_2$ and $d_3$, may also be bounded from above, to reflect demand constraints. Furthermore, capacity bounds can be also included to reflect current behavioral patterns or to impose environmental policy options.

The objective is to minimize the sum of all current unit costs and the costs of all primary resources (equation 1). Constraint 2 establishes the balance between the quantities of primary resources used by the activities and the amounts extracted from the environment. Constraint 3 says that consumer demand, $\mathbf{d_1}$, must be satisfied. Constraint 4 states market clearing for the intermediate goods. Constraint 5 states that the environmental impacts should be at most equal to the targets defined (vector g).

## MODEL FORMULATION AND NUMERICAL SOLUTION

This section presents an illustrative example brought from the Portuguese used tire market describing how the LCAA methodology can be used to provide a sample model of a product's entire life-cycle, with emphasis on alternative end-of-life recovery processes.

A simplified flow chart is presented in figure 1. The figure illustrates the vertical dimension of the product-material chain. The production activities include the manufacture of tire's raw materials: steel, textile and compound rubber —with the possibility of using a fraction of recycled rubber— and the manufacture of new and retreaded tires. Furthermore, in order to follow the environmental effects of a manufactured product over its entire life, using tires is not considered as a final and ultimate state. Instead, the life cycle is traced to include the possible recovery activities, namely recycling of tire's constituent materials, energy recovery (co-incineration in cement plants), tire retreading and landfilling.

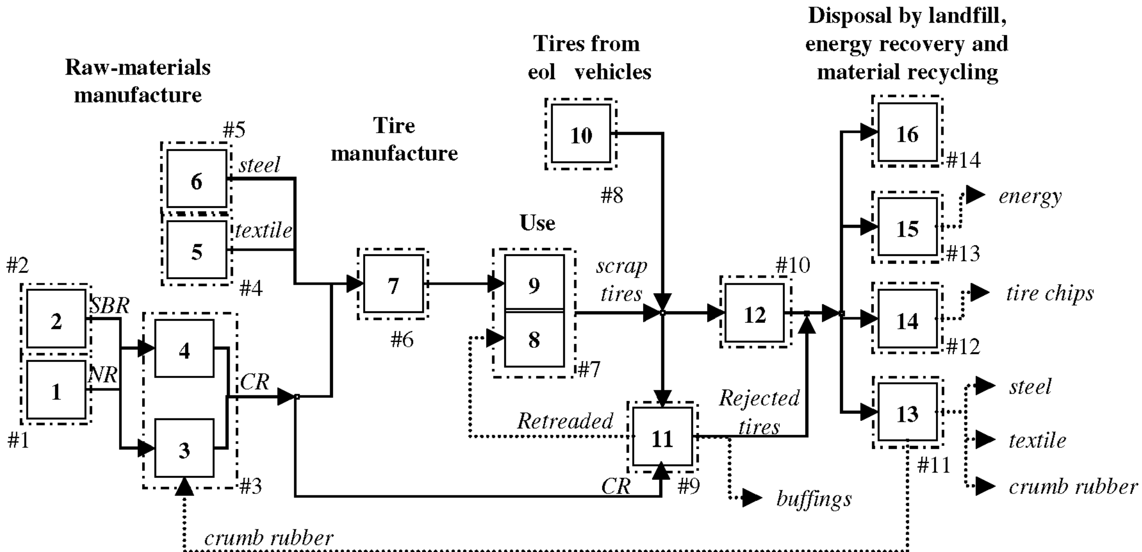


Figure 1. Flowchart illustrating the logistics of the production, distribution and recovery of tires

Reading the diagram from left to right, the following sixteen activities can be recognized in the logistics flow:

1. Extraction and manufacture of natural rubber (NR)
2. Manufacture of synthetic rubber: Styrene-butadiene rubber (SBR)
3. Making compound rubber with NR, SBR and crumb rubber (recycled)
4. Making compound rubber with NR and SBR
5. Manufacture of textile (crayon cords)
6. Manufacture of steel cords
7. Tire manufacture
8. Using new tires (including collection of used tires)
9. Using retreaded tires (including collection)
10. Collection of tires from end-of-life vehicles
11. Retreading tires
12. Collection of scrap tires
13. Recycling: Tire chips production
14. Recycling: crumb rubber, textile and steel production
15. Co-incineration of scrap tires in cement plants
16. Landfill disposition

The spatial dimension is also considered; fourteen locations are defined in Figure 1 (stippled rectangles with cardinal numbers). No regional breakdown of the production activities is considered. Stocks of materials are not featured in the example.

The arrows show the direction of the logistics flow. Note the loops feeding flow back (stippled lines in the diagram) from activity 11 (retreading tires) to 8 and from 13 (recycling) to 3. It should be noticed that about two casings in each three inspected are not suitable for retreading; these are called rejected tires (see figure 1). In addition, those tires that are accepted have the old tread removed. The rubber particles that are removed are called buffings (rubber), being sold to the rubber industry. Buffing a passenger car tire generates about 0.8kg of ground rubber, Ferrer (1997). Rejected tires are collected and disposed of together with worn-out tires not considered for retreading.

Granulated recycled rubber (Crub_1) can be used in the manufacture of compound rubber, this is currently done only in a small percentage of granulate and for some types of tires, being in fact beneficial to the production process (Pentreath 1998). It is assumed that the maximum percentage of recycled rubber in compound rubber is 20% (refer to activity X3).

As discussed before, the model distinguishes four classes of commodities: *primary goods (*P*) intermediate goods* (I)*, final goods* (F) and *environmental goods* (E). The *primary goods* considered in this study include a considerable number of commodities, namely primary resources, materials and energy. The *Intermediate goods* are outputs that serve as inputs into subsequent activities, being listed in Table 3. Notice that tires (new or retreaded) are considered as intermediate goods, rather than final goods. Instead, the final good in our system is the service delivered by the use of tires.

Table 3. Intermediate goods and units used

| **Name** | **units** | **Description** |
|---|---|---|
| NR | [ton] | Natural rubber |
| SBR | [ton] | Synthetic rubber |
| CR | [ton] | Compound rubber |
| textil | ton | Crayon cords |
| steel | ton | cord wire |
| n_tire | kunit | new tires |
| r_tire | kunit | Retreaded tires |
| w_tire | kunit | worn-out tires |
| c_tire | ton | scrap and rejected tires |
| c_rub1 | ton | Crumb rubber: granulated rubber, particle size < 0.5mm |

Intermediate goods can be either used as inputs in activities represented in the model or to be sold outside. In particular, consider "C_rub1" that can be used in activity 3 or to be sold outside. Similarly, final goods can be domestically used (consumed) or to be sold outside. The demand curves for intermediate and final products sold outside are horizontal with fixed and given prices. The model calculates the volume of products sold.

The final products considered in this study are listed in table 4, including main products and new and retreaded tires, for which fixed and given domestic demand values were defined. The remaining final products that result from the tire recovery processing activities represent outputs, usually with positive market value. In addition, energy recovered, by co-incinerating tires is considered as a final product with relative economic profits associated with the substitution of coal or oil, as fuel.

According to Snyder (1998), energy produced from the combustion of scrap tires and buffings is a low-value use. Higher-value products require tires and buffings to be chopped into narrow distributions of particle sizes, but in a number of different size ranges. The commercial markets for tire chips and crumb rubber comprise particle sizes ranging from approximately 20 mm down to 80 mesh. The particle size ranges considered are represented in table 4. To achieve these size requirements, several processes come into play. The case study presented here considers two alternative recycling activities: #13 and #14. The former activity produces tire chips, which can be used, for example, as soil amendment, lightweight aggregate and fill material, in highway construction, to replace wood chips in composting, as sub-grade thermal insulation, etc.. In activity #14, scrap tires are chopped, the wire and the textile are removed permitting further comminution of the tire chips (using grinding processes) to the intended granulated product specification, which depends on the prospective further use. Recovered wire offers interesting potential as high-quality steel crap. Currently, in Portugal, one of the most interesting and promising large-volume uses for crumb rubber is a road building material, chiefly as an additive or supplement to asphalt. Asphalt (or bitumen) is used as a binder for stone and sand in road construction. Other important uses for granulated or crumbed rubber include civil engineering projects, the manufacture of compound rubber and molded rubber plastic blends.

The economical value (i.e. the price) of the recycled materials and the energy recovered is exogenously determined in the corresponding commercial markets by the available alternative materials and energy sources, which are external to the tire product-material life cycle chain represented in figure 1. Furthermore, it should be noticed that some final products might have negative economic values. Examples of these are harmful residues to be regenerated/incinerated or, from the current example, textile filaments, to which no important use has been found to date, Snyder 1998. These filaments are usually baled and discarded in a landfill, representing therefore a cost to the recycling plant.

Table 4. Final products

| Name | units | Description |
|---|---|---|
| N_tire | kunits | New tire |
| R_tire | kunits | Retreaded tire |
| r_buf | ton | Buffings from retreading |
| r_chip | ton | tire chips |
| r_text | ton | Recycled textile |
| r_steelt | ton | Recycled steel |
| r_ener | GJ | Energy recovered from scrap tires used as fuel in cement plants |
| c_rub2 | ton | Granulated crumb rubber: 0.5 < particle size < 2mm |
| c_rub3 | ton | Granulated crumb rubber: 2 < particle size < 7mm |
| c_rub4 | ton | granulated crumb rubber: 7< particle size < 15mm |

It should be also mentioned that the LCAA format presented in the previous section includes the possibility of having sinks of energy or of pollutants (i.e. the existence of an $A^{E}_{pr}$ matrix, with non-zero values from some chemical substances). In the current application, cement kilns co-incinerating scrap tires are an example of that because, besides the energy savings due to the replacement of usual fuel by tires, there is a relative reduction in the emission of certain pollutants when burning tires instead of the usual fuel. Pentreath (1998) refers a reduction of up to 40% in the emissions of nitrogen oxides due to staged combustion effects in which less thermal nitrogen oxides are generated.

The transportation of all the intermediate goods along the product-material chain is also featured by the model and is represented in figure 1 by arrows connecting the regions with links. Transportation in each link is also treated as an activity, with inputs/outputs and costs per unit of intermediate good transported. Energy is the main input and emissions of pollutants the outputs. Numerical values of these coefficients were calculated based on the average distances between the regions and on environmental and technological I-O data (per km) specific for each type of transport used in the corresponding links.

The optimization of the logistics flow features a series of alternative activities, for example: the manufacturing of compound rubber can be based only on natural and synthetic rubber or also include a fraction of recycled crumb rubber. A tire can be a new one or a retreaded one. A worn-out tire can be used as fuel in cement plants, disposed of as waste in landfill, chopped in tire chips or granulated to permit the further use of its recycled materials.

Assuming that all firms minimize costs and that all markets clear, the model is solved for all the unknowns. The levels of operation of all production and transportation activities, the supplies of all primary goods and the production of intermediate and final products to be sold in commercial markets not included in the tire material-product chain studied.

FURTHER ASSUMPTIONS – Our calculations are intended to highlight the recovery aspects of the used tires and simplify other aspects, namely the regional dimension of production and distribution. Single locations for the production activities are chosen. Only one type of tire: an average typical passenger car, (refer to table 1) is considered. Consumer demand for new tires and retreaded tires was fixed at current levels in 1995: The domestic demand for new tires was 3 millions and for retreaded tires 300 thousand units. The volume of used tires collected from end of life vehicles was estimated in 600 thousand tires (20 percent of the demand for new tires). Fixed and given prices were assumed for the final products produced in the recycling plants and for the energy recovered in cement plants.

Data concerning industrial operations, including retreading and recycling of tires was adapted from current industrial operations of main Portuguese mills, being representative of operations that have not changed significantly in the preceding years.

The Environmental indicator analyzed here is energy use and the quantity of waste tires disposed of in landfill is also presented.

SCENARIO ANALYSIS – The assumptions of the environmental scenarios to be solved by the model are outlined below. Two alternative scenarios were considered, involving the 1995 situation and the current situation (2000 data):

- **Scenario 1:** This scenario simulates the 1995 situation before banning landfill of tires. This is a reference case, to which the second scenario will be compared. No environmental restrictions are imposed. The only restrictions featured are those necessary to assure the market clearing of intermediate and final goods, to assure balance between transportation levels and corresponding levels of operation of activities.
- **Scenario 2:** Illustrates the current situation (2000 data), after the implementation of a European policy directive banning the disposal of used tires in landfill. The domestic maximum operating capacities for the industrial recovery activities were included as constraints in the model.

NUMERICAL RESULTS – The programming model was coded in the GAMS (General Algebraic Modeling System) software, see Brooke et al. (1998) for details. The mathematical program includes 67 single equations and the coefficient matrix features 427 nonzero elements.

The operating levels that minimize the overall costs of production are presented in Figure 2, for both scenarios analyzed.

The results show that banning the disposal of tires to landfill (scenario 2) results in the exhaustion of the operating capacity of activities X14 and X15 (max. 10000 tons). This allows for the more costly activity X13 to be operated and to produce a considerable amount of recyclable goods, as represented in table 5.

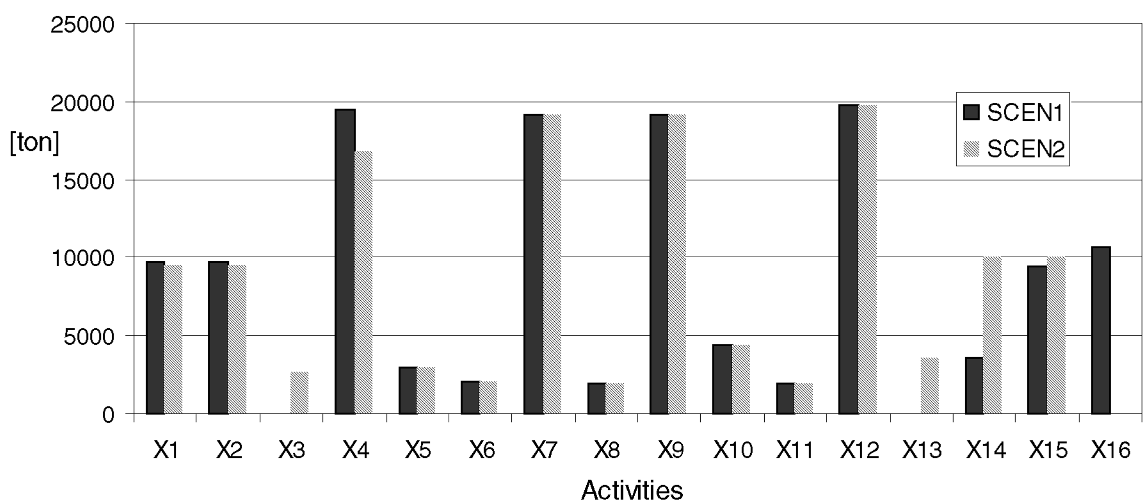


Figure 2. Operating level of activities

Table 5. Recyclable materials produced

| Good | Scen. 1 | Scen. 2 |
|---|---|---|
| r_buf [ton] | 240 | 240 |
| r_chip [ton] | 3188 | 9000 |
| r_text [ton] | - | 181 |
| r_steel [ton] | 0 | 542 |
| r_ener [GJ] | 2598000 | 275000 |
| c_rub1 [ton] | - | 542 |
| c_rub2 [ton] | - | 542 |
| c_rub3 [ton] | - | 542 |
| c_rub4 [ton] | - | 542 |

In particular, the crumb rubber (c_rub1) is recycled at activity X13 allowing for the production of compound rubber with recycled rubber (activity X3). NR and SBR volume productions are correspondingly reduced.

The total energy consumption for both scenarios and the volume of tires disposed of as waste, in landfill is shown in table 6. The reduction in energy consumption represents about 5% of the total energy used. However, it should be noticed that there is almost no change in the volume of tires incinerated in the cement plants from the first to the second scenario.

Table 6. Energy consumption and scrap tires disposed of in landfill

| | Energy use [GJ] | Waste [Tons] |
|---|---|---|
| Scen. 1 | $2.6 \times 10^6$ | 10627 |
| Scen. 2 | $2.5 \times 10^6$ | 0 |

## CONCLUSION

The feasibility and potential of the LCAA methodology for optimizing the life cycle of products, with emphasis in alternative end of life processing activities was demonstrated. Integrated economic, environmental, energy and material-product system models are developed and applied.

The LCAA methodology allows the analysis of "What if scenarios" and, in particular, the consequences of the prohibition of tires landfill was analyzed in the Portuguese economy context. As a result, alternative end-of-life activities were quantified and it was concluded that 10627 ton/year of landfill were avoided with an additional reduction of 5% in energy use in the total life cycle of tires.

Further research of the LCAA methodology includes its extension as a non-linear program, in order to model competition between substitutable products with distinct price-sensitive demand functions. This approach can be used to model competition between new and retread tires together with other end-of-life processing technologies.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

Parameters:

Physical (product-material) data:

$\boldsymbol{A}_{pr}$: is a matrix of input coefficients; each element denotes the quantity of inputs required to operate a production activity at unit level;

$\boldsymbol{A}_{tr}$: is a matrix of input coefficients; each element denotes the quantity of resources (e.g. fuel) required to operate a transportation activity at unit level,

$\boldsymbol{B}_{pr}$: is a matrix of output coefficients; each element is the quantity of outputs (intermediate, final or subproducts) obtained when an activity is operated at unit level;

$\boldsymbol{B}_{tr}$: is a matrix of output coefficients; each element denotes the quantity of outputs (emissions of pollutants) emitted when a transportation activity is operated at unit level;

$\boldsymbol{d}$: is a column vector of final demand, it is known and given.

Economic data:

***c*$_{pr}$:** is a row vector of unit costs of operating the various production activities, it is known and given (these are unit costs to be reckoned above the use of inputs already included in the $A_{pr}$ matrix);

***c*$_{tr}$:** is a row vector of unit costs of operating the various transportation activities, it is known and given (these are unit costs to be reckoned above the use of inputs already included in the $A_{tr}$ matrix);

***c*$_{rs}$:** is a row vector of unit costs of primary resources, it is known and given.

***p*$_{sp}$:** is a row vector of unit values of sub-products produced is industrial activities, which are sold to markets external to the model represented. This vector is exogenously determined, being known and given.