Life cycle activity analysis: logistics and environmental policies for bottled water in Portugal⋆

Life Cycle Activity Analysis – Logistische und umweltpolitische Strategien für Flaschenwasser in Portugal

Fausto Freire[1], Sten Thore[2] and Paulo Ferrão[3]

[1] Department of Mechanical Engineering, Faculty of Sciences and Technology, University of Coimbra, 3030 Coimbra, Portugal
[2] The IC[2] Institute, The University of Texas at Austin, TX 78705-3596, USA
[3] Department of Mechanical Engineering, Instituto Superior Técnico. 1046 Lisboa, Portugal

Abstract. An innovative mathematical programming decision support model – *Life Cycle Activity Analysis (LCAA)* – is presented, integrating considerations of optimal allocations of resources and impacts upon the environment during the life cycle of products. LCAA is based on the classical formulation of *activity analysis* and on the *life cycle assessment* framework. The concept of linear activities is extended to embrace mass and energy fluxes over the entire life cycle of products including their environmental impacts. Special attention is given to the presence of loops in the product chains, such as those occurring when materials/products are recovered (reused, recycled.). An application brought from the Portuguese bottled water industry is described. The model features alternative activities for production technologies and product recovery strategies and permits the joint consideration of monetary costs and environmental burdens. The results obtained under five scenarios, including distinct disposal strategies and environmental constraints, are discussed.

Zusammenfassung. In diesem Beitrag wird ein innovatives mathematisches Entscheidungsunterstützungsmodell – die Life Cycle Activity Analysis (LCAA) – präsentiert, welches die optimale Allokation von Ressourcen und Auswirkungen

Correspondence to: F. Freire (e-mail: fausto.freire@dem.uc.pt)

auf die Umwelt während des Lebenszyklusses eines Produktes beinhaltet. LCAA basiert auf der klassischen Formulierung der Aktivitätsanalyse und auf dem methodischen Gerüst des Life Cycle Assessments. Das Konzept der linearen Aktivitätsanalyse wird erweitert, um Massen- und Energieflüsse während des gesamten Produktlebenszyklusses sowie deren Auswirkungen auf die Umwelt einzubeziehen. Eine besondere Aufmerksamkeit wird auf bestehende Zyklen in Prozessketten gelegt, die bei der Wiederverwendung / Verwertung von Materialien/Produkten auftreten. Es wird eine Anwendung aus der portugiesischen Flaschenwasser-Industrie vorgestellt. Das Modell zeichnet sich durch verschiedene alternative Aktivitäten für Produktionstechnologien und Wiederverwendungsstrategien aus und erlaubt die gleichzeitige Betrachtung von monetären Kosten und Umweltbelastungen. Die Ergebnisse, die aus fünf Szenarien zu verschiedenen Entsorgungsstrategien und Umweltschutzrestriktionen gewonnen werden, werden diskutiert.

Key words: Activity analysis – Life cycle – End-of-life strategies – Environmental policy – Portuguese bottled water market

Schlüsselwörter: Aktivitätsanalyse – Lebenszyklus – End-of-life-Strategien – Umweltpolitik – portugiesischer Flaschenwassermarkt

1 Introduction

The relationship between fundamental natural systems on the one hand and human, cultural, technological, and economic systems on the other is becoming increasingly complex. Environmental burdens often occur in conjunction with flows of substances, materials and products through the economy. Several methods have been developed to study such physical flows, e.g. environmental Life Cycle Assessment (LCA), Materials Flows Analysis and Substance Flow Analysis (MFA/SFA), Environmental Impact Assessment (EIA). The purpose of LCA is to study the environmental impacts of a product or a service from the "cradle" to the "grave"[1] . MFA is based on input/output analysis and is used to analyze the materials throughput or the materials intensity of important sectors or large functional systems of the national economy, and therefore concentrates on bulk mass flows. SFA is used to identify the causes of specific environmental problems in the economy and find possibilities for amending or preventing those problems, Bouman et al. (2000). A significant effort is currently being spent in engineering and environmental sciences to collect environmental and life cycle data associated with numerous processes and materials and to make the LCA and MFA/SFA calculations.

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

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[1] Note that the use of the term "life cycle" in the environmental literature is quite different from the concept of the life cycle of a product used in the business literature (=the cycle from the market introduction to the obsolescence).

of materials. A new start and a comprehensive and multidisciplinary scientific framework are required for understanding issues of materials and environmental flows. A holistic view is certainly necessary.

In the pages to follow, we propose a new mathematical programming model – *Life Cycle Activity Analysis (LCAA)* –, which integrates engineering, environmental and economical sciences, including operations research as LCAA looks for optimal solutions of multi-variable complex systems. Our work is motivated by a desire to build bridges between engineering and environmental sciences on the one hand, and economics and operations research on the other. LCAA integrates Life Cycle Assessment with Activity Analysis, a well-known procedure in economics solving for optimal levels of production and for the optimal allocation of resources.

Antecedents

From the point of view of the economist, our calculations draw on classical input-output analysis, see Leontiefïs own early work, Leontief (1970), and later discussions such as Lave et al. (1995) and Hendrickson et al. (1998). Our work formalizes these interconnections as applied to an instance of production with recycling and reutilization. Recovery introduces closed loops in the production sequences, so that downstream outputs are returned as inputs upstream.

LCAA ties mathematical programming formulations of Activity Analysis to the environmental impacts of activities. Activity Analysis was developed by Koopmans (1957). For this pioneering work, Koopmans received the 1975 Nobel Prize in economics (shared with I. Kantorovich). However, the original formulation, Koopmans (1957), was not well suited for numerical solution, since it assumed that there were as many commodities as activities, and that the resulting system of equations had a non-singular solution. A major step was the reformulation of activity analysis as a linear program, permitting any number of activities and any number of commodities, see Charnes and Cooper (1961). Classical activity analysis can be presented as a tool of partial modeling for the representation of an industry or a sector of the economy, providing a modern format of representation of the production chain, Thore (1991). Recent attempts to adapt activity analysis to engineering and environmental sciences have reverted to simple matrix calculations; see e.g. Ayres (1995), and Heijungs (1997) and the mathematical programming associations were lost. A major purpose of our own work is to reestablish these connections, providing standard linear (and nonlinear) programming formats for the calculation of environmental impacts, see Thore and Freire (1999).

The classical formulation of activity analysis distinguishes three classes of goods: primary goods (natural resources or materials), intermediate goods and final goods (outputs). We shall here extend this well-known activity format to include one more category of goods: environmental goods (actually, more literally, environmental "bads") such as emission of pollutants.

The environmental outputs are aggregated into a number of environmental impact categories, such as global warming, ozone depletion, etc. This approach links up with the development of the LCA 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. The idea of creating markets for environmental goods is still in its infancy, and no market balancing conditions can be formulated for them. Instead, environmental targets are formulated reflecting the stance of a policy-maker.

In order to follow the environmental effects of a manufactured product over its entire life, we no longer consider consumption as a final and ultimate state. Instead, the life cycle is traced to take into account the possible subsequent phase(s) after immediate consumption, including possible recovery (reuse, recycling, energetic valorization.).

Recent work

The integration of physical models with economic models has been attempted a number of times, see Perrings (1987), Leontief (1970), Ruth (1993), Bloemhof-Ruward (1996), Heijungs (1997), Kandelars (1998), Gielen (1999) and Duchin and Steenge (1999). However, none of these attempts has been completely satisfying. Each model serves its own purposes, having its own strong points as well as its limitations, as discussed in Bouman et al. (2000). The most appropriate model to be used in one environmental problem does not always work in another. In any case, the integration of physical models with economic models is an art still in its infancy. Hopefully, integrated models will one day provide answers to important environmental policy questions. In the meanwhile, we have a long way to go, merging results from many distinct disciplines.

Recently, the concept of a "material-product (M-P) chain" was suggested by Opschoor (1994) and Kandelaars (1998). It is defined as a system of linked flows of materials and products supporting the provision of a certain service. The objective is an integrated model-based analysis of resource and pollution problem for policy-making. An M-P chain is an economic structure of connected material-product flows. The economic modeling of M-P chains means combining elements of physical flow and economic allocation. The analysis includes static or dynamic optimization, simulation and partial equilibrium analysis (see Kandelaars, 1998).

Using the concept of an M-P chain, Kandelars and Van den Bergh (1996) presented a static optimization model for rain gutters. Their goal was to explore how policies or strategies applied to different stages of the material-product chain differ in their impacts. To measure these, they recorded indicators such as the use of materials and products, and the costs of meeting demand for a particular service. However, the inputs of other primary resources and the emissions to the environment and their environmental impacts were not considered. As a result, their "best" policy can only be understood in terms of recovery of materials or waste sent to landfill.

Spengler et al. (1997) developed sophisticated operations research models for two selected planning problems: (i) recycling of industrial byproducts and (ii) dismantling and recycling of products at the end of their lifetime. These models have been applied to real industrial problems. The dismantling and recycling planning model is based on linear activity analysis and is formulated using a mixed integer

linear programming model. The recycling management model is based on a multi-stage capacitated warehouse location problem and was applied to the German iron and steel industry (see also Dyckhoff and Ahn, 1998).

Azapagic and Clift (1998, 1996) developed a system optimization approach to facilitate the identification and choice of the Best Practicable Environmental Option (BPEO) in improvement assessment. This multi-objective optimization approach generates a number of optimal solutions, which show explicitly what can be gained and what lost by choosing each alternative. According to the authors, the main advantage of this method is that generating optimum solutions does not require *a priori* articulation of preferences so that the whole set of solutions can be explored. The emphasis is then of the range of choices from a series of solutions, rather than definition of preferences before analyzing all the trade-offs among objectives. This methodology has been applied to a case study on boron products to evaluate the BPEO and possible improvements in the system, Azapagic and Clift (1999).

MATTER[2] is a dynamic linear programming model, originally developed as a tool for the analysis of macroeconomic energy systems (MARKAL). A joint project of five Dutch institutes, coordinated by the Energy Research Foundation (ECN), extended it to materials system analysis "from cradle to grave". It consists of an integrated energy and materials system model for Western Europe used for the analysis of greenhouse gas (GHG) emission reduction strategies, see Gielen (1999, 1998). The time span was divided into nine periods of equal length, from 40 to 80 years. The dynamic approach allowed the study of the relation between materials consumption and product demand in one year and waste release in subsequent years.

Bloemhof-Ruwaard et al. (1995) classified the interactions between operations research and environmental management under the twin headings of "supply chain modeling" and "environmental chain modeling". The *supply chain* comprises the extraction of raw materials, production, distribution, use of goods and waste collection. In the *environmental chain*, emissions and waste are transported and transformed, resulting in water, air and soil pollution with damaging effects to the environment. See also Daniel et al. (1997).

In conclusion, LCAA integrates environmental and economic questions. To demonstrate the potential of LCAA and the attendant numerical calculations, we report on an illustrative case study brought from the Portuguese industry of bottled water, including results obtained with scenario analysis. The scenarios include distinct disposal strategies and environmental constraints, reflecting issues raised by the current problematic associated with the implementation of packaging and packaging waste management policies.

The paper is organized in five sections, including this introduction. Section 2 provides the mathematical background and gives an overall view of the LCAA methodology. Section 3 describes the main characteristics of the Portuguese bottled water market and gives an account of the environmental considerations of current packaging management policies. Section 4 presents an application of the LCCA

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[2] MATTER is an acronym for <u>MAT</u>erials <u>T</u>echnologies for greenhouse gas <u>E</u>mission <u>R</u>eduction

methodology, describing a detailed model of the manufacture, reuse and recycling of glass bottles used for mineral water in Portugal. A numerical prototype is solved. Five scenarios including distinct disposal strategies and possible environmental constraints set by policy makers are proposed. The scenario results are discussed with emphasis on the implications brought from the dual constraints associated with the LCCA program. Section 5 offers some concluding remarks.

2 Mathematical analysis

The Life Cycle Activity Analysis model uses an input-output format. The following notation is employed:

Decision variables, to be determined:
    x is a column vector of levels of production activities,
    t is a column vector of levels of transportation activities,
    w is a column vector of supply levels of primary resources.

Parameters:

A_{pr}	is a matrix of input coefficients; each element denotes the quantity of inputs required to operate a production activity at unit level;
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;
B_{pr}	is a matrix of output coefficients; each element is the quantity of outputs obtained when an activity is operated at unit level;
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;
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;
d	is a column vector of final demand, it is known and given;
g	is a column vector of environmental goals set by a policy-maker.

The list of goods is partitioned into four classes:

- inputs of primary goods (P);
- intermediate goods (I);
- final goods (F) and
- environmental goods (E).

Correspondingly, matrices A_{pr} and B_{pr} become partitioned into: $A_{pr} = (-A^P, -A^I, 0, -A^E)$ and $B_{pr} = (0, B^I, B^F, B^E)$. Conventionally, one enters the A-coefficient of each input with a minus sign and the B-coefficient of each output with a plus sign. This format includes the possibility of having $-A^E$, i.e. sinks

of pollutants. Examples of this could be incinerators (reducing dangerous residues by burning them) or, according to the Kyoto protocol, planting new forests to capture CO_2, called biomass carbon sinks. Matrices A_{tr} and B_{tr}, however, are only partitioned into $A_{tr} = (-A_{tr}^P)$ and $B_{tr} = (B_{tr}^E)$, since the list of goods used in the transportation activities only include primary resources and environmental emissions (no intermediate or final goods are considered).

The basic mathematical format of Life Cycle Activity Analysis can now be written as the following linear program:

$$\min c_{pr} \cdot x + c_{tr} \cdot t + c_{rs} \cdot w \tag{1}$$

subject to:

$$-A_{pr}^P \cdot x - A_{tr}^P \cdot t + w \qquad \geq 0 \tag{2}$$

$$\left(-A_{pr}^I + B_{pr}^I\right) \cdot x \qquad = 0 \tag{3}$$

$$B_{pr}^F \cdot x \qquad \geq d \tag{4}$$

$$\left(-B_{pr}^E + A_{pr}^E\right) \cdot x - B_{tr}^E \cdot t \geq -g \tag{5}$$

$$x, t, w \qquad \geq 0 \tag{6}$$

To assure that, for each intermediate commodity in each link, there is conservation of the quantities of 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 *w* 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. 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) states market clearing for the intermediate goods. Constraint (4) says that the demand must be satisfied. Constraint (5) states that the environmental impacts should be at most equal to the targets defined (vector *g*).

Environmental impact assessment

We now turn to the full accounting of physical flows between processes and between the processes and the environment. The B^E and $-A^E$ matrices constitute an inventory table, summing up the outflows and subtracting the inflows of environmental commodities associated with economic activity. The environmental goods can be flows of chemical substances into the environment, or flows of substances from others activities or the environment.

Table 1. Environmental impact categories and equivalent units used

Environmental impact category	Equivalent units
Greenhouse effect	kg CO_2
Ozone layer depletion	kg CFC11
Acidification	kg SO_4
Eutrophication	kg PO_4
Heavy metals	kg Pb
Carcinogens	kg B(a)P
Winter smog	kg SPM
Summer smog	kg C_2H_4
Pesticides	kg act.s

Flows of substances generated by economic activities do not necessarily present environmental problems by their own. They are recognized as such only when they pose problems to society. Thus, there is an intrinsic value-bound aspect in the definition of an environmental problem (Heijungs, 1997). To deal with this matter, one may establish scientific relationships between pollutants and a set of environmental impact categories (such as the greenhouse effect, acidification or the ozone layer depletion) and between resources extraction and depletion problems. This approach is based on the definition of a set of environmental impacts categories. These are directly defined in terms of the kind of damage done to the environment by pollutants in air, water or soil and by the depletion of available natural resources. The environmental impact categories considered in our research are listed in Table 1. The phase of defining a list of environmental impact categories is usually designated in the LCA methodology as *"classification"* (Berg et al., 1996).

Form the column vector *E(i)* as the sum of all environmental commodities released into environment, which results from the multiplication of the unit environmental outputs by the levels of operation of all activities:

$$E(i) = (-B_{pr}^E + A_{pr}^E) \cdot x - B_{tr}^E \cdot t \tag{7}$$

The vector *E(i)* can easily be a list of several hundred specific emissions. According to the *"characterization"* phase in the LCA methodology, these emissions are aggregated into a set of environmental impact categories using the following formulation:

$$I(j) = F(j,i) \cdot E(i) \tag{8}$$

where

I(j)   is a column vector of environmental impact categories (e.g. greenhouse effect, measured in kilograms of CO_2 equivalents),

F(j,i)   is a matrix of category impact coefficients (such as the kilograms of CO_2 equivalents generated by each kilogram of individual substance released into the environment).

Equation (5) may then be written on the alternative form:

$$F(j,i) \cdot [(-B_{pr}^E + A_{pr)}^E) \cdot x - B_{tr}^E \cdot t)] \geq -g' \tag{9}$$

where g' is a vector of goals defined directly in terms of environmental impact categories:

$$g' = F(j,i) \cdot g \tag{10}$$

More advanced formulations are also possible, treating the vector of individual environmental goals g as an unknown variable rather than a given parameter. This means searching out an optimal combination of individual goals (possibly trading off one individual goal against another) while still satisfying the aggregate goals laid down on the impact categories. The programming formulation then is relations (1)–(4), and adjoining

$$(-B_{pr}^E + A_{pr}^E) \cdot x - B_{tr}^E \cdot t + g \geq 0 \tag{11}$$

$$F(j,i) \cdot g \qquad\qquad\qquad \leq g' \tag{12}$$

$$x, t, w, g \qquad\qquad\qquad \geq 0 \tag{13}$$

which is a linear program in the unknowns x, t, w and g.

In addition to the impact categories mentioned in Table 1, we shall also consider (i) the quantity of glass (in tons) sent to landfills (denoted as waste glass), and (ii) the total energy consumption (GJ LHV[3]).

3 The Portuguese bottled water industry: structure, reuse and recycling of bottles

The bottled water market can conveniently be divided into two sectors: *"horeca"* (hotels, restaurants and cafes) and *take-home* (supermarkets, shops, etc.) The former represents places where the water is consumed on the premises. The latter includes stores where the consumer takes the bottles home. The distinction is made in accordance with Portuguese packaging law 366-A/97. It is important because different recovery targets are specified for each of these markets.

Bottled water is sold in units of 0.25, 1.5 and 5 liters, made of glass, PVC (polyvinyl chloride) or PET (polyethylene terephthalate). In our study, attention is focused in the glass bottles alone, as these are the only bottles being reused. In addition, glass is the only material for which important recycling rates are achieved in Portugal. Collection of used glass is practiced over the entire country.

Water bottling is carried in locations immediately adjacent to the springs. The bottling company buys empty bottles from a glass mill or utilizes a cleaned used

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[3] LHV stands for lower heating value, which should be distinguished from high heating value (HHV). They represent two alternative ways of denoting the energy content of fuels. The LHV assumes that all the H_2O resulting from the fuel combustion is in the vapor phase.
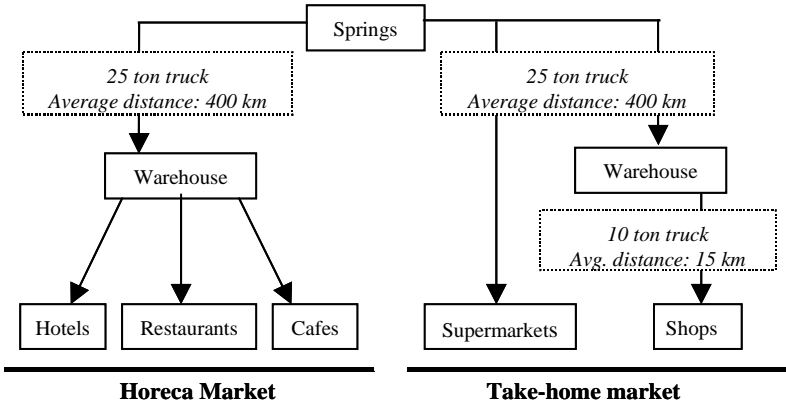
Fig. 1. Flowchart illustrating the bottled water distribution from springs to markets

bottle. The glass mill, in its turn, manufactures bottles from raw materials (the main raw material is silicon sand) and/or from cullet (collected crushed glass). Glass mills have collected cullet for recycling in Portugal since 1983, without governmental intervention: the main incentive is the reduction of production costs (mainly energy costs) that occurs when the raw materials are replaced by cullet.

The distribution of bottles from the springs to the market is typically handled by the bottling company itself, using road transport (25-ton and 10-ton trucks) and regional warehouses. The great majority of the springs are located in the northern region of the country; most glass mills are located in the center. On average, a truck has to cover a distance of about 300km from the mill to the spring.

Figure 1 illustrates the distribution of bottled water from springs to markets, including the associated average distances. Notice that a truck transporting returnable bottles returns to the springs filled with empty bottles whereas a truck transporting one-way bottles returns empty. One-way bottles are eventually collected as regular trash (by the municipalities) and are sent to the landfills, or they are recycled as cullet glass and sent to the glass mills.

There are in Portugal about 20 independent companies marketing bottled water under more than twenty-six different brands. Their annual sales volume is about 600 millions liters (1997 data). The six largest companies (nine brands) have a market share of more than 80%.

Environmental considerations for packaging management policies
in the European Union

Packaging has motivated various disputes between environmentalists and industry. The short life cycle associated with packaging motivates environmentalists to claim that packaging should be reduced at the source to its smallest proportions and reuse should be promoted. Industry argues that hygiene, protection, convenience, also have their rights and that the weight of one-way packaging has been dramatically reduced.

Responding to this dispute, European Commission proposed some Directives with the objective of harmonized managing of packaging and its resulting waste, while ensuring a high level of environmental quality.

Pearce (1998) reviews the practical implementation of environmental policy within the expanding jurisdiction of the European Union (EU). The author primarily concentrates on the need for some form of environmental appraisal techniques to evaluate regulatory initiatives by the European Commission (EC).

The EC packaging and packaging waste directive was finalized in December 1994. In its final form, the directive may be summarized as follows. The objectives are:

- to reduce the overall impact of packaging on the environment by reducing packaging at source,
- to eliminate harmful materials in packaging waste, maximize the recovery of packaging waste for re-use, recycling, composting and energy recovery, and minimize the quantity going to final disposal (land-fill); and
- to bring national policies on packaging and packaging waste closer together to remove obstacles to trade and competition.

The directive covers all types of packaging in the European Union – industrial, commercial, office, shop "or any other level". Within six and half years of adoption of the directive (five from implementation by national law), the main recovery objectives are:

- 50–65% of packaging, by weight, must be recovered where recovery includes any activity which confers economic value on the waste (i.e. recycling, re-use, energy recovery),
- 25–45% of packaging by weight must be recycled, with a minimum of 15% of each material (paper, aluminum, steel, plastics) being recycled.

These targets are relaxed for Greece, Ireland and Portugal who must attain at least 25% recovery by the five-year deadline, or achieve the targets for the rest of EU by 2005.

The directive is clear in indicating that re-use and recycling are "preferable in terms of environmental impact" to other forms of recovery and to disposal. This hints at the so-called "waste hierarchy" which has gained credence in European policy discussions on waste management. The hierarchy, from the best to worst, is source reduction, re-use, recycling, composting, energy recovery, and landfill.

An application brought from the bottled water Portuguese domestic market making use of the LCCA methodology is presented in the next section.

4 Model formulation and numerical solution

The LCAA programming format presented in Section 2 is applied to provide a sample model of the manufacture, reuse and recycling of glass bottles used for mineral water in Portugal.

A simplified flow chart is presented in Figure 2. The figure illustrates both the vertical dimension of the industry – the production chain from the glass mills
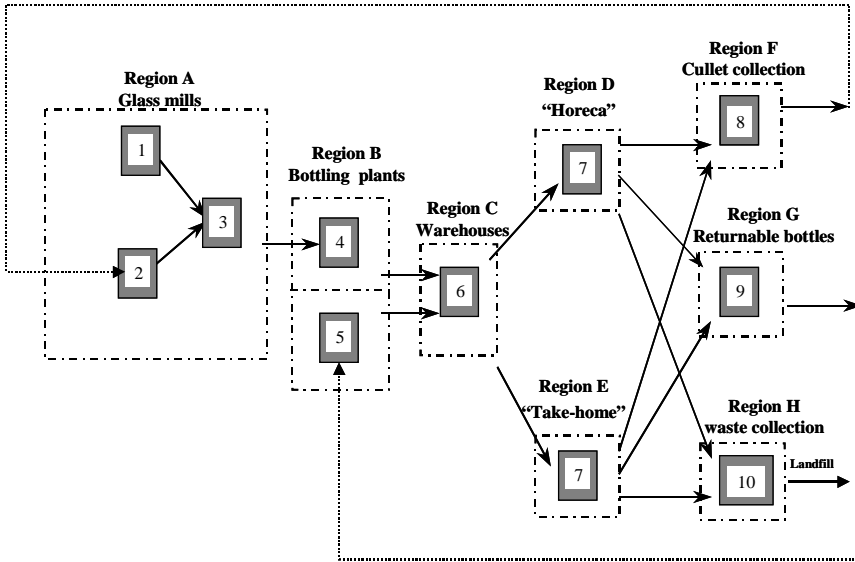
Fig. 2. Flowchart illustrating the logistics of the production and distribution of mineral water in glass bottles

to consumption and landfills, including the recovery of glass bottles (reusing and recycling) – and the spatial dimension. No regional breakdown of production is shown, but the overall market is broken down into the two sectors: "horeca" (hotels, restaurants and cafes, see Section 2) and the take-home market. Reading the diagram from left to right, the following regions are recognized in the logistics flow:

- Region #A: Glass mills (manufacturing glass bottles from raw materials and from cullet glass),
- Region #B: Bottling plants (filling and cleaning new and returnable glass bottles),
- Region #C: Warehouses,
- Region #D: "Horeca" market,
- Region #E: Take-home market
- Region #F: Cullet collection plants,
- Region #G: Returnable bottles plants,
- Region #H: Empty bottles collected and disposed of as waste in landfill.

The arrows show the direction of the logistics flow. Note the loops feeding flow back from regions #F (cullet) and #G (used bottles) to regions #A and #B (stippled lines in the diagram). Stocks of materials are not featured in the example.

Ten production activities were considered. Notice that some activities are carried out at more than one node – see activity #7, for example.

- Activity **#1**: Making glass from raw materials,
- Activity **#2**: Making glass from glass cullet,
- Activity **#3**: Manufacturing empty bottles (from bulk glass),

- Activity **#4**: Cleaning and filling bottles,
- Activity **#5**: Cleaning and filling returned glass bottles,
- Activity **#6**: Distribution (and warehousing) of bottles,
- Activity **#7**: Consumption of mineral water,
- Activity **#8:** Collection and filtration of glass cullet,
- Activity **#9:** Collection of returnable bottles,
- Activity **#10**: Landfill disposition of glass,

As discussed before, the LCAA model distinguishes four classes of commodities: *primary goods* P, *intermediate goods* I, *final goods* F, and *environmental goods* E. Primary goods include resources, materials and energy. Resources are inflows directly from the environment. Materials are drawn from the technosphere. They represent economic activities that take place outside the present model. Energy is a resource extracted from the environment. The primary goods considered in this study are listed in Table 2.

Table 2. Primary goods and units used

Name	Units	Description
Resources		
dolomite	[ton]	raw material for manufacture of glass
feldspar	[ton]	raw material for manufacture of glass
limestone	[ton]	raw material for manufacture of glass
sand	[ton]	raw material for manufacture of glass
soda	[ton]	raw material for manufacture of glass
sundries	[ton]	sundries for manufacture of glass
water	[ton]	process water (cleaning)
min_water	[ton]	mineral water in bulk
Materials		
glue	[ton]	material for labeling bottles
NaOH	[ton]	material for washing the bottles
paper	[ton]	paper for labeling
HCl	[ton]	material for washing the bottles
Energy		
diesel_b	[GJ]	diesel fuel (44 MJ/kg, 0.86kg/l)
elect	[MWh]	electricity (1MWh = 3.6GJ)
elect_wout	[GJ]	electricity without emissions
heat_gas	[GJ]	natural gas
heat_oil	[GJ]	thick-fuel oil
unspecif	[GJ]	unspecified energy

Intermediate goods are outputs that serve as inputs into subsequent activities, see Table 3. Notice that a bottle of mineral water in the hands of the consumer is considered as an intermediate good, rather than a final good. Instead, the final good in our system is the *consumption service* delivered by the distributed product.

Table 3. Intermediate goods and units used

Name	Units	Description
cullet	[ton]	glass cullet (after collection)
glass	[ton]	melted glass for bottles' production
reused	[kunit]	reused bottles (after transportation)
newbt	[kunit]	new bottle 25ml (weight: 0.154kg)
fill	[kunit]	filled bottle (before distribution)
fill_d	[kunit]	filled bottle (after distribution)
used_bt	[kunit]	used bottle (after consumption)

The transportation of intermediate goods is represented in Figure 2 by links (arrows) connecting several of the regions. Transportation activities use energy as inputs and generate environmental "bads", such as emissions of pollutants, which are aggregated into environmental impact categories as exhibited in Table 1. Numerical values of these coefficients were calculated based on the distances between the regions and on environmental and technological I-O data[4] (per km) specific for each type of transport used in the corresponding links.

The optimization of the logistics flow features a series of alternatives activities, for example: The manufacturing of a bottle can be based on raw materials or on glass cullet. A bottle to be filled can be a freshly made or a cleaned used bottle. A used bottle can be recycled back to the bottle manufacturer, it can be returned back to the bottle filler for reuse, or it can be disposed of in the landfill.

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, and the supplies of all primary goods.

Further assumptions

Our calculations are intended to highlight the recovery of glass and bottles and simplify other aspects, namely the regional dimension of the production and distribution. Only a single manufacturer of glass bottles, one location of the springs and one type of bottles (0.25 liter) are therefore considered. The average distances between glass mills, warehouses, collection plants and markets can be found in Appendix 1 (Table 7).

Detailed numerical data were obtained from Portuguese companies bottling and distributing spring water under several brand names. The data have been adjusted so that it reflects typical rather than actual operations. Similarly, data concerning the glass bottles production were adapted from current industrial operations of a main Portuguese manufacturer of glass bottles, being representative of operation that has not changed significantly in the preceding years. To preserve commercial confidentiality economic costs are not presented.

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[4] These data characterize typical processes and were taken from commercial databases available in the software SimaPro4.0, developed by Pré-Consultants (1998).

The environmental emissions data, both from industrial processes and from the transportation activities, were in some cases supplemented with data from international databases.

Consumer demand for the final product (consumption of bottled water) was fixed at current levels in 1997. See below:

- Total demand in "horeca" market: 60000 thousand bottles per year
- Total demand in the take-home market: 20000 thousand bottles per year.

As discussed in Section 3.1, the current packaging and packaging waste management policies do not explicitly propose goals (g') in terms of environmental impacts categories. Instead, policy targets are formulated in terms of recovery objectives, such us minimum percentages of re-use, recycling or total material recovery. Nevertheless, this model calculates the vector of environmental impact categories, $I(j)$:

$$I(j) = F(j, i) \cdot [(-B_{actv}^{E} + A_{actv}^{E}) \cdot x - B_{trns}^{E} \cdot t)] \tag{14}$$

appearing on the left hand side in relation (14).

4.1 Environmental scenarios

The settings of the environmental scenarios to be solved by the model are outlined below. Five alternative scenarios were considered, specifying behavioral patterns, the current situation (1997 data) and different strategies for recovery.

- **Scenario 1:** This is a reference case, to which the following scenarios 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:** The percentage of used bottles available to be refilled was limited to *a maximum of 30%* (24 000 thousand bottles). This scenario reflects the fact that not all the used bottles will be available to be refilled. People's behavior limits the quantity of used bottles available, since consumers need to return the bottles before they can be refilled.
- **Scenario 3:** The minimum percentage of bottles sent to landfill in both markets (collection of waste bottles to landfill) *was set to 20% of the total of bottles distributed*, which represent approximately 2 464 tons of glass. This scenario recognizes the fact that a percentage of bottles will always end up in landfill as waste.
- **Scenario 4** describes the current situation (1997 data), in terms of the percentage of bottles being recycled and reused. The following constraints were included reflecting current recovery ratios: *In the "horeca" market, 45% of all bottles are returned. In the take-home market, only 30% of the bottles are returned.* In addition, *30% of the bottles are manufactured using cullet*. We called this procedure "calibration". No additional environmental policy instruments were imposed.

- **Scenario 5.** The following policy directives were assumed: *In the "horeca" market, all the bottles must be returned to be refilled*, i.e. no bottles in this market are allowed to be sent for recycling or disposed of as waste in landfill. *In the take-home market, at least 10% of all the bottles must be returned for refilling*. Furthermore, reflecting current behavioral patterns, *(i) at least 50% of the take-home bottles are disposed of as waste in the landfills and (ii) no more that 10% of the bottles are returned to be refilled*. This latter assumption together with the policy directive for the take-home market sets the ratio of refilling to 10%.

4.2 Numerical results

The LCAA programming model was coded in the GAMS (general algebraic modeling system) software, see Brooke et al. (1998) for details. The mathematical program includes 54 equations and the coefficient matrix features 304 nonzero elements.

First, results from Scenario 1 are reported. They will serve as a benchmark for the other scenarios. It represents a kind of utopia for the bottling market, since it assumes that all the used bottles are equally available to be refilled, recycled or disposed of as waste. Thus, industry can choose the recovery options that best fulfill their needs. However, in the actual society, people's behavior limits the quantity of bottles available to be refilled and recycled. Consumers need to return the bottles before they can be refilled. They need to deposit them in the collectors before the glass can be recycled.

Selected material flows (measured in thousand units, kunit, or tons) from the direct solution and dual values (shadow costs of intermediate goods, $/kunit) are exhibited in Figure 3. Company-level financial information had to be protected and thus the monetary unit ($) was multiplied by a certain factor. As it turns out, all the used bottles (72 727 kunit) are returned to the bottlers to be refilled and, consequently, no bottles are sent to be recycled or to be disposed of in landfill. In addition, the bottlers purchase 10 951 thousand freshly manufactured bottles from the glass mills every year. These bottles have been made from raw materials.

It should be noted that the total input of the filling industry adds up to 83 678 thousand bottles per year and the difference to the total demand (80 000 thousand), represents the bottles that are broken along the production and distribution chain (4.6%). In addition, 9.1% of the distributed bottles are broken in the reverse logistic chain. The percentage of bottles brake in the entire life cycle sums up 13.7%. Alternatively, this inefficiency can be interpreted as the maximum number of times (cycles) that in average a bottle is refilled – 13.7% losses indicates that a bottle does 7.3 cycles. It is assumed that all these broken bottles will end up as waste disposed of in landfill (1686 tons of glass).

Looking at the dual solution, the shadow price of final consumption comes out as 56.7$ per thousand bottles and it is identical in both markets (see Fig. 3). The full-imputed price of a filled bottle (78.4$/kunit) can be calculated by adding the shadow value of a reused bottled (21.7$/kunit) to the consumption shadow price.
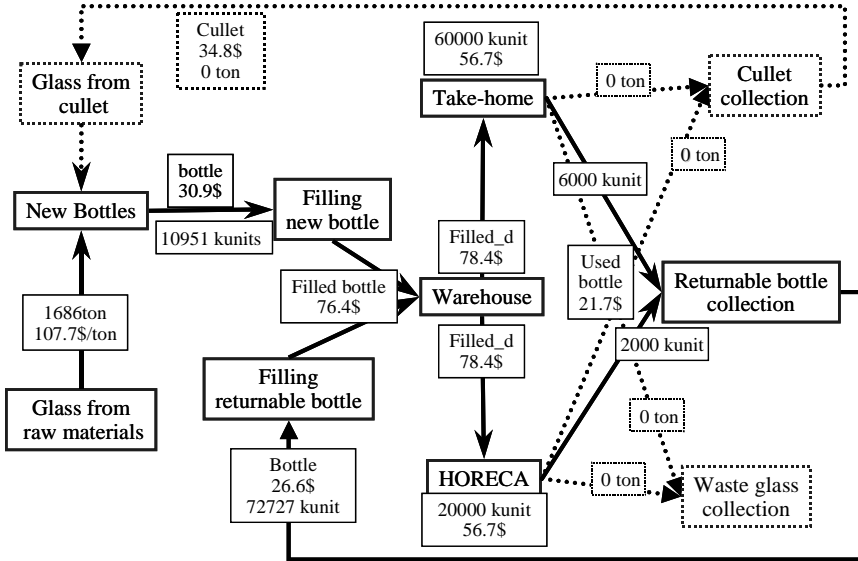
Fig. 3. Selected material flows and shadow costs for Scenario 1

Some implications brought from the dual variables associated with the activities are relevant to understanding the optimization results. The duals will be referred to as the shadow costs of manufacturing and transporting intermediate goods. In particular, analyzing why the optimal solution does not include sending cullet back to the glass mill is described below.

The cost of one ton of glass produced with cullet (activity #2) cannot exceed its shadow cost – i.e. the shadow value of the intermediate good *"glass"* – as stated by the corresponding dual complementary slackness condition. "Glass" can be produced either with raw materials (activity #1) or with cullet (activity #2). The manufacture with raw materials includes two types of cost elements: the cost of resources (raw materials, energy.) and the cost of operating the activity #1. These costs are exogenous to the model. Consider now the production of "glass" using collected cullet. There are four types of cost elements: (i) the shadow cost of cullet, (ii) the shadow cost of transporting[5] cullet, (iii) the cost of resources and (iv) the cost of operating activity #2. The model determines the first two, but the last two are exogenous.

Manufacturing glass making use of raw materials sets the shadow value of "glass" to be 107.7$ per ton. By complementary slackness, the production of glass with cullet is not operated because the sum of all costs exceeds that value. The remaining costs are transportation (8.5$), resources (37$) and operating the activity (27$). The manufacture of glass with cullet were to be operated, its shadow would have to equal 34.8$/ton.

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[5] The shadow values of transporting intermediate goods are obtained from the complementary slackness conditions for the corresponding dual variables.

Table 4. Shadow costs of consumption

Market	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5
horeca, $/kunit	56.7	74.0	56.7	80.3	56.7
Δ(%)	–	30%	0%	42%	0%
take-home $/kunit	56.7	74.0	56.7	80.3	74.0
Δ(%)	–	30%	0%	42%	30%

Notice that the shadow value of a used bottle is quite high: 21.7$ per thousand bottles. Since an empty bottle weighs 0.154kg, we can calculate what would be the approximate value of cullet if some of those bottles were sent back to be recycled. The result is 140.9$/ton. Because this figure is higher than the "maximum" cost of cullet enabling its use (34.8$/ton), the model does not consider manufacturing glass with cullet.

Ultimately, the optimal solution does not include manufacturing glass with cullet because the shadow value of a used bottle is excessive. This follows from the fact that all used bottles are available to be refilled. Also, note that the activity of collecting bottles for refilling is operated at a positive level. Hence, the shadow cost of a used bottle (21.7$/kunit) is equal to the shadow value of a filled bottle (76.4$/kunit) – either a freshly made bottle or a reused one – minus the costs of cleaning/filling the used bottle and the costs of collecting and transporting it.

This reference scenario (**scenario 1**) corresponds to a perfect world. The subsequent more realistic scenarios introduce, step-by-step, shortcomings to this "ideal" situation, making allowance for consumer recovery attitudes, and for the presence of possible environmental policy constraints.

The shadow costs of consumption for the five scenarios and the variation relatively to the reference scenario, Δ(%), are shown in Table 4. Energy consumption and glass disposed of in landfills are show in Table 5. The environmental impact levels are listed in Table 6.

Scenario 2 illustrates the fact that the availability of used bottles to be refilled depends on the efficiency of collection, i.e. the percentage of bottles that are returned by consumers after being used. Limiting the amount of used bottles available to be refilled to 30% results in the decrease of the shadow value of the used bottle and, consequently, in using all the remaining bottles (70%) as cullet in the manufacture of glass. The shadow cost of consumption increases by 30% and the energy consumption increases by 37% (relatively to the reference scenario). Nevertheless, looking at Table 5 it can be seen that the total amount of glass disposed of in landfill resulting from the broken bottles along the life cycle is reduced by 42%. This is because the losses in the collection chain of cullet are considerably lower than in the collection and refilling of used bottles. Consequently, there is a reduction in the amounts of primary resources consumed, particularly those used in the manufacture of glass. However, there is an increase in the consumption of diesel, which is due to the high transportation distances – collection and transporting of cullet to the glass mills and transporting freshly manufactured bottles to the springs. The use of primary resources for all the scenarios is listed in Table 8 (Appendix 2). Looking at

Table 5. Glass disposed of as waste in landfills, and energy consumption

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5
waste glass [tons]	1686.5	981.9	3862.4	6224.4	2938.6
Δ(%)	–	–42%	129%	269%	74%
energy [GJ]	131372	180331	153911	197597	153523
Δ(%)	–	37%	17%	50%	17%

Table 6. Environmental impact levels

Environmental category	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5
Greenh. effect [ton]	8941.0	13769.5	11146.0	15432.6	11102.4
Δ(%)	–	54%	25%	73%	24%
Acidification [ton]	99.0	156.3	120.5	165.5	121.6
Δ(%)	–	58%	22%	67%	23%
Eutrophication [ton]	14.8	21.4	17.1	22.0	17.4
Δ(%)	–	45%	16%	49%	18%
Winter smog [ton]	34.3	54.9	64.6	107.9	56.5
Δ(%)	–	60%	89%	215%	65%
Summer smog [ton]	14.9	22.4	18.0	24.1	18.3
Δ(%)	–	50%	21%	62%	23%

Table 6, one sees that there is a general increase in the impact levels, which follows similar trends for all the environmental categories.

Scenario 3 illustrates the fact that a percentage of bottles will always be disposed of in landfills after being used. Requiring this value to be at least 20% of the distributed bottles (16000 thousand units) results in the increase of the manufacture of bottles by 129%. No cullet is used in the manufacture of the bottles. Just as in the reference scenario, this is due to the relatively high shadow cost of the used bottle (10.9 $/kunit). Consequently, the shadow value of consumption is the same as in scenario 1. Looking at Table 5 it can be seen that glass disposed of as waste increases by 129%. Due to mass conservation, and since this is a "steady-state" (static, for economists) model, the amount of glass disposed of must be equal to the amount of bottles manufactured. Otherwise, there would be a violation of the first law of Thermodynamics. See also Tables 9 and 10 (Appendix 2) listing the operating level of the production and transportation activities for all the scenarios

Energy consumption increases by 17% and all the impact levels increase relatively to the reference scenario. However, the environmental impact increases do not follow very similar trends (between 16% to 89%).

The *calibration* imposed under **scenario 4** – by which the current recovery ratios (1997 data) are simulated – results in a more realistic scenario. Table 4 shows that the shadow cost of consumption in both markets increases by 42%. The amount of glass disposed of as waste is higher than in any of the previous scenarios (+269%). This results from the current low percentage of bottles being recycled and reused. Consequently, as can be seen in Table 8 (Appendix 2), this scenario exhibits the lowest consumption of process water – mainly used for cleaning bottles before re-

filling. Looking at Tables 5 and 6 it can be seen that the calibration scenario exhibits the highest values of energy consumption and the highest levels of environmental impact for all the categories.

The disposal policies defined under **scenario 5** result in a considerable reduction of the glass disposed of and energy used. This reduction, due to the high recovery targets imposed, amounts to 53% and 22%, respectively and comparatively to the *calibration* scenario. Nonetheless, the total amount of waste and energy used are higher than in the reference scenario. Additionally, there is also a reduction in the shadow values of consumption. Looking at Table 4 it can be seen that this reduction is distinct for the both markets. The shadow cost of consumption in the "horeca" market is identical to the value calculated under the reference scenario, but in the take-home market, this figure is 30% higher. This difference reflects the different recovery targets imposed in the two markets. Looking at Table 6 it can be seen that, comparatively to the calibration scenario, there is a considerable reduction in all the environmental impact levels. Because all the impacts exhibit similar trends – i.e., they are all mitigated comparatively to the calibration scenario – in this particular example there is no need to use a multicriteria analysis to assess the policy directives imposed in scenario 5. The result would be the same, independently of the weighting factors used for the environmental impact categories.

The bottled water market can cause less environmental damage and use less energy consumption in many different ways, such as more recycling and more reuse of bottles. Distinct strategies can be used to obtain higher recovery ratios.

5 Concluding remarks

The immediate purpose of this paper has been to demonstrate the feasibility and potential of the LCAA methodology. The aim is not prejudiced by the simplifications assumed in the numerical example presented. It is still possible to demonstrate the types of environmental strategies and policies that can be achieved with this approach.

Life cycle activity analysis combines the advantages of both environmental life cycle assessment and activity analysis without suffering from some of their obvious shortcomings. LCAA is imbedded in a model of relevant industrial activities, permitting the presence of alternative technologies and determining the optimal level of operation of each activity. LCAA models the economy as a system represented by activities and physical and monetary flows between these activities, providing an integrated view of the entire logistic system of production and commercialization of products (or services). The referred activities represent the processes necessary to provide the product or service being studied. At specific nodes of the logistics chain alternative activities are available capable of supplying/demanding the same intermediate product. Therefore, many products and services can be produced/used through a number of alternative (sets of) processes. This material-product chain model covers the entire product's life cycle and emphasis is given to the presence of alternative end-of-life strategies (e.g., reuse, recycling, incineration, landfill). The model calculates the least-cost system configuration. Process activities, financial flows and material-product flows characterize the system configuration.

This mathematical formulation permits the representation of the life cycles of products based on individual activities through the identification of inflows and outflows associated with each activity and its links with other activities, including the transportation of intermediate goods between regions. The format allows explicitly the identification of all mass and energy fluxes – and therefore its verification through the thermodynamics laws. Additionally, this joint format allows the quantification in financial terms of the costs associated with limitations imposed (through determination of the respective shadow values).

The numerical example used to illustrate the LCAA methodology proposed in this paper showed that it is possible to derive environmental strategies/policies that are defendable and predictable. The potential for reducing the environmental impact of a sector can be explored. Although our first results are encouraging, much further research obviously remains to develop a practical and reliable support-decision system for environmental policy.

Our paper shows how a model of an integrated economic, environmental, energy and material-product system can be developed and applied. Once the LCAA mathematical program has been written down, the methodology allows the analysis of "What if.? scenarios". In this manner, an integrated approach can provide both environmental and market advantages, as well as helping to identify more sustainable industrial and commercial practices for the future.

Further research, and limitations of the approach

Through a series of field studies of instances of recycling and/or reuse of various products, the present authors are currently involved in a program of assessment and evaluation of the scope of the LCAA modeling format. In this manner, we hope to obtain a certain degree of standardization of application.

One particular extension of LCAA pursued by the authors is to include non-linearity in the activities' technological and environmental I-O data.

The data chosen for the numerical illustrations in the present paper – involving the Portuguese market for bottled water – were supposed to be time-independent. This assumption is also used by standard approaches such as LCA and MFA. It may be permitted when short (up to one year) product life cycles (including disposal and recovery) are considered. However, many life cycle problems involve much longer time spans, simply because many products are durable and last for decades before they are disposed of. Further complications are introduced when processes and products gradually change over the long run. It may be possible to deal with such situations by estimating the LCAA model using time series data for time-dependent variables.

Unfortunately, lack of time series data may strongly limit the extension of LCAA to include such dynamic issues. For both static and dynamic models, accuracy and completeness of data is a very important. In the absence of reliable data, both the LCAA analysis and the assessment of its results will be seriously hampered.

The considerable amount of information needed by the LCAA model requires the co-operation of many different specialists. The industrial engineer's approach operating on process or plant level and focused on logistics and cost accounting

will be one ingredient in this joint effort. The economist's approach operating on regional or macro economic level will be another. The environmental scientist/engineer evaluating environmental impacts needs certainly to be integrated. All these contributions need to be brought together in a complementary fashion.

Appendix 1

Table 7. Average distances between regions (for the identification of regions, see Fig. 2)

Origin	#A	#B	#C	#C	#D	#D	#D	#E	#E	#E	#F	#G
destination	#B	#C	#D	#E	#F	#G	#H	#F	#G	#H	#A	#B
Distance [km]	300	400	15	15	0[a]	0[a]	40	0[b]	0[b]	70	400	0[c]

[a] The bottles are collected and returned at the *"horeca"* market.
[b] These distances are negligible, because we assume that people do not take the car expressly to return empty bottles or to go deposit cullet in the containers.
[c] This distance is considered negligible since the trucks have to return to the warehouse, either empty or full with bottles.

Appendix 2

Table 8. Consumption of primary goods

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5
Resources, ton					
dolomite	167.3	105.1	383.2	620.1	292.7
feldspar	126.5	79.4	289.7	468.8	221.3
limestone	125.6	78.9	287.7	465.7	219.8
sand	1317.2	827.3	3016.9	4882.5	2304.6
soda	168.3	154.5	385.5	640.5	301.9
sundries	7.9	16.6	18.2	33.3	15.6
water	71146.0	51524.0	65140.8	51253.8	64390.1
min_water	20000.0	20000.0	20000.0	20000.0	20000.0
Materials, ton					
glue	8.0	8.0	8.0	8.0	8.0
NaOH	74.2	51.6	67.3	51.3	66.4
Paper	92.8	92.8	92.8	92.8	92.8
HCL	11.9	8.3	10.8	8.3	10.7
Energy					
diesel, GJ	65673.4	93418.1	74455.5	94439.3	75947.7
Elect, MWh	5448.4	4291.2	5058.8	4197.2	5027.8
elect_wout, GJ	397.0	1461.0	909.2	1885.4	879.9
heat_oil, GJ	19802.8	13271.2	17803.8	13181.2	17554.0
unspecif, GJ	14129.7	51470.7	32361.5	66926.9	31238.6

Table 9. Operating level of production activities

Region	Activity	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5
H1	X1	1686	1059	3862	6251	2950
H1	X2		7737		2644	1184
H1	X3	10951	57120	25081	57756	26847
H2	X4	10736	56000	24589	56623	26320
H2	X5	69264	24000	55411	23377	53680
H3	X6	80000	80000	80000	80000	80000
H4	X7	60000	60000	60000	60000	60000
H5	X7	20000	20000	20000	20000	20000
H6	X8		7815		2670	1196
H7	X9	72727	25200	58182	24545	56364
H8	X10			2464	5411	1540

Table 10. Operating level of transportation activities

Link	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5
H1-H2	10951	57120	25081	57756	26847
H2-H3	80000	80000	80000	80000	80000
H3-H4	60000	60000	60000	60000	60000
H3-H5	20000	20000	20000	20000	20000
H4-H6		32280		6862	
H5-H6		20000		11000	8000
H4-H7	60000	27720	44000	18000	60000
H5-H7	20000		20000	9000	2000
H4-H8			16000	35138	
H5-H8					10000
H6-H1		7815		2670	1196
H7-H2	72727	25200	58182	24545	56364

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