British Journal of Applied Science & Technology
6(1): 34-48, 2015, Article no.BJAST.2015.065
ISSN: 2231-0843

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Energy Efficiency, Sustainable Development and Natural Resources Conservation: Multicriteria Life-cycle Analysis of Daily-Used Materials with a Long-term Vision

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Authors' contributions

This work was carried out in collaboration between both authors. Author CEET has designed the study, performed the search of adequate data, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Author BM has created the PROMETHÉE software and managed the analyses of the study and literature searches. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJAST/2015/10831
Editor(s):
(1) Marko Likon, Insol Ltd., Cankarjeva 16a, 6230 Postojna, Slovenia.
Reviewers:
(1) Khalil Kassmi, Physics, University of Oujda, Morocco.
(2) Anonymous, India.
(3) Anonymous, Kyonggi University, Republic of Korea.
Complete Peer review History: http://www.sciencedomain.org/review-history.php?iid=764&id=5&aid=7213

Policy Article

Received 12th April 2014
Accepted 19th September 2014
Published 15th December 2014

ABSTRACT

This paper explores the role of energy use in sustainable development and the potential sources to increase energy efficiency during the whole life-cycle of any material and its production process. It is the first paper of a research project exploring a decision making model for a multidisciplinary problem in nature. It deals with Multicriteria decision making for plastic materials used in a day to day basis. We analyze plastic materials used to manufacture disposable polyethylene bags among other materials that can be used for their substitution. We are also interested in plastic (polyethylene Terephtalate or PET) bottles and its possible substitutes.

Sustainability considers the concept of exergy loss, Green House Gases emissions, real energy

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flows needed to the chain of manufacture processes, material balances in the productions chains and value added. These concepts are presented as a set of criteria to make decisions of alternative substitute materials.

The materials analyzed for possible substitutions comparison for the case bags are: Low Density Polyethylene (LDPE), LDPE with a pro degrading additive, unbleached Kraft paper, cotton and polypropylene (PP). For the case of polyethylene Terephtalate (PET) bottles, aluminum and glass are included for analysis as substitution materials, but more important yet the possibility of recycling is also considered.

A case study for Mexico's market is developed to prove the methodology, offering some interesting data about consumption and production of bags and bottles.

Keywords: Sustainable development; multicriteria decision making; exergy analysis; green house gases emissions; polymers science.

1. INTRODUCTION

Scientific and technological development enable to provide a wide variety of goods and services, but also put at risk the quality and longer-term viability of the biosphere as a result of unwanted, 'second order' effects [1]. These effects are those related to pollution, as mainly global warming, acid rain, water and soil contamination, etc.

Over a period of some 15-20 years, the international community has been grappling with the task of defining the concept of 'sustainable development'. Starting from Brundlandt's [2] report on sustainability that states sustainable development as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs,* it continues to be evident that sustainability is a multidisciplinary topic including challenges for technology, based on the efficient use of energy. A lot of parameters and criteria are essential for long-term global sustainability [3].

This investigation focuses on two theses. The first one is that plastic bags and bottles for individual use are not efficient on the energy efficiency point of view, considering also global pollution and waste problems, within their full life-cycle: Production, use and disposal [4].

During the production of those items, there are both a waste of nonrenewable resources and also Green House Gas (GHG) emissions. Their lifetime is very short, mainly at the end of their use, i.e. their final use. Hence the efficient use of energy and of raw materials is essential for long-term global sustainability.

Our second thesis concerns different materials or ways to use plastics getting longer use life-cycle, saving energy and avoiding pollution. We strongly believe that technology-driven sustainability and economic growth is possible without wasting nonrenewable resources and energy [5,6].

General relations about energy efficiency, exergy, and a thermodynamic parameter, such as relative irreversibility, are first introduced. The whole chain of production since natural gas liquids or crude oil are the start point of production chain's until the production of plastic bags and bottles, are considered to perform the exergy analysis, comparing them with other materials with a lower energy and nonrenewable resources consumption [7,8,9].

To choose which material (including the actual ones) is better and to choose the best substitution alternatives, we propose to use a multicriteria approach [10], based on the PROMETHÉE-GAIA methods [11] can be used, including several criteria such as: Exergy efficiency and irreversibility; nonrenewable resources used over their life-cycle; profit. Those are suitable criteria to remedy the present plastic materials waste in their full energy life-cycle and reduce GHG emissions. Other important references about multicriteria approach and PROMETHHE-GAIA methods are: [12].

Generally, sustainability is associated with ecology and energy. However, it has major implications, since it is a general concept that covers from the system's birth until the implementation of tasks for quality improvement of human life and the environment (Rotsein, E and G. Staphanopoulos, 1976).

The quantification of sustainability is important but it is also difficult to optimize because of the relations between energy, economic, ecological and social factors. That's why we use multicriteria decision aid in order to take into account the most important interactions between energy, economic, ecological and social factors translated into proxy variables of them [13].

In this work, the "exergy" concept is understood *as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium with reference environment; it can be linked with environmental impacts because through the exergy analysis, the irreversibility in the process can be known and thus, it can lead to a better behavior to increase energy* [14].

The Life Cycle Analysis (LCA) is a useful tool in many cases to assess the environmental impacts produced by processes. Within several definitions among others we have taken ISO's 14040:2006: Compilation and evaluation of the inputs, outputs and the potential environment impacts of a product system throughout its life-cycle [15]. International Standard ISO 14040, [16].

In using the above concepts and methods to apply to plastic materials, we present in Fig. 1 all associated concepts that can be viewed integrally.

2. METHODOLOGY

A methodology has been created in order to perform the whole analysis considering the different stages, as it follows in Fig. 2.

Considering the diagram presented in the above figure, all the involved concepts are described in the Appendix at the end of this paper.

3. CASE STUDIES

3.1 Goal and Scope Definition

The goal of this study is to compare and analyze the exergy losses embedded with the production of the materials used in the application of film blown bags (i.e., shopping bags) and PET bottles used mainly to bottled water. For the purpose of this paper, plastic bags are defined as supermarket and retail shopping bags and bottles are considered to be of one liter.

3.2 Polyethylene Bags and PET Bottles Functional Unit

Bags functional unit is a repeated use of 300 times for reusable bags, which is the average lifetime, while the other kinds of bags are used only once. Because of the carrying capacity of the plastic bag, the functional unit is taken to be the use of 900 polyethylene bags and 675 paper bags (the number of single use bags to carry goods from a store to home equivalents to the use of one reusable bag were calculated).

The functional unit of PET study is 1 Kg (26 bottles of 1 Lt or 1 ton PET, 26,000 bottles of 1 liter. This base of calculation was used for the Exegetic Life Cycle Analysis and the atmospheric emissions.

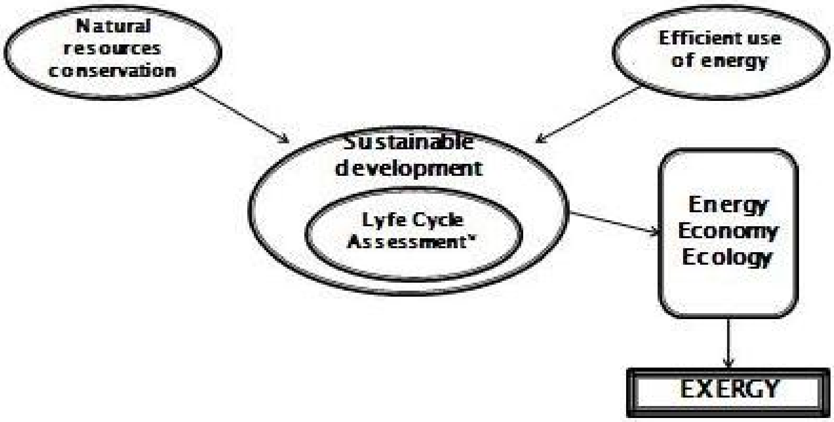


Fig. 1. Methods and concepts used in this paper

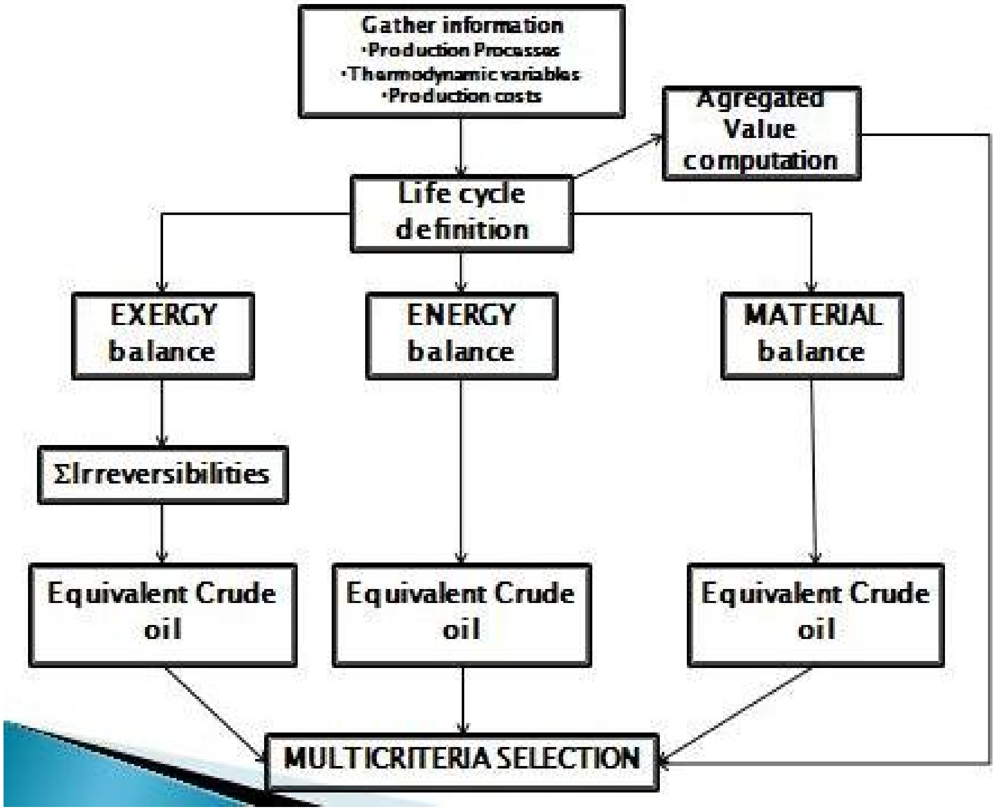


Fig. 2. Methodology used in this paper

3.3 Materials Studied

3.3.1 Materials to manufacture bags

Five types of grocery bags were analyzed. Three of them are disposable bags: The commonly used plastic bag made from Low Density Polyethylene; a LDPE bag containing a Pro degrading, unbleached Kraft paper bags and two reusable: A Polypropylene fiber bag and a cotton bag. For the Exergy analysis, calculations were based upon the information in Table 1, which shows the assumptions and main characteristics related to every type of bag.

Polyethylene is not biodegradable because it has large molecular weight and its large molecules cannot enter easily into the cells of microorganisms. After many years of research, it has now been established that the mechanism of polyethylene biodegradation, known as ‘oxo-biodegradation’, involves two stages. They are: (1) Abiotic (photo or thermo) oxidation and (2) Microbial biodegradation. In the first stage, polyethylene is oxidized leading to the reduction of its molecular weight significantly. Also, hydroxyl (OH), carbonyl (C=O) and carboxyl (COOH) groups are introduced into polyethylene chain leading to further oxidation of polyethylene.

Pro-oxidants (Pro degrading) are transition metal ion complexes and they are added to Polyethylene in the form of either stearate or other organic ligand complexes. Fe3+, Mn2+ or Co2+ stearate are the most commonly used as pro-oxidants. Polyethylene that has been oxidized by pro-oxidants will be more susceptible to microbial attack than the initial polyethylene film.

3.3.2 Materials to manufacture bottles

The methodology described was applied to the case of PET bottles, having as possible substitute materials: Aluminum cans and glass bottles. We use the term “primary materials” to refer to those materials obtained from the raw materials, while the term “secondary materials” is referred to the materials produced in a recycling process.

Table 1. Main characteristics of the bags analyzed

Composition	Disposable			Reusable	
	LDPE (film grade)	**LDPE + Pro degrading**	**Unbleached kraft paper**	**PP fiber**	**Cotton (Unbleached)**
Size (cm)	25+15x50	25+15X50	35+10x40	37+10x39	31+21X33.5
Carrying capacity (kg)	3	3	4	9	10
Weight (g)	5.6	6	42.6	60	90
Functional unit (f.u.)	900 bags	900 bags	675 bags	1 bag	1 bag
Weight f.u. (kg)	5.04	5.4	28.755	0.06	0.09
Expected life	single use	single use	single use	300 times used	300 times used

(f.u.= functional unit)

3.4 Data Sources

The LCA of the two case studies are carried out with the aid of the software package SimaPro 7.1. The Aspen Plus database is also used for thermo-chemical data. Chemical technology encyclopedias have also been consulted [17,18], as well as existing and publicly available Life Cycle Assessments reports. The Process Economic Program reports (PEP) are mainly from where the information on raw materials, by products and utilities come from.

3.4.1 Characteristics of the bags analyzed

The characteristics of the bags analyzed are presented in Table 1.

3.4.2 Characteristics of the bottles analyzed

The PET analyzed has an intrinsic viscosity between 0.72-0.84, optimal for a bottle grade resin. Also, the color of PET and glass bottles is clear.

In any case it was considered the labels and lids of containers.

The reference flow of these materials for packaging is show below:

3.5 Considerations about the Bags Case Study

The cotton composition was found to be of 94% cellulose, 1.3% protein (%N x 6.25), and 1.2% peptic substances. Therefore for the exergy content of cotton, the relation of NCV to chemical exergy of cellulose was considered.

The Pro degrading additive was modeled as stearic acid and small amount of Manganese (Mn) metal to represent the presence of manganese stearate. The bag contains 97% PE, 3% additive. There are no extensive data available on production of stearic acid and on Manganese stearate. Fertilizers considered are urea, K_2O_5 and P_4O_{10}.

3.6 Considerations about the Bottles Case Study

The raw materials in the PET production are Terephthalic Acid and Ethylenglycol. The first compound is obtained from the crude oil refining and the second compound from natural gas processing in a cryogenic plant.

The aluminum is mainly composed of bauxite mineral which in turn contains other minerals such as gibbsite ($Al_2O_3.3H_2O$), boehmite γ-$Al_2O_3.H_2O$) and impurities among which are kaolinite ($Al_2Si_2O5(OH)4$), hematite (Fe_2) and goethite (α-FeO(OH)), although these impurities are negligible.

The raw materials in the glass production are SiO_2, Na_2CO_3, $CaCO_3$, and feldspar.

4. RESULTS

Taking Mexico's consumption of plastic bags and bottles as a case study, we have dimensioned the pollution problem, the energy degradation and the hydrocarbons waste.

In Mexico in 2011 the consumption of high and low density Polyethylene is of approximately 600,000 ton/year. Considering that 900 bags are equivalent to 5.04 Kg, this is equivalent to 107 100 million bags/year. The gross benefit for producers is about 2 US$/kg. It means it is a good business. From the point of view of nonrenewable resources waste, in Mexico an equivalent of 8.25 million US$/day (considering a crude oil international price of 84 US$/barrel) is crapped.

For the case of the 1-liter PET bottles, Mexico has produced 9,760 million of bottles/year in 2011. In this case the gross margin benefit is more or less 0.050$US/bottle. Only 10% of these bottles are really effectively recycled. As a consequence there is an important world surplus of raw material, i.e. Poly (ethylene Terephtalate). This implies that recycling business needs a special strategy for long term substitution. The number 9,760 million bottles crapped are equivalent to 3,579 million US$/year.

Based on the advantages of exergy analysis, especially for resource use, we investigate exergy as a tool in assessing the industrial reutilization or recycling of waste plastics as those related in this paper. It is more or less obvious that recycling or co-generation of electric and heat through incineration may contribute to sustainability comparing it with disposing them into the environment.

Starting with nonrenewable resources the overall plastics production coming from oil or natural gas including all the chain production, the Cumulative Exergy Consumption *(CExC)* can be calculated [13].

4.1 PE bags VS. Alternative Materials Bags

Table 2 summarizes the input and output flows of exergy during the selected production processes for the PE and the possible substitute bags. In such way, it has been possible to identify the life cycle steps with the main exergy losses due to the process irreversibility and to the environmental pollutant releases.

Low Density Polyethylene was produced by a high pressure process autoclave reactor [18]. This gives a total of exergy losses of 244.005MJ/f.u. for the total Polyethylene production. Considering the characteristics of composition of ox degradable bags (97% LDPE and 3% additive), the total exergy losses for polyethylene degradable bags are 259.6 MJ/f.u. As for bags made of unbleached Kraft paper, the total exergy losses for this process are 3492.576 MJ/f.u. In the case of reusable bags, the life cycle of Polypropylene, manufactured by a bulk slurry phase loop reactor process, presents a total of 2.018 MJ/f.u exergy losses. On the other hand, we found a total of 292.73 MJ/f.u of exergy losses for the cotton bags.

Total exergy outputs do not take into account exergy of emissions since they are considered as losses, therefore emissions are not considered for the calculations of irreversibility related to the processes. Although other emissions to air, water and soil are not included. CO, methane, SO_2 and mostly CO_2 emissions are the main substances related to pollution.

Table 2. Reference flow of packaging materials

Material	Reference flow (ton)
PET	1
Aluminum	2.319
Glass	14.84

Table 3 illustrates the results of the exergy analysis, which represents the exergy destruction by process irreversibility associated with each production stage on the life cycle of the examined materials. As can be seen from the columns, the production of unbleached Kraft paper destroys the highest quantity of exergy, which represents a much more relevant input than PE bags from the point of view of exergy consumption. Table 4 shows the emissions embedded within the life cycle of the alternatives analyzed.

Table 3. Exergy flows of the different alternatives for shopping bags all in MJ/f.u

	Disposable			Reusable	
	LDPE (film grade)	**LDPE+Pro degrading**	**Unbleached kraft paper**	**PP fiber**	**Cotton (Unbleached)**
Exergy Inputs exergy	933.733	952.33	4054.086	19.0984	294.491
Outputs irreversibility	689.728	692.7089	561.51	17.08	1.757
Emissions	236.527	251.5312	3484.78	1.887	292.623
Total exergy	7.478	8.0899	7.796	0.1314	0.111
losses	**244.005**	**259.6211**	**3492.576**	**2.0184**	**292.734**

Table 4. CO_2 emissions for the alternatives for bag manufacturing

Material	kg CO2/f.u.	MJ/f.u.
LDPE (film grade)	16.559235	7.478
LDPE + Pro degrading	17.9142224	8.0899
Unbleached Kraft paper	17.2634122	7.796
PP fiber	0.29097131	0.1314
Cotton (Unbleached)	0.24579768	0.111

The production of low density polyethylene bags with an ox degrading additive has the highest exergy embedded on emissions. From Table 4, it is clear that the production of 1 polypropylene bag, which is equivalent to the use of 900 PE bags, involves the lowest losses of exergy. These data suggest that the employment of alternative materials instead of Polyethylene for the production of retail shopping bags is not always the best choice, even if the material inputs are lower between the functional units like it is the case of cotton reusable bags.

In some countries at the end of its first use, PE and PET can be simply disposed in the environment without any conversion, increasing the pollution and wasting energy. Disposal of plastic is not an option in Europe and US. The European legalization forbidden disposal of the plastic materials. All materials with energy value above 6.000 MJ/ton must be reused or at least energetically exploited.

Alternatively, they can be converted through incineration or through land filling with methane capture for heat and/or electricity production. They also can be recycled resulting in the same plastics if it is possible.

Of course recycling systematically generates the highest output value. In the case of polyethylene it is only possible to recycle 60% in the best case.

4.2 PET Bottles vs. Alternative Bottle Materials

We have performed the calculations for PET manufacturing process from Terephthalic acid and Ethylen glycol. We consider the input-product coefficient of PEP (Process Economic Program).

Fig. 3 shows a simplified flow diagram of the total steps for producing PET bottles.

4.2.1 Glass bottles

For glass bottles considers the same variables, i.e. exergy and energy balances including of course total irreversibility and GHE. The functional unit is also an equivalent of 26,000 one liter bottles. Total irreversibility of glass bottles production is 93,581 MJ/fu.

4.2.2 Aluminum cans

The same variables are considered: Exergy calculations to obtain the irreversibility in each production step. The functional unit is also 26,000 bottles of one liter.

The results of glass bottles show that the total irreversibility of aluminum cans production is 151,831MJ/fu.

It is important to remember that another interesting alternative to substitute PET bottles produced from oil and gas as raw materials is to use recycled PET bottles. The same treatment is applied for glass and aluminum bottles, i.e. recycling processes for each one of them.

Once calculated the total irreversibility of the materials in primary and secondary production, we present in summary the following Table 5.

Table 5. Irreversibility in bottle materials

	Irreversibility (MJ/fu)	
Material	Primary production	Recycling
PET	146,347	13,037
Glass	93,581	53,688
Aluminum	151,831	8,416

Fig. 4 shows the irreversibility for PET, glass and aluminum bottles considering its primary and secondary production; it is possible to consider that the recycling aluminum cans minimize the irreversibility better than PET and glass bottles. However, the irreversibility in the recycling PET bottles is important with a reduction of 136,334 MJ/fu.

4.3 Multicriteria Decision Making

In the last step of the methodology that has been introduced previously, we use the PROMÉTHÉE- GAIA multicriteria decision aid methodology.

In order to make decisions about the substitute materials or the recycling process, the different alternatives have to be evaluated through different criteria.

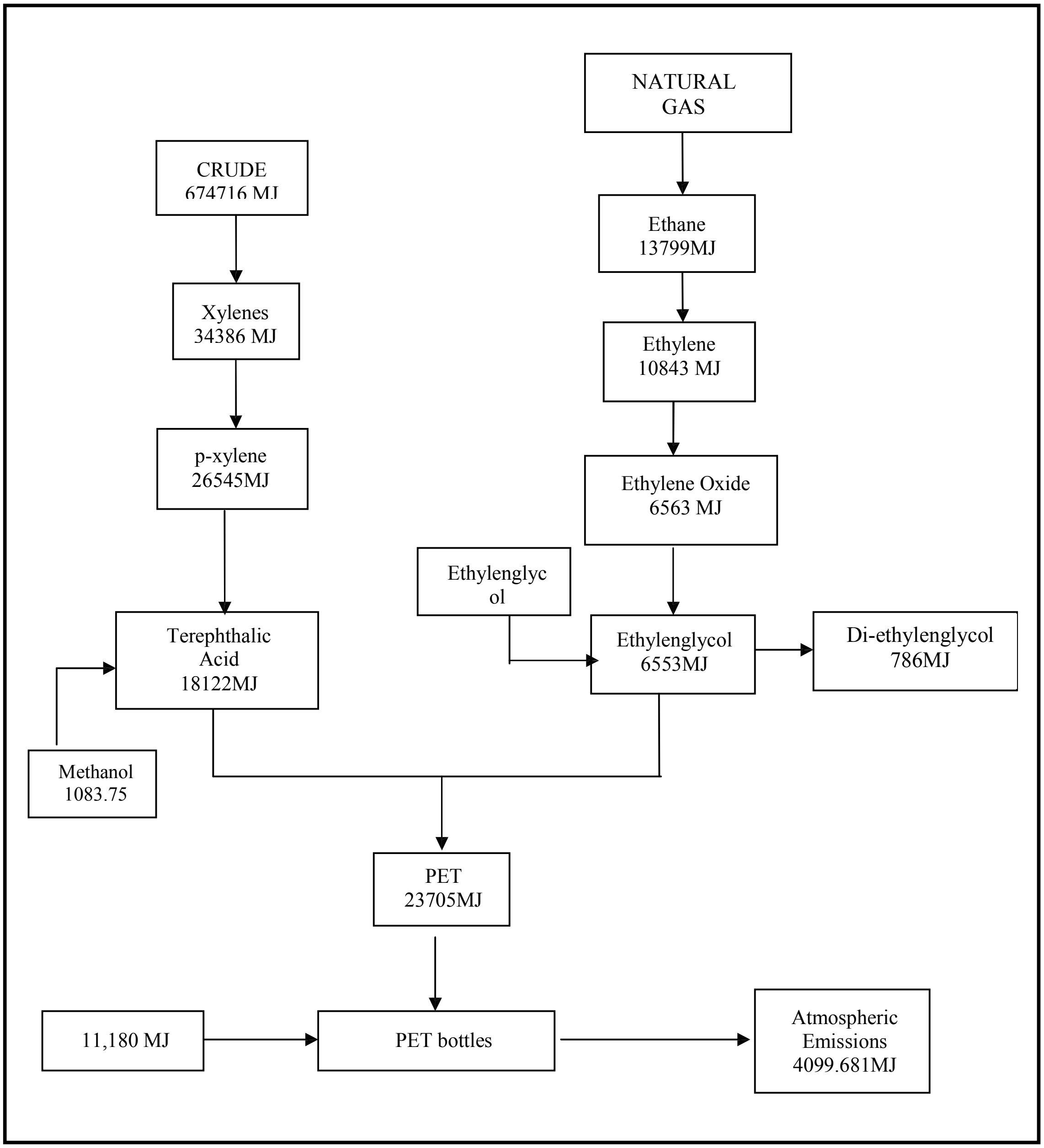


Fig. 3. Flow diagram to produce PET bottles and exergy balance of production

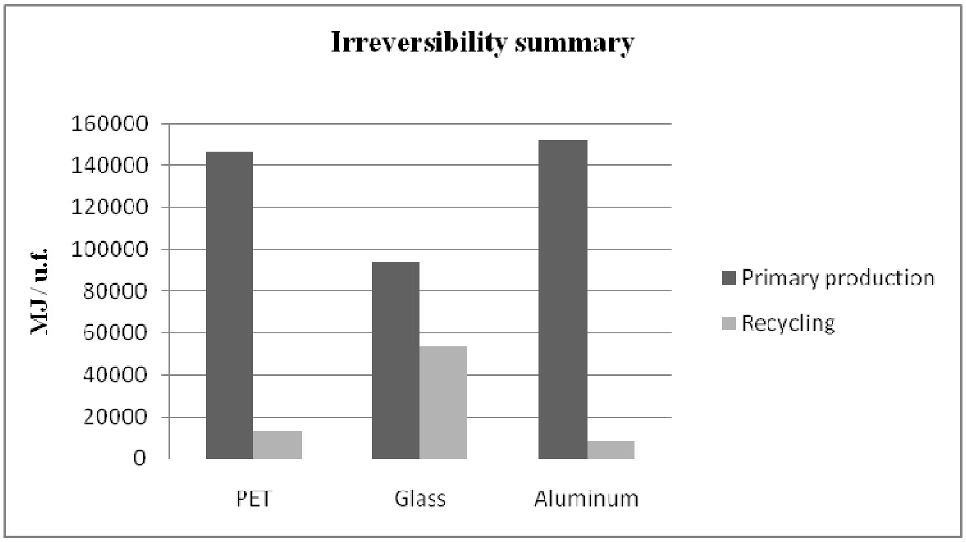


Fig. 4. Irreversibility summaries

4.3.1 Multicriteria results for the bags case study

For this case the following criteria are considered:

- Minimize process irreversibility in the whole life cycle of each alternative using the exergy analysis.
- Minimize the use of nonrenewable resources used in their life cycle.
- Minimize the real quantity of energy in each one of the processes involved in their life cycle.
- Maximize the end product value [total cost of production plus 25% on Return on Investment].
- Minimize GHG emissions in the whole life cycle.

The evaluations of the alternatives for each criterion have been calculated according to our methodology. The multicriteria analysis is done using the *Visual PROMETHEE* software, as follows.

The evaluations and preference parameters are shown in Fig. 5. As the criteria are quantitative the V-shape and Gaussian preference functions have been used and the corresponding thresholds have been determined based on the distribution of the evaluations. The Irreversibility and GHG criteria receive twice the weight of the other criteria as they are considered to be the most important ones.

Fig. 6 shows the PROMETHEE partial ranking resulting from the analysis: The polypropylene (PP) and unbleached cotton (Cotton) are clearly at the top of the ranking and should thus be the most preferred solutions. At the bottom of the ranking we find the low density polyethylene (LD PE) followed by two incomparable choices (Biodegr PE and Kraft). According to PROMETHEE, polypropylene is thus the best alternative.

The GAIA visual analysis can be used to better understand why this ranking is obtained. Both alternatives (points) and criteria (axes) are represented:

- The orientation of the criteria axes indicates which criteria are conflicting with each other: In this case Value is conflicting with Irreversibility (opposite directions) which means that the best alternatives for Value are also the worst for Irreversibility. In between and orthogonal to those two criteria axes we find a group of three criteria that are more in agreement with each other (Energy, Mass balance and GHG).
- The position of the alternatives with respect to the criteria axes indicates what their specific features are. For instance Kraft is very good on Value but very weak on Irreversibility, while it is the opposite for PP.
- The red decision axis is a representation of the weighing of the criteria. It indicates

where the best solutions should be located according to the priorities expresses by the weights. It is oriented towards the PP solution which is indeed at the top of the PROMETHEE ranking.

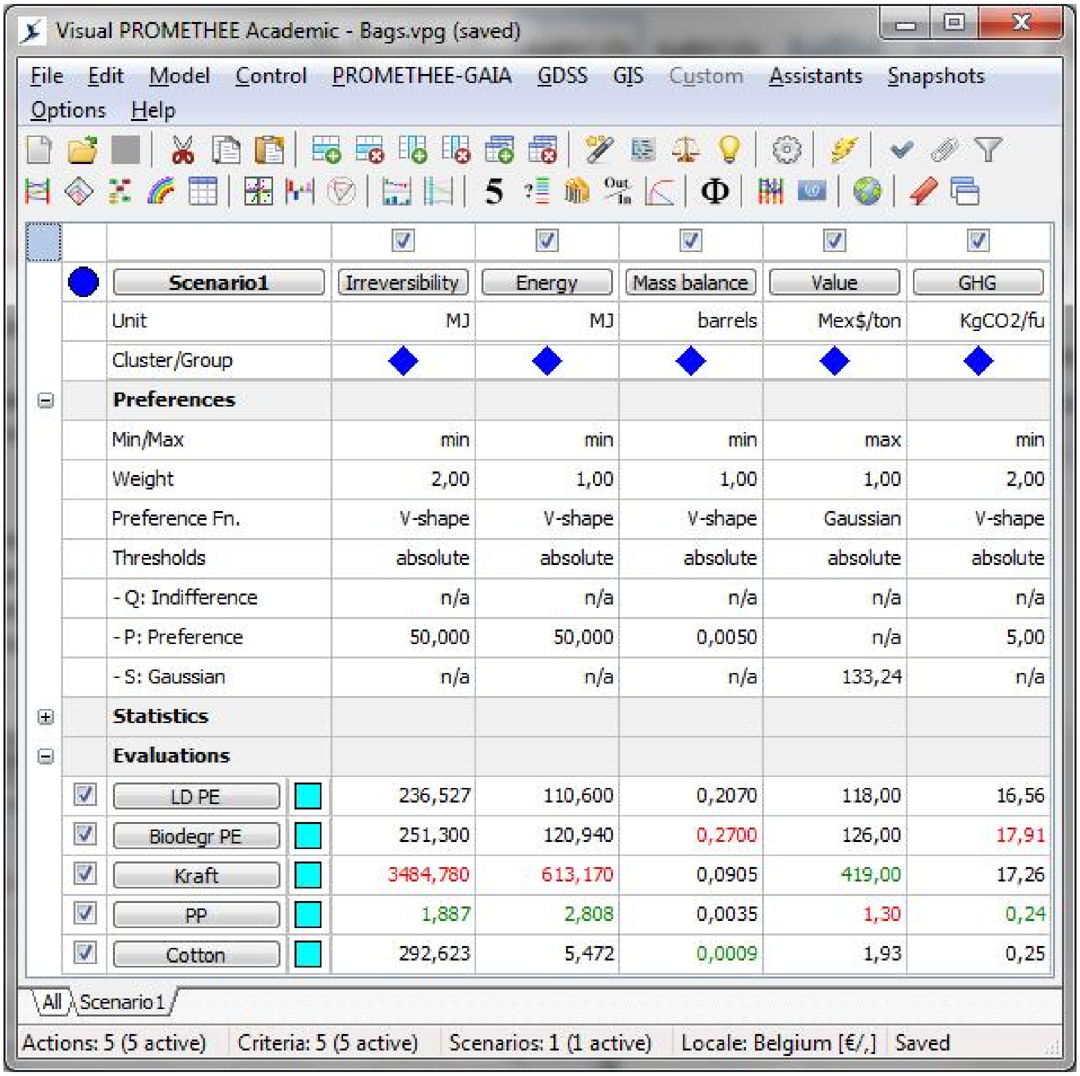
4.3.2 Multicriteria results for the bottles case study

The criteria used in this case are the following:

a) Total Irreversibility (MJ/fu)
b) Energy consumption (MJ/fu) to be interpreted also as measure of natural resources.
c) GHG emissions (Ton. CO_2 eq)
d) Profit ($/fu)

The alternatives studied are divided into two groups: Bottles made from primary materials (virgin) and secondary materials (recycled) for each of the three types of packaging materials considered.

Fig. 7 shows the resulting multicriteria table that has been analyzed with Visual PROMETHEE. As in the previous case, V-shape preference functions have been used and a larger weight has been allocated to the Irreversibility and GHG criteria.



		☑	☑	☑	☑	☑
●	Scenario1	Irreversibility	Energy	Mass balance	Value	GHG
	Unit	MJ	MJ	barrels	Mex$/ton	KgCO2/fu
	Cluster/Group	◆	◆	◆	◆	◆
⊟	**Preferences**					
	Min/Max	min	min	min	max	min
	Weight	2,00	1,00	1,00	1,00	2,00
	Preference Fn.	V-shape	V-shape	V-shape	Gaussian	V-shape
	Thresholds	absolute	absolute	absolute	absolute	absolute
	- Q: Indifference	n/a	n/a	n/a	n/a	n/a
	- P: Preference	50,000	50,000	0,0050	n/a	5,00
	- S: Gaussian	n/a	n/a	n/a	133,24	n/a
⊞	**Statistics**					
⊟	**Evaluations**					
☑	LD PE 🟦	236,527	110,600	0,2070	118,00	16,56
☑	Biodegr PE 🟦	251,300	120,940	0,2700	126,00	17,91
☑	Kraft 🟦	3484,780	613,170	0,0905	419,00	17,26
☑	PP 🟦	1,887	2,808	0,0035	1,30	0,24
☑	Cotton 🟦	292,623	5,472	0,0009	1,93	0,25

Actions: 5 (5 active) | Criteria: 5 (5 active) | Scenarios: 1 (1 active) | Locale: Belgium [€/,] | Saved

Fig. 5. Multicriteria table – Bags

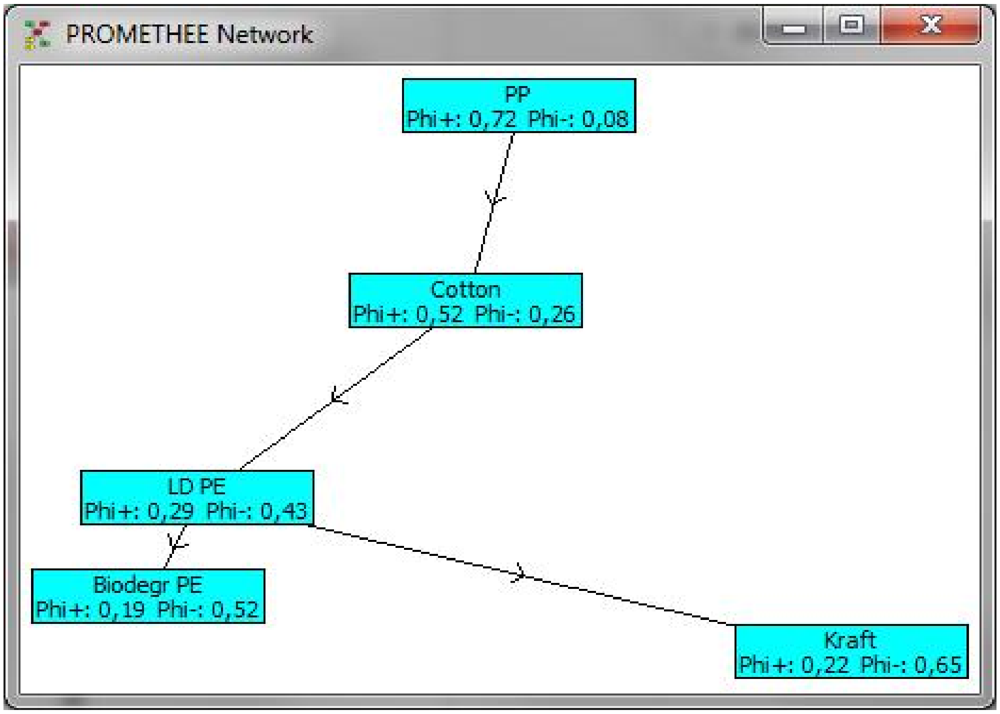


Fig. 6. PROMETHEE ranking – Bags

There is no incomparability in the PROMETHEE ranking for this set of data. Fig. 8 shows the complete PROMETHEE ranking:

- At the top of the ranking are two recycled solutions (displayed in green): Alu recycl and PET recycle.
- The four other solutions are clearly worse. They include the three primary solutions (displayed in red) as well as Glass recycl.
- The two glass solutions (primary and recycled) are at the bottom of the ranking and thus amongst the worst choices.

It is worth noting that recycling of aluminum and of PET do reach a higher level than their respective primary materials to meet the goal of sustainability, while glass recycling is not improving much over the primary materials.

The GAIA analysis brings the following comments:

- There is a strong conflict between Profit on one hand and Energy and Irreversibility on the other hand.
- The recycled solutions (displayed in green) are located on the rights side of the GAIA plane while the primary solutions (in red) are located to the left: The recycled solutions are indeed better on the Energy and Irreversibility criteria, while the primary solutions are better for Profit. Two clusters of relatively different solutions are thus observed.
- The two glass solutions (primary and recycled) are the worst solution for GHG emissions. Hence their low positions in the PROMETHEE ranking.

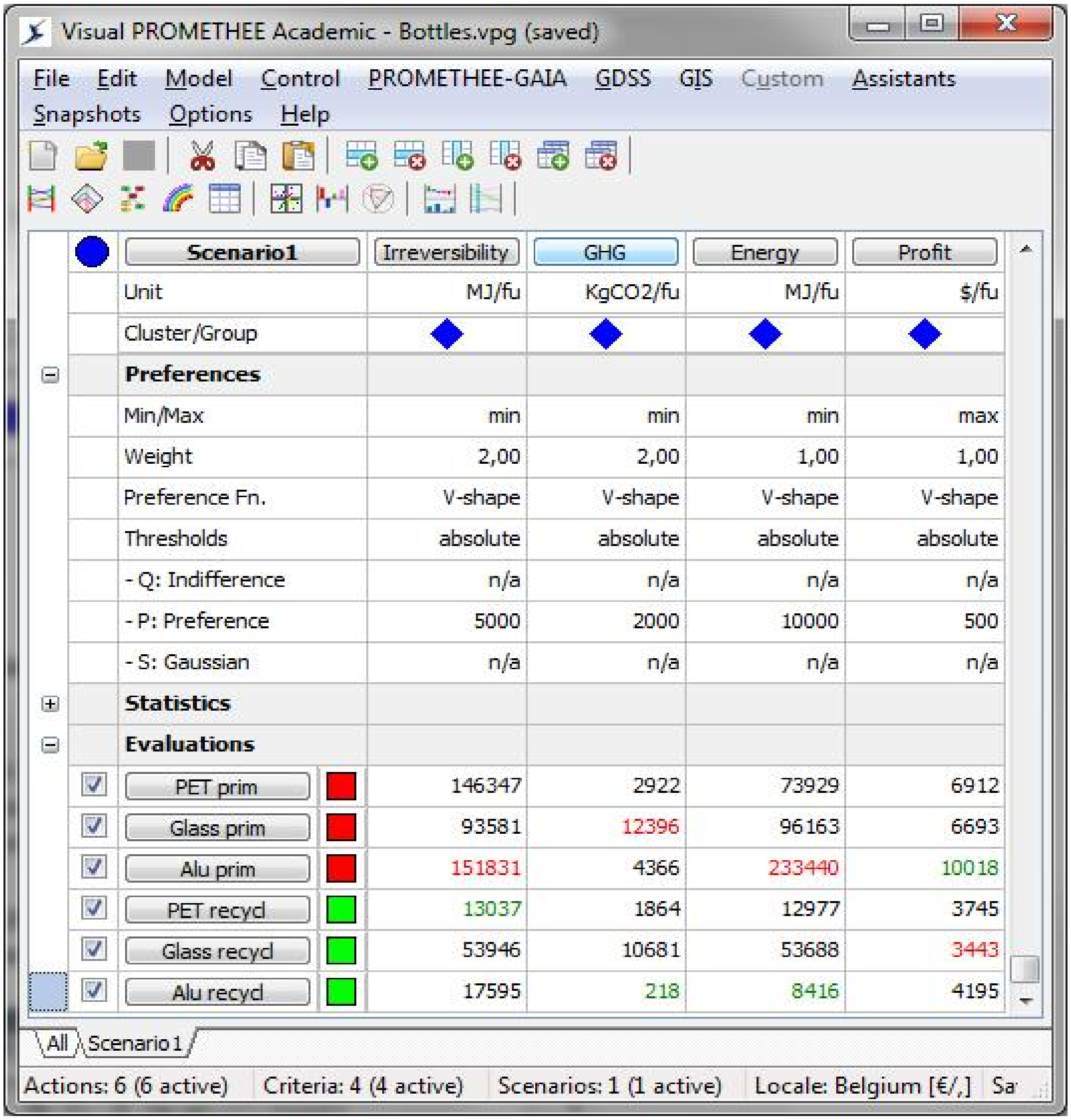
To summarize:

- In the primary materials the aluminum cans compete to a lesser extent due to an energy- intensive in the electrolysis process. However, in the recycling process the aluminum is the best material according to the criteria used.
- The recycled PET is also a good alternative at the second position in the PROMETHEE ranking, not far from recycled aluminum.
- In the recycling process the glass bottles are in last position with a negative preference flow, so there is less competition.

On the basis of the results of the PROMETHEE analysis, it is possible to set a combination of different substitution strategies that should be analyzed from the point of view of supply of raw materials. Indeed it is not realistic to switch immediately and completely from the current situation to a substitute solution. It is thus necessary to define a long-term change strategy.

For instance, we could consider the following substitution strategy: The growth rate of PET (currently 10% per year in Mexico) could be gradually reduced from 2016 to 2035. On the basis of a 10% relative yearly reduction, the amount that would be replaced by 2035 is 406,692 Ton/year, of which one half could be replaced by secondary aluminum and the other half by secondary PET. In other words, 5% of growth rate of primary PET will be replaced by secondary aluminum and the other 5% by secondary PET.

The impact of this strategy on Irreversibility, Energy and CO2 emissions is detailed in Table 6 below:



	●	Scenario1	Irreversibility	GHG	Energy	Profit
		Unit	MJ/fu	KgCO2/fu	MJ/fu	$/fu
		Cluster/Group	◆	◆	◆	◆
⊟		**Preferences**				
		Min/Max	min	min	min	max
		Weight	2,00	2,00	1,00	1,00
		Preference Fn.	V-shape	V-shape	V-shape	V-shape
		Thresholds	absolute	absolute	absolute	absolute
		- Q: Indifference	n/a	n/a	n/a	n/a
		- P: Preference	5000	2000	10000	500
		- S: Gaussian	n/a	n/a	n/a	n/a
⊞		**Statistics**				
⊟		**Evaluations**				
	☑	PET prim 🟥	146347	2922	73929	6912
	☑	Glass prim 🟥	93581	12396	96163	6693
	☑	Alu prim 🟥	151831	4366	233440	10018
	☑	PET recycl 🟩	13037	1864	12977	3745
	☑	Glass recycl 🟩	53946	10681	53688	3443
	☑	Alu recycl 🟩	17595	218	8416	4195

Actions: 6 (6 active) Criteria: 4 (4 active) Scenarios: 1 (1 active) Locale: Belgium [€/,] Sa

Fig. 7. Multicriteria table – Bottles

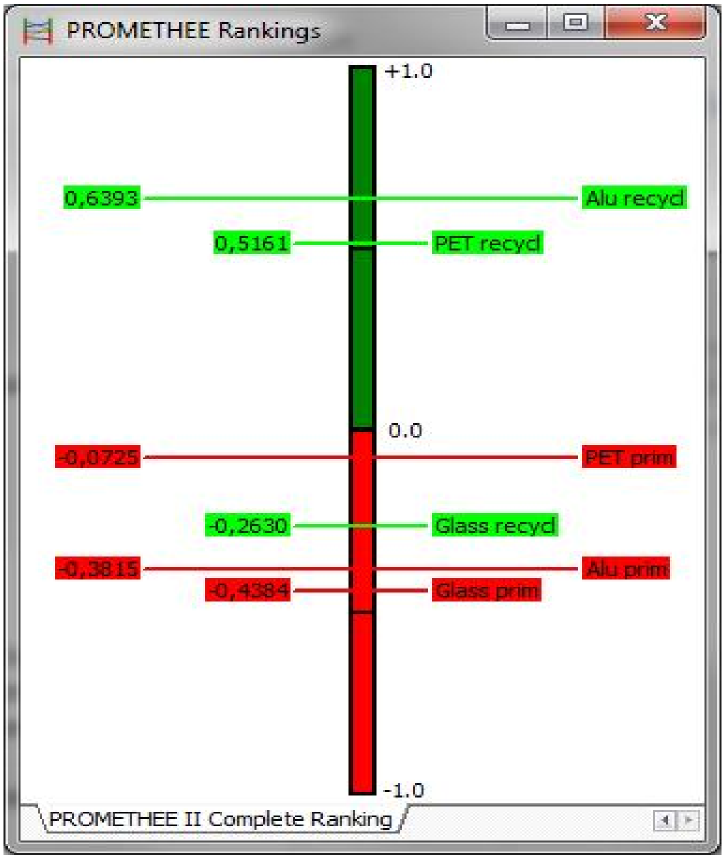


Fig. 8. PROMETHEE ranking – Bottles

Table 6. Substitution strategy

Yr	Irreversibility (Million barrels oil equiv.)		Irreversibility, energy and ton CO_2eq. Energy (Million barrels oil equiv.)		Millions of tons CO_2eq	
	No Re	With replace	No Re	With replace	No Re	With replace
21	28.9	26.20	14.6	13.31	6.5	5.94
26	46.5	42.15	23.5	21.39	10.5	9.59
30	68.2	61.82	34.4	31.31	15.4	14.07
35	109.8	99.52	55.4	50.43	24.8	22.66

No Re=Without Replacement

5. CONCLUSION

Exergy aspects of the substitution problem between plastic bottles and bags for other materials more exergy adequate are presented in this study.

MCDA is useful for assessing the different alternatives as different and often conflicting criteria have to be taken into account in the context of sustainable development.

In this context, exergy analysis is a very useful tool, which can be successfully used in the performance evaluation of waste materials with a very short life cycle.

As another conclusion, the authors expect that the analyses reported here will provide the researchers with knowledge about how effective and efficient it is to use renewable resources. This knowledge is also needed for identifying energy efficiency and/or energy conservation opportunities, as well as for establishing adequate energy and exergy management strategies for those items or also for other types of materials or services.

It is not possible to substitute polypropylene bags to polyethylene bags without an agreement between government, enterprises and consumers.

Some other concluding remarks which can be extracted from this study are the following:

1) From PE material balance, we have 0.207 crude oil barrels/PE bags (f.u.), equivalent to 17.46 US$/f.u., taking an export price of crude oil of 84.4US$/bl.
2) From the energy balance, we obtained 110.63 MJ/PE bags (f.u.); that quantity and considering a crude oil heat value of 6263.6 MJ/ bl, equals to 0.0176 barrels of crude oil per f.u. or 3.5 bl/ton PE.
3) Considering 160 billion bags consumed/year, it is equivalent to dispose into the landfill 4,754,261 US$/day.
4) The production of unbleached Kraft paper destroy the highest quantity of exergy, which represents a much more relevant input than PE bags from the view point of exergy consumption.
5) The production of polyethylene bags with an ox degrading additive has the highest Exergy embedded on emissions.
6) It is clear that the production of 1 polypropylene bag that is equivalent to the use of 900 PE bags, involves the lowest losses of exergy.
7) These data suggest that the employment of alternative materials instead of polyethylene for the production of retail shopping bags is not always the best choice.
8) From PET material balance, it is known a requirement of 113 crude oil barrels/ PET Bottles (f.u.), equivalent to 9,537 US$/f.u., taking an export price of crude oil of 84.4 US/bl.
9) From PET energy balance, we obtained 85, 110 MJ/PET bottles (f.u.); equivalent to 14.28 crude oil barrels/ PET bottles (f.u.).
10) The irreversibility in the primary production of PET bottles corresponds in 41% to the refining of crude oil for the production of Xylenes, which makes it the more irreversible stage. In the production of glass bottles highest irreversibility for the melting process contributing in 50%; while in the manufacture of aluminum cans, the electrolysis process has a contribution of 60% on the same criteria.
11) In the case primary material which produce more air emissions is glass (7,184 MJ/u.f.), followed by aluminum cans (4,235 MJ/u.f.) and PET bottles (4,100 MJ/u.f.).
12) According to the multicriteria results, it is feasible the substitution of primary PET bottles for secondary aluminum and secondary PET.
13) Through the suggested substitution strategy, the irreversibility, energy and CO_2 emissions, could have a significant reduction.

ACKNOWLEDGEMENTS

This research was made possible thanks to a grant from both CONACYT (Mexico) and FNRS (Belgium). The authors are very thankful for this.

COMPETING INTERESTS

Authors declare that there are no competing interests.

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