	Green Engineering (458.701)	Final (June 13, 2011)

[1] (70 points) At the supermarket checkstand, customers are asked to choose whether their purchases should be placed in unbleached paper grocery sacks or in polyethylene grocery sacks. Some consumers make their choice based on the perception of the relative environmental impacts of these two products. This problem will quantitatively examine life cycle inventory data on the energy use and air emissions for these two products. Life cycle inventories for paper and polyethylene grocery sacks have resulted in the data given below, and these data will be used in comparing the two products. Assume that the functional unit (FU) to be used in this comparison is a defined volume of groceries to be transported and number of repetitive use, and that based on this functional unit, 3 plastic sacks are equivalent to 2 paper sacks.

Air emissions and energy requirements for paper and polyethylene grocery sacks.

Life cycle Stages	Paper sack air emissions (oz/sack)	Plastic sack air emissions (oz/sack)	Paper sack air energy req'd (Btu/sack)	Plastic sack air energy req'd (Btu/sack)
Materials manufacture plus product manufacture plus product use	0.06	0.015	900	500
Raw materials acquisition plus product disposal	0.05	0.005	700	200

Note: These data are based on past practices and may not be current.

(a) (20 points) Using the data in the Table, determine the amount of energy required and the quantity of air pollutants released per the functional unit. Both the air emissions and the energy requirements per the functional unit are functions of the recycle rate, so perform your calculations at three recycle rates: 0%, 50% and 100% recycled. Note that a 50% recycle rate indicates that half of the sacks are disposed of and the other half are recycled after the product use stage of their life cycle. Assume no emission or energy for recycled sacks.

(b) (20 points) Plot the energy requirements calculated in Part (a) as a function of the recycle rate for both sacks per the functional unit. Do the same for the air emissions. Compare the energy requirements and air emissions of the sacks at different recycle rates.

(c) (10 points) Discuss the relative environmental impacts of the two products. Do the results allow for a comprehensive comparison?

(d) (10 points) The material and energy requirements of the plastic sacks are primarily derived from petroleum, a non-renewable resource. In contrast, the paper sacks rely on petroleum to only a limited extent and only for generating a small fraction of the manufacturing and transportation energy requirements. Compare the amount of petroleum required for the manufacture of two polyethylene sacks to the amount of energy necessary to provide 10% of the energy required in the manufacture of one paper sack. Assume 0% recycle and that 1.2 lb of petroleum is required to manufacture 1 lb of polyethylene. The higher heating value of petroleum is 20,000 BTU/lb.

(e) (10 points) Does the uncertainty in the equivalency between paper and plastic sacks affect any of your conclusions?

[2] (30 points) The amine-phosgene route for the production of toluene diisocyanate (TDI) in which the reaction of phosgene with toluenediamine in a chlorobenzene solvent. Approximate stoichiometric data, based on the patent data, are given in the table below.

Amine-phosgene route: $C_6H_3(CH_3)(NH_2)_2 + 2\ COCl_2 \rightarrow C_6H_3(CH_3)(-N=C=O)_2 + 4\ HCl$

compound	lb per lb TDI	cost ($/lb)	PEL (mg/m^3)	Overall inhalation toxicity factor	overall oral toxicity factor
Amine-phosgene route					
toluene diamine	-0.76	0.576	0.1	NA	NA
chlorobenzene	-0.01	0.550	350	100	100
hydrochloric acid	0.40	0.027	7	100	100
phosgene	-1.26	0.610	0.4	NA	NA
TDI	1.00	1.840	0.14	10,000	100

The TDI manufacturing facility produces 90 million pounds per year of TDI. The process is typically run at 90% selectivity and raw material that is not converted into product is disposed of at the cost of following wastetreatment.

Wastes generated per pound of TDI

- 6.0 lbs of gasesous effluent to be treated
- 9.0 lb of water to be treated
- 0.45 lb of organic solid waste to be incinerated

A process improvement allows the process to be run at 98% selectivity, allowing the facility to produce 98 million pounds per year of product.

(a) (10 points) Is the waste treatement cost per raw material costs reasonable? What is the dominant cost among the waste treatment?

(b) (10 points) What is the next revenue of the facility (product sales - raw material cost - waste disposal cost) before and after the change?

(c) (10 points) How much of the increased net revenue is due to increased sales of product and how much is due to decreased waste disposal cost?

SOLUTION

[1] (a) (20 points)

0% recycle rate:

2 paper sacks: air releases = 2 x (0.06+0.05) = 0.22 oz/FU
energy = 2 x (900+700) = 3200 Btu/FU

3 plastic sacks: air releases = 3 x (0.015+0.005) = 0.06 oz/FU
energy = 3 x (500+200) = 2100 Btu/FU

50% recycle rate:

2 paper sacks: air releases = 0.5 x 2 x (0.06+0.05) = 0.11 oz/FU
energy = 0.5 x 2 x (900+700) = 1600 Btu/FU

3 plastic sacks: air releases = 0.5 x 3 x (0.015+0.005) = 0.03 oz/FU
energy = 0.5 x 3 x (500+200) = 1050 Btu/FU

100% recycle rate: (assume no emission or energy for recycled sacks)

2 paper sacks: air releases = 0 x 2 x (0.06+0.05) = 0 oz/FU
energy = 0 x 2 x (900+700) = 0 Btu/FU

3 plastic sacks: air releases = 0 x 3 x (0.015+0.005) = 0 oz/FU
energy = 0 x 3 x (500+200) = 0 Btu/FU

(b) (20 points)

The life-cycle energy consumption and air emissions of plastic sacks are about 66% and 27%, respectively, of those for paper sacks on an equal functional unit basis. Only 100% recycle are the life cycle inventories equal for these choices of grocery sacks.

(c) (10 points) Paper sacks probably have a higher environmental impact compared to plastic sacks. The air emissions are significantly higher and the energy consumption is slightly more. However, this conclusion is uncertain because with the information given, it is impossible to determine the specific chemical releases and therefore the specific characterization of impacts. Specific impacts of energy consumption will only be known if the fuel type is identified for each sack. The composition of the air releases for each sack is unknown. One type of sack might have significant toxic emissions compared to the other sack, which in many cases would outweigh the differences in mass emission rate.

(d) (10 points) The material and energy requirements of the plastic sacks are primarily derived from petroleum, a non-renewable resource. In contrast, the paper sacks rely on petroleum to only a limited extent and only for generating a small fraction of the manufacturing and transportation energy requirements. Compare the amount of petroleum required for the manufacture of two polyethylene sacks to the amount of energy necessary to provide 10% of the energy required in the manufacture of one paper sack. Assume 0% recycle and that 1.2 lb of petroleum is required to manufacture 1 lb of polyethylene. The higher heating value of petroleum is 20,000 BTU/lb.

Petroleum consumption comparison: assume 0% recycle rate
Paper sack: 10% of energy needed to manufacture one paper sack is fossil fuel based
= (0.1) (900+700) Btu/paper sack = 160 Btu/paper sack
Petroleum needed = 160 Btu/paper sack x (1/20,000) ib petroleum/Btu = 8×10^{-3} lb petroleum

2 Plastic sacks: 1.2 lb petroleum needed for energy to creat 1 lb polyethylene for sacks
Petroleum needed = 2x(500+200)/20,000 = 7×10^{-2} lb petroleum

Total mass of petroleum for 2 sacks
= (7×10^{-2} lb petroleum)(1 lb polyethyene/1.2 ib petroleum) = 0.06 lb petroleum

(e) (10 points) Large uncertainty in the functional unit equivalency between paper and plastic sacks will change the conditions of this study. For example, if instead of 2 plastic sacks being equivalent to 1 paper sack, 4 plastic sacks are actually needed, then the air emissions and energy releases of plastic sacks would be the dominant compared to paper.

[2] (a) (10 points)
Waste disposal operating costs = 6.0 x 0.00015 + 9.0 x 0.000074 + 0.45 x 0.8 = 0.3616 $/lb TDI
Waste disposal operating costs/raw materials cost = (0.3616/1.21) = 0.3
TOO MUCH. NOT REASONABLE!!
Treatment of organic solid waste to be incinerated is dominant.

(b) (10 points)
Cost of raw materials = 0.76 x 0.576 + 0.01 x 0.550 + 1.26 x 0.610 = $1.21/lb TDI
Original Process (90% selectivity): net revenue = 1.84 - (1.0/0.9)(1.21) - (0.11)(0.36) = $0.456/ib TDI
Improved Process (98% selectivity): net revenue = 1.84 - (1.0/0.98)(1.21) - (0.02)(0.36) = $0.550/lb TDI

(c) (10 points) The net change in revenue from this process improvement is due to a reduction in raw material costs of $0.11 /lb TDI and due to a reduction in waste treatment cost of $0.0324/lb TDI. raw material costs are dominant factor for enhancing revenue.