The object of this column is to enhance our readers' collection of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and which elucidate difficult concepts. Please submit them to Professors James O. Wilkes and Mark A. Burns, Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

ENVIRONMENTAL IMPACT OF PAPER AND PLASTIC GROCERY SACKS

A Mass Balance Problem with Multiple Recycle Loops

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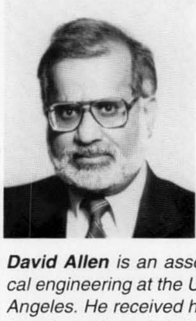
Environmental issues are becoming increasingly important in the design of chemical processes and chemical products. Incorporating these issues into an already crowded chemical engineering curriculum is a challenge. One way to address this challenge is to develop entire courses dedicated to environmental issues. An alternative strategy is to develop homework and design problems that can be used in existing chemical engineering courses, illustrating both fundamental engineering principles and environmental issues

For the past year we have been developing such problems for the chemical engineering curriculum. One of the problems developed for the mass and energy balances course is given below. The problem illustrates the concept of recycle, a topic normally covered in a mass and energy balance course, and the problem exposes students to the issue of product life-cycle analysis. Specifically, the problem compares paper and plastic grocery sacks based on energy requirements and environmental impacts. The problem is divided into five sections:

1. Background material
2. A problem statement
3. Open-ended questions for discussion
4. A solution
5. References and suggestions for further reading

Sections 1-3 and 5 can be distributed to the students as a homework assignment. The problem solution takes between two and three hours for most students.



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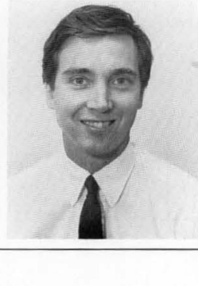

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BACKGROUND

At the supermarket checkout stand, consumers are asked to choose whether their purchases should be placed in unbleached paper grocery sacks or in polyethylene grocery bags. Many consumers make their choice based on their perception of the relative environmental impacts of these two products.

The analysis framework for this problem will be the mass flow diagram shown in Figure 1. For the problem, we can simplify Figure 1 considerably. First, consider the recycle loops. Almost all recycled grocery sacks are returned to the raw material formulation stage, so we can ignore the product recycle and remanufacture loops. This simplification leads to the mass flow diagram shown in Figure 2 (and Figure 3).

These two figures define our life-cycle analysis framework for comparing paper and plastic grocery sacks.

In the figures we have listed the air emissions generated per unit of production for both plastic and paper grocery sacks. Before a quantitative comparison between the two products can be made, however, we must consider how the products are used. Although both are designed to have a capacity of 1/6 barrel, fewer groceries are generally placed in plastic sacks than in paper sacks, even if the practice of double-bagging (one sack inside the other), used in some stores, is taken into account. There is no general agreement on the number of plastic grocery sacks needed to hold the volume of groceries usually held by a paper sack. Reported values range from 1.2 to 3. In this problem we will use a value of 2.0 plastic grocery sacks required to replace a paper grocery sack.

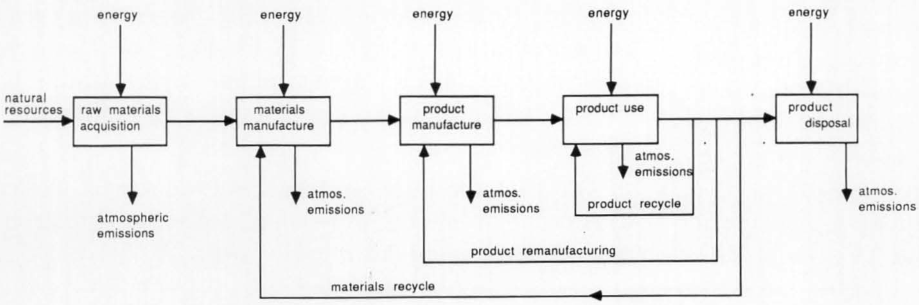

Figure 1. The life cycle for manufactured goods: an analysis template

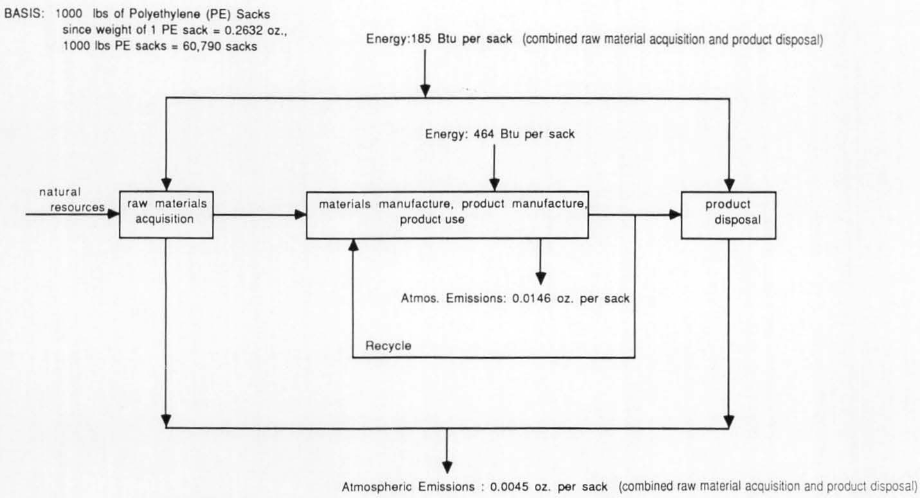

Figure 2. The life cycle for manufactured goods: polyethylene (PE) grocery sacks (Source: Franklin Associates, Ltd.—see suggestions for further reading.)

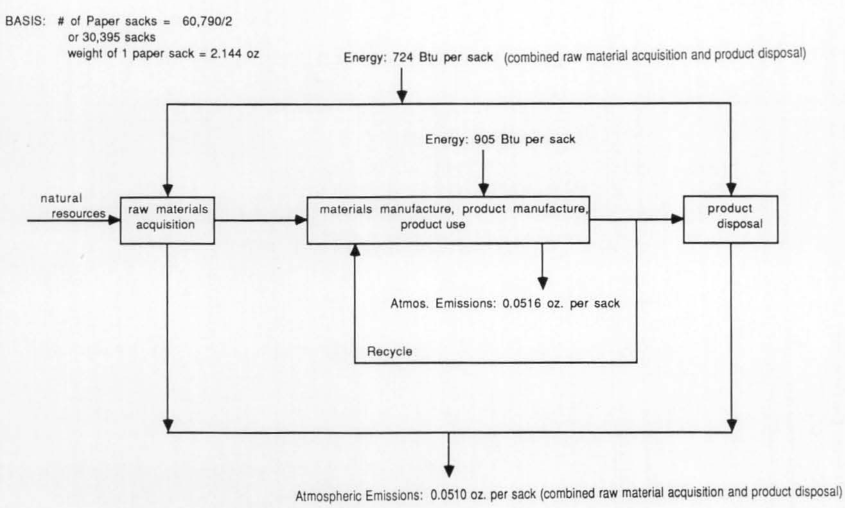

Figure 3. The life cycle for manufactured goods: paper grocery sacks (Source: Franklin Associates, Ltd.—see suggestions for further reading.)

PROBLEM STATEMENT

a) Using the data in Figures 2 and 3, determine the amount of energy required and the quantity of air pollutants released per 1,000 lb of production of plastic sacks. Also determine the amount of energy required and the quantity of air pollutants released for the quantity of paper sacks capable of carrying the same volume of groceries as the 1,000 lb of polyethylene sacks. Both the air emissions and the amount of energy required are functions of the recycle rate, so perform your calculations at three recycle rates, 0% recycled, 50% recycled, and 100% recycled.

b) Plot the results of part a) for both types of sacks. Compare the energy requirements and atmospheric emissions of the paper and plastic grocery sacks as a function of recycle rate.

c) Based on your results, discuss the relative environmental impacts of the two products. Note that in part b) of the problem, you compared the quantity of air emissions released. As shown in Table 1, the qualitative characteristics of the air emissions due to paper sacks are different than those due to plastic sacks. In your discussion you should consider whether or not it is valid to compare directly the mass of atmospheric emissions due to the two products.

d) The material and energy requirements of the plastic sacks are primarily satisfied using petroleum, a non-renewable resource. In contrast, the paper sacks rely on petroleum only to a limited extent and only for generating a small fraction of the manufacturing energy requirements.[1] Most of the energy requirements of pulp and paper manufacturing are met by burning wood chips.

Compare the amount of petroleum required for the manufacture of two plastic sacks to the amount of petroleum 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.

Questions for Discussion

1) Is 100% recycle really feasible for the products being analyzed or for any consumer products? Consider at least two points in your analysis: contaminants on or within the sacks, and mechanical wear and tear of the grocery sacks.

2) In this problem you have considered only two choices for delivery of groceries: paper sacks and plastic sacks. Can you suggest other alternatives?

SOLUTION

a) The energy requirements and total atmospheric pollutants for both paper and polyethylene (PE) grocery sacks, extracted from Figures 2 and 3 of the problem statement, are listed in Table 2. All values pertaining to PE sacks are based on 1,000 lbs of product, or 60,790 PE sacks. Values for the paper sacks are based on 60,790/2 = 30,395 sacks, the number required to hold an equivalent volume of groceries.

b) The data from part (a) are plotted in Figures 4 and 5. These figures show the effect of recycle rate on energy requirements and atmospheric pollutants. At 0% recycle, PE sacks (on an equal-use basis, two PE sacks per paper sack) require approximately 20% less energy than paper sacks. However, as the recycle rate increases, this difference in energy requirement decreases linearly. At recycle rates above 80% there appears to be no significant difference in energy requirements for PE and paper sacks. Therefore, on the basis of energy alone, paper sacks would be considered competitive with PE sacks, at high (>80%) recycle rates.

The plot for total atmospheric emissions shows a similar declining difference between the products, with increasing recycle rates. At 0% recycle,

TABLE 1
Profile of Atmospheric Emissions for Paper and Plastic Grocery Sacks
(Source: Franklin Associates, Ltd.)

	Atmospheric Pollutants Per Use (lb)			
	Emissions for 2 Polyethylene Sacks		Emissions for 1 Paper Sack	
Atmospheric Emissions (lbs)	0% Recycling	100% Recycling	0% Recycling	100% Recycling
Particulates	0.8×10^{-4}	0.8×10^{-4}	24.6×10^{-4}	2.8×10^{-4}
Nitrogen Oxides	2.1×10^{-4}	1.7×10^{-4}	9.2×10^{-4}	8.0×10^{-4}
Hydrocarbons	5.8×10^{-4}	3.2×10^{-4}	4.9×10^{-4}	3.9×10^{-4}
Sulfur Oxides	2.6×10^{-4}	2.7×10^{-4}	13.6×10^{-4}	10.6×10^{-4}
Carbon Monoxide	0.7×10^{-4}	0.6×10^{-4}	7.0×10^{-4}	6.5×10^{-4}
Aldehydes	0.0	0.0	0.1×10^{-4}	0.1×10^{-4}
Other Organics	0.0	0.0	0.3×10^{-4}	0.2×10^{-4}
Odorous Sulfur	-	-	4.5×10^{-4}	0.0
Ammonia	0.0	0.0	0.0	0.0
Hydrogen Fluoride	-	-	-	-
Lead	0.0	0.0	0.0	0.0
Mercury	-	-	-	-
Chlorine	-	-	-	-

TABLE 2
Energy Requirements and Atmospheric Emissions for Paper and Plastic Sacks

	0% Recycle		50% Recycle		100% Recycle	
	Energy Required (MM BTU)	Atmospheric Polutants lbs	Energy Required (MM BTU)	Atmospheric Polutants lbs	Energy Required (MM BTU)	Atmospheric Polutants lbs
Polyethylene 60,790 sacks	39.5	73.0	33.8	64.0	28.2	55.6
Paper 30,395 sacks	49.5	195.0	38.5	146.5	27.5	98.0

total atmospheric emissions are 60-70% lower for PE sacks; this difference gradually declines to 40% at 100% recycle.

c) PE sacks generate lower amounts of atmospheric emissions at all recycle rates—a fact that may be significant if there are no qualitative differences between the emissions. However, the emission composition data of Table 1 show both quantitative and possible qualitative differences in the emissions assigned to PE and paper. In the case of paper sacks, the amount of particulates, nitrogen oxides, and sulfur oxides is higher than for PE. As might be expected, higher levels of hydrocarbon emission are assigned to PE sacks. These hydrocarbons are also very likely to be qualitatively different from the hydrocarbon emissions generated by paper-sack production. It would be difficult to assess the respective environmental impacts of the hydrocarbon emissions without a much more detailed description of the emissions. Also, lack of emission data from other sources within the life cycle (*i.e.,* incineration and emissions from landfills) makes the comparison of PE and paper sacks incomplete and any comprehensive comparison difficult.

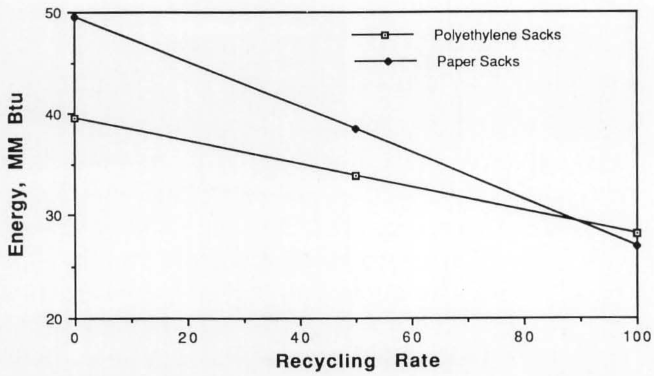

Figure 4. *Energy requirements for grocery sacks.*
Basis: 60,970 polyethylene sacks, 30,395 paper sacks.

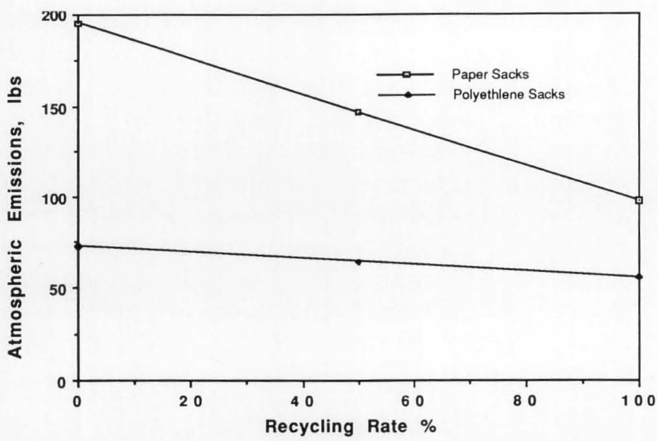

Figure 5. *Atmospheric emissions for grocery sacks.*
Basis: 60,970 polyethylene sacks, 30,395 paper sacks

d) *Petroleum requirements of polyethylene sacks:*

Fuel:

$$\left(\frac{39.5\times10^6\ \text{BTU}}{60,790\ \text{sacks}}\right)\left(\frac{1\ \text{lb petroleum}}{2\times10^4\ \text{BTU}}\right)=0.032\ \frac{\text{lb petroleum}}{\text{sack}}$$

Material

$$\left(\frac{0.2632\ \text{oz}}{\text{sack}}\right)\left(\frac{1\ \text{lb}}{16\ \text{oz}}\right)(1.2)=0.020\ \frac{\text{lb petroleum}}{\text{sack}}$$

Total = 0.052 lb petroleum/sack

Petroleum requirements of paper sacks:

Fuel:

$$\left(\frac{49.5\times10^6\ \text{BTU}}{30,395\ \text{sacks}}\right)(0.1)\left(\frac{1\text{lb petroleum}}{2\times10^4\ \text{BTU}}\right)=0.008\frac{\text{lb petroleum}}{\text{sack}}$$

Two polyethylene sacks require more than an order of magnitude more petroleum than a paper sack.

Sample Answers for the Questions for Discussion

1) The term "100% recycle" implies that all of the material in a grocery sack can be recovered, but complete material recovery is generally impossible to achieve. In the case of polyethylene and paper sacks, manufacturers invariably print identification labels or advertisements on the sack. The printing is usually done with an ink or dye that is undesirable in the remanufacturing process and is not easily removed. In addition, a variety of consumer items, such as foods and beverages, can contaminate the sacks in a similar manner. In both cases, the contaminants could lower the quality of remanufactured sacks to a point where the sacks are unusable. Therefore, in order to meet quality specifications, some of the recycled material containing the contaminants at concentrated levels is removed as a purge stream, and additional raw material and energy are required.

2) Many nations have adopted the reusable grocery sack concept with significant success, where success is measured by the number of people actively practicing the concept. Shoppers may reuse their durable sacks made out of nylon, jute, or thick cotton-string netting hundreds of times. The effect of grocery sack reuse as opposed to sack recycle is illustrated in Figure 1. Sack reuse is represented by the product recycle loop; note that there is less energy, atmospheric emissions, and waste associated with the product recycle loop than with the materials recycle loop. All material and manufacturing steps are bypassed for the life of the sack. However, because the manufacture of typical durable grocery sacks involves an order of magnitude more energy use and emissions than the manufacture of a paper or plastic sack, the consumer must use the sack at least ten to twenty times before an environmental benefit is achieved.

CONCLUSION

Assessing the total environmental impact of any product is a difficult process, involving evaluations of processing steps ranging from raw material acquisition to post-consumer waste disposal. Comparing the environmental impact of competing products is even more complex. Making comparisons between products usually involves making trade-offs between very different environmental impacts.

The purpose of this problem is to illustrate the difficulties involved in comparing the total environmental impact of different products. Paper and plastic grocery sacks were used as a case study. To compare paper and plastic grocery sacks we found that we must evaluate the trade-offs between energy use, pollutant emissions, and the depletion of natural resources. Plastic sacks appear to result in less atmospheric emissions and require less energy. On the other hand, paper sacks rely on a renewable resource for material and energy. Thus there is no clear, environmentally superior product. The consumer is left with a difficult choice, and as illustrated in the problem this choice must be made with incomplete information.

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Suggestions for Further Reading

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- Federal Office of the Environment, "Comparison of the Effects on the Environment from Polyethylene and Paper Carrier Bags," Bismarckplatz 1, 1000 Berlin 33, RFG, English version. August (1988)
- Riggle, D., "Recycling Plastic Grocery Bags," *Biocycle,* p 40, June (1990) ❐

Second Law of Thermodynamics

Continued from page 81.

The extra cost of erasing these digits exactly cancels any energy gain elsewhere in the system.

The conundrum of Maxwell's demon has been resolved by applying the concepts of thermodynamics of irreversible computation.

In our discussions, we assumed the behavior of the demon to be completely deterministic, *i.e.,* one instruction is completed before it goes on to the next instruction. What is not so clear is what would happen if the demon could wander a little, *i.e.,* if the demon knew its instructions but was not quite sure of the order in which to carry them out. The demon would then proceed from one step to another, going forward or backward, in a somewhat random fashion. In the long run, this might allow the demon to extract some work.

There is no doubt what the outcome of the above argument is going to be, but it is a loophole which has yet to be closed.

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Liquid-Liquid Processes

Continued from page 71.

information is obtained by the Stirred Transfer Reactor, which is a modified Lewis cell. The interfacial area between the contacted liquid phases needed for the estimation of mass transfer and reaction rates is calculated from information about the drop size distribution and the dispersed-phase volume fraction. The former is obtained by the Microphotographic Technique and/or the Laser Capillary Spectrophotometer Technique and the latter by the Ultrasonic Technique.

Tracer concentration measurements by the Laser Photometric Technique yield information about flow properties, *i.e.,* axial mixing parameters in both phases. Drop size-concentration bivariate distributions are obtained by the Laser Capillary Spectrophotometry Technique. This information is extremely valuable in model discrimination and parameter estimation of models describing droplet breakage and coalescence. It also provides information on dispersed phase mixing. Finally, the Ultrasonic Technique is also employed for the control of the dispersed-phase volume fraction in extraction columns to secure non-flooding optimum operation.

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1. Flett, D.S., *The Chemical Eng.,* **32**, 1 (1981)
2. Tavlarides, L.L., J.-H. Bae, and C.K. Lee, *Sep. Sci. and*