Abstract

PAI, PRASHANT PADMANABH. Environmental Implications of Packaging Material Choice and Associated Solid Waste Management Alternatives (Under the direction of Drs. S.R. Ranjithan and M.A. Barlaz).

Packaging materials (e.g., beverage containers) constitute a significant portion of the municipal solid waste. Frequently, alternative packaging systems (for example, aluminum versus glass containers, light weighting of plastic packaging by redesigning the production processes) are explored to identify cheaper, environmentally friendlier, and less waste generating options. Life cycle analysis is commonly used to estimate the environmental impacts in such comparative studies. This incorporates, in general, emission of environmental pollutants and energy consumption associated with the alternative production processes as well as the waste management processes. Although the solid waste management (SWM) processes may change from one municipality to another, these studies consider a fixed waste management option (e.g., recycling via a commingled recyclable material collection and recovery) for that packaging material. Also, changes in the packaging systems can potentially affect the way other waste items are managed, especially when the municipality is attempting to meet different SWM goals, such as diversion targets, emission targets, and budget constraints. The focus of this research is to investigate the impact on net environmental emissions due to the substitution of beverage container material (for example, aluminum for glass). Implications of changes in the packaging material on the SWM alternatives is first examined using an existing integrated solid waste management decision support tool (ISWM DST) that estimates the cost and life cycle inventories of emissions and energy consumption for SWM alternatives. Then the net environmental effects in terms of life cycle emissions associated with the product manufacturing processes as well as the SWM processes are examined for alternative packaging materials (e.g., aluminum and glass). This investigation is extended to examine impact of packaging material substitution on the tradeoff between SWM cost and greenhouse gas emissions. An illustrative case study is used to demonstrate the results.

Environmental Implications of Packaging Material Choice and Associated Solid Waste Management Alternatives

By

Prashant Padmanabh Pai

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Department of Civil Engineering

Raleigh, NC
2001

Approved by:

Dr. S. Ranji Ranjithan Chair of Advisory Committee	Dr. Morton A. Barlaz Co-chair of Advisory Committee
Dr. E. Downey Brill, Jr.	Dr. John W. Baugh, Jr.

Biography

Prashant Pai was a graduate research assistant in the Department of Civil Engineering at the North Carolina State University at Raleigh, North Carolina from August 1999 to June 2001. Mr. Pai received his bachelor's degree in Civil Engineering in April 1999 from the Indian Institute of Technology, Bombay, India. At NC State, Mr. Pai undertook coursework and research in the area of Environmental Systems Analysis under the guidance of Drs. S. Ranjithan and M.A. Barlaz.

At the Environmental Systems Lab at NC State, Mr. Pai conducted research in modeling environmental problems, especially those related to solid waste management and global climate change. His research interests also include application of optimization techniques to engineering problems, operations research, and software engineering and development. Presently, Mr. Pai is a Software Engineer in the Environmental Programs division at MCNC, Research Triangle Park, North Carolina.

Acknowledgements

I would like to thank my advisor, Dr. S. Ranjithan, for his advice, support and vision. I appreciate his direction, which helped me become multi-disclipinary, a necessary requirement in these changing times. I am grateful to my co-advisor, Dr. Morton Barlaz for his dedication, support and guidance. I would also like to thank my committee members Drs. E. Downey Brill and John Baugh. Jr. for their encouragement and feedback.

I am indebted to my "project mates" Ken Harrison and Ozge Kaplan for support, academic and beyond. Life was much easier with them and the rest of Mann 431 (Christos Anastasiou, Jenny Parmar, Can Kuterdem, Kishan Chetan). I thank Sudeep Vaswani for allowing me to use the results of his research. Publix such as Sujay, Sachin, Manish, Rajesh, Girish, Vijay, Prabhas, Dibyendu, Harish, Arvind, Mike, Mohammed deserve mention for making my life at State better. I would like to thank my fiancee, Girija Gavankar, for being with me and supporting through this time. Finally, I remember my guiding light, my grandfather, Janardhan Anant Shanbhag, who passed away on April 11th 2001 in Mumbai, India and my family, with whom I was unable to be with at the fateful time.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1: Introduction

With increasing environmental concerns, environmental implications associated with production of consumer items and their disposal in municipal waste stream is getting new attention. This awareness has given birth to approaches such as design for the environment (DfE), which encourages industries to move towards more environment friendly manufacturing practices (US EPA, 1999). Packaging materials, which constitute a significant portion of municipal waste stream, have become the focus of a number of environmental improvement programs. Producers are now evaluating alternative products and product delivery systems to reduce material and energy consumption and to minimize contribution to the waste stream (Hyde et al 2001, and Spengler et al, 1998). Till recently, cheap raw materials, abundant energy availability and low disposal costs supported indiscriminate use and disposal of packaging with little regard to the overall environmental implications. With increasing challenges in waste disposal, waste management is being viewed in a broader context, especially since waste is a potentially beneficial source of revenue via recyclable material and energy recovery. In addition, associated environmental benefits can potentially be significant.

Life cycle Assessment (LCA) provides a methodology for comprehensive evaluation of environmental burdens such as air and water emissions, energy use and raw material consumption (US EPA, 1995; SETAC, 1993). Life cycle assessment has been widely used to evaluate the environmental impacts of packaging materials (Tellus, 1993, Keoleian and Spitzley, 1999, Ayalon et al., 2000, Kuta et al., 1995, Azapagic and Clift, 1999, DEPA, 1998). An essential phase in a product life cycle is the product's fate when it enters the municipal waste stream at the end of its use as a product. According to the USEPA waste characterization report, discarded packaging materials constitute a significant portion of the solid waste stream (USEPA 1998).

When choices in the types of packaging materials as well as their production are made, they affect the environmental implications associated with not only the production processes of that packaging material, but also the fate of the packaging material in the waste stream. Constituent product properties such as weight and volume affect the waste management choices, and therefore the resulting environmental implications associated with waste processing activities. Typical packaging material studies, including those mentioned above, assume a fixed, pre-selected waste management strategy when examining the net environmental effects. As numerous solid waste management (SWM) options (e.g., collection of recyclables as commingled waste vs. mixed waste that is separated later, combustion, with energy recovery, of combustible recyclable material vs. recovery as recyclable materials) are available, pre-selecting an option may not reflect the most efficient alternative. Also, the waste management choices are made in an integrated manner in consideration of all other waste items and waste processing options. These choices are also influenced by the municipality's local waste management goals, e.g., diversion, recycling, or energy recovery goals. Hence, a product LCA study based on a single fixed waste management option may not fully reflect the interactions between packaging alternatives and waste management options.

It would be more appropriate to first generate SWM strategies that perform well with respect to environmental or economic factors for a municipality or region, and then study the environmental implications of changes in packaging materials in light of the SWM strategy adopted in specific communities. Consideration of various solid waste management options would provide a more accurate estimate of the tradeoffs associated with shifts in packaging materials. This requires a tool that models the cost and environmental factors of alternative SWM strategies and compares these alternatives to identify the most efficient alternatives. The integrated solid waste management decision support tool (ISWM DST) developed at North Carolina State University provides these capabilities (Solano et al., 2001a, 2001b;Harrison et al., 2001). ISWM DST incorporates process models for most of the commonly used municipal waste management unit processes. Using a life-cycle methodology, each unit process model estimates the cost and environmental factors associated with handling every item in a waste stream. These factors are then coupled with waste flow equations to form an integrated SWM model that is able to represent and compare all feasible SWM alternatives for a given set of site-specific inputs corresponding to a municipality. An underlying search procedure is then utilized to identify SWM strategies that meet user-defined design goals at site-specific levels (e.g., minimize cost while meeting a target diversion rate, or minimize greenhouse gas emissions while not exceeding a budget level).

By changing the input waste composition and properties in ISWM DST and then applying it to identify the SWM alternatives, the cost and environmental effects of shifts in packaging systems on waste management at site-specific levels can be now studied.

Coupling these effects with the effects at the production level will provide the basis for investigating the net effects associated with shifts in packaging systems. The primary objective of this study is to develop an approach for estimating and comparing the net environmental effects associated with shifts in packaging systems for consumer products. To demonstrate the application of the approach, this study considered the effects associated with substituting beverage container material. Two packaging systems were considered for beverage containment: Aluminum Cans (including plastic for wrapping six packs and cardboard for containing six packs), and Single use Glass Bottles (including tinplate for bottle caps, non-recyclable paper for labels, cardboard for holding six-packs). The following sections present: the description of the problem used in the illustrative case study; the definition of the production and waste system; the methodology; the description of the scenarios analyzed; and the results.

behavior is assumed to be largely independent of the packaging system, i.e., the consumption amount of the beverage is not significantly affected by the container packaging system. The primary question focuses on the relative environmental implications of switching one beverage container material to another. This requires the integration of the cradle-to-gate life cycle of the packaging materials, and the subsequent gate-to-grave life cycle mainly consisting of waste management. This integration needs to capture the interrelationships between the production and waste processing aspects of the materials. For example, the characteristics, such as density, weight, and combustibility, of the packaging material can potentially affect the way that material is handled in the waste management phase. Similarly, the amount recovered as a recycled material would potentially affect the virgin-recycle mix during the production phase. This is dependent on the site-specific waste management goals (e.g., local diversion targets, cost constraints, etc.) being considered by each municipality.

As a shift in the beverage container material can potentially affect the SWM choices and vice versa, the question of which material is environmentally more beneficial to use for beverage containers needs to be addressed under different scenarios. This includes varying cost constraints on the SWM choices by the municipality, and selecting different waste processing options to achieve the similar site-specific SWM goals. These scenarios should also help in evaluating whether a decision to make a shift in the beverage container material would be equally beneficial for municipalities with varying local considerations and restrictions.

3. System Definition and LCI Estimation

3.1 System Boundary

As the underlying method is based on life-cycle inventory (LCI) estimates of emissions associated with production and waste management, the system boundaries must be first defined to provide a common basis for including (or excluding) processes that contribute to emissions. While it may be appropriate to include all processes that contribute significantly to the environmental impacts of a system, it is particularly important to include in a comparative LCI study those processes that signify any difference among the alternative strategies examined. For example, processes, such as consumer use of finished products through final disposal in the municipal waste stream, are common for beverage systems based on aluminum and glass, and therefore the emissions associated with those processes would not contribute to the difference in emissions between those two systems.

The packaging system life cycle includes unit processes from the manufacturing phase through the waste management phase. This includes primary, secondary and transport packaging materials. Primary materials (e.g., glass bottles) are used to contain the beverage while secondary materials (e.g., paper for labels, cardboard for boxes) are additional items used in the overall storage and distribution of the containers. Packaging for transport (e.g., wooden planks for crates) is also included.

The primary materials considered in this study are disposable glass bottles and aluminum cans. The containers considered in this study hold a standard volume of 330 mL. of beverage. An aluminum can has a mass of 14.45 grams and that of a disposable glass bottle is 145 grams. (DEPA, 1998).

The unit processes considered are grouped into two sections:

1. Upstream Processes: From extraction of virgin materials and manufacture of a product through the final use by consumer.
2. Downstream Processes: From its entry into the municipal solid waste (MSW) stream through its final disposal or recovery as a recyclable.

A depiction of a product life cycle is provided in Fig 1. All the solid rectangles represent unit processes in the product life cycle and the arrows indicate the transportation of outputs of the source unit processes to the destination unit processes.

Since the objective of this study is to analyze the impact of product substitution on waste management strategies, a ton of MSW generated by the community under consideration is designated as the functional unit.

3.1.1 Upstream Processes

Primary packaging and some secondary packaging are manufactured from a combination of corresponding virgin and recycled content. It is assumed that the LCI for the manufacture of both primary materials (i.e., aluminum and glass) and corrugated board

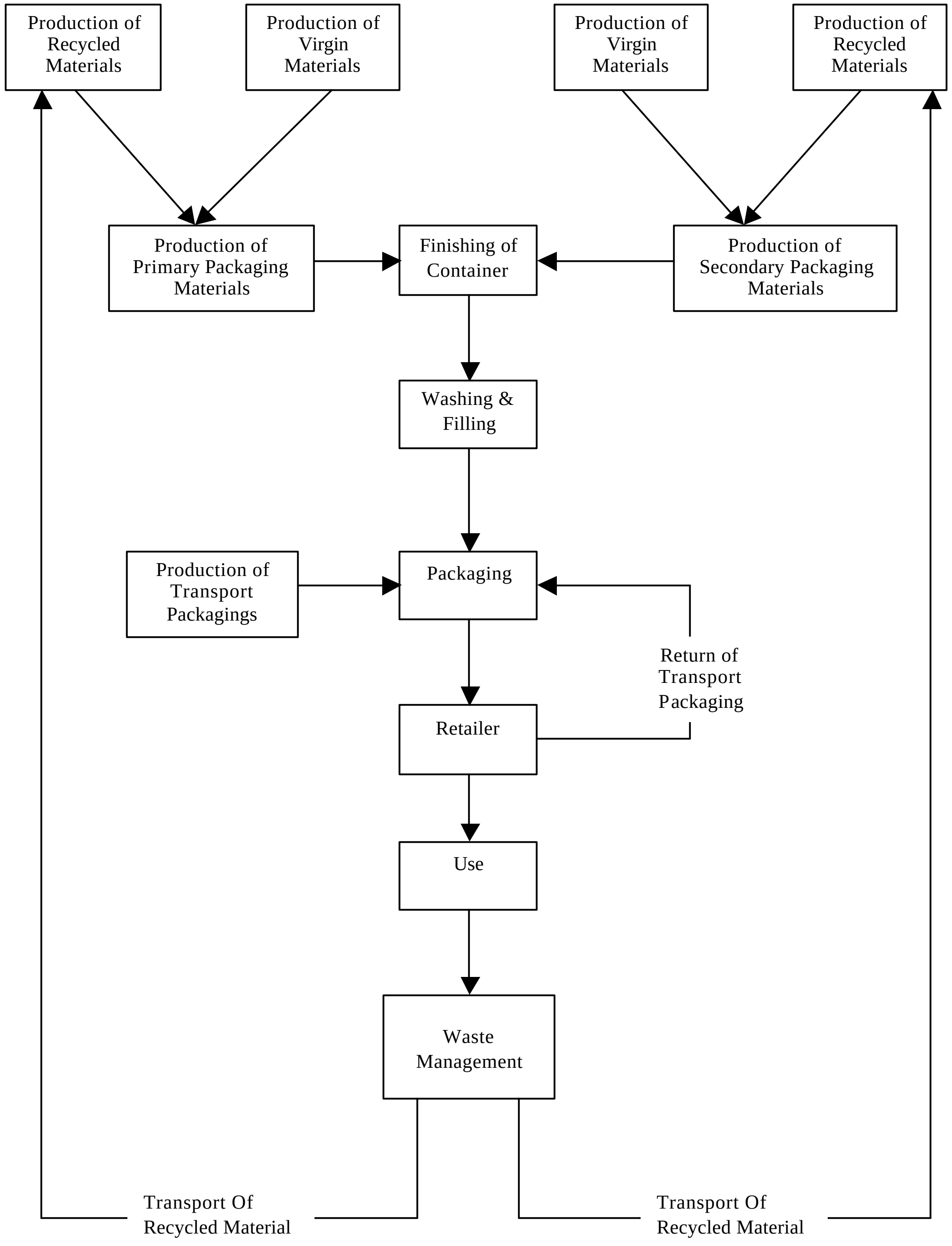

Fig. 1: Processes in a Product Life Cycle

from virgin and recycled material can be combined linearly (USEPA, 2000). The "virgin" processes include mining and refining of the raw materials, and obtaining a common item, e.g., aluminum sheets. A common item is a common intermediate product for the manufacturing processes from both virgin and recycled materials. For example, aluminum ingot is produced from both virgin and recycled material, and forms the common starting material for aluminum can production. The "recycled" processes include remanufacturing of recycled content through production of common item. After production, the primary container is subjected to a finishing process and then washed and filled with beverage. The LCI for these processes is included in the system. The system includes the production of secondary and transport materials except for the finishing processes. This exclusion is estimated to be small compared to the LCI for production itself (DEPA, 1998 and Tellus, 1993). Transport packaging is usually returned to the manufacturer with some loss. Hence some quantity is manufactured in a steady state environment. The energy recovered from incineration of waste transport packaging is assumed to offset consumption of fuels and electricity required for heating.

Materials manufactured in the system reach their ultimate fate in the system itself. Hence, if recycled paper is used in the manufacture of an item, e.g., cardboard, then there are no offsets due to it not reaching its alternative fates, e.g., use in other product systems or being landfilled.

Emissions are reported in two categories: process-related and fuel-related. Process emissions are those emitted during a processing step while fuel emissions are those, which result from combustion of fuels.

The transportation of packaging materials between unit processes as well as the distribution of beverage (including packaging materials) from the brewery or bottler to the retailer and the return of empty packaging (where appropriate) is included in the system. The efficiency of distribution varies between different packaging systems, and hence it is included in the system. The transport between the retailer and the consumer is not included. This data is not significant particularly since beverages are typically purchased along with multiple other items. The LCI due to sorting and other processes at the retailer estimated to be less than 1% of the total energy demand (DEPA, 1998) is not included in the overall LCI.

3.1.2 Downstream Processes

Waste management consists of waste collection, transfer, separation, treatment, remanufacturing of products from recycled waste components, disposal, and inter-node transportation. The volume and composition of the entire solid waste stream affect the manner in which individual materials are handled. Hence, the system includes the management of the entire solid waste stream and not only of the materials under consideration. The system includes waste generated in the residential, multifamily and commercial sectors but excludes industrial process waste, sludge, construction and demolition waste, pathological waste, agricultural waste, mining waste and hazardous waste. The ash generated from MSW combustion is included in the system.

The upstream remanufacturing processes do not include collection, separation and transportation of recyclables to a remanufacturing facility as these processes are accounted for in waste management. It is assumed that recyclables, in cases where they are used as inputs in manufacturing processes, come from the MSW stream due to recycling (see Fig. 1). The ratio of virgin to recycled content used in the manufacture of the packaging material is adjusted according to the quantity of available recycled material from solid waste management. For example, if 5 tons of new cans are to be manufactured and if 3 tons of recycled cans are available from the downstream processes then only 3 tons are required from the virgin manufacturing process.

3.1.3 Energy Considerations

The LCI includes both the pre-combustion emissions associated with fuel production as well as direct fuel combustion emissions. In the system, energy is utilized in form of electricity, steam in boilers and transportation fuels. The emissions associated with the consumption of electrical energy are calculated based on the national fuel mix (Dumas, 1997). In some processes, steam is used as a heating medium, and the LCI is considered for the production and use of steam (Vaswani, 2000).

3.2 Sources of Data

Ten LCI parameters, presented in Table 1, are tracked through the life cycle of each packaging material. These parameters were selected to represent emissions to both air and water media and since consistent emissions data for these parameters were available for all the unit processes in the overall system.

The data used to compare packaging materials were obtained from a variety of sources (USEPA, 2000 and DEPA, 1998) and adapted to U.S. conditions, as it was not possible to obtain consistent data for the entire life cycles of primary, secondary and transport materials from a single source. It is assumed that emissions due to the manufacturing processes are independent of the location. However, all emissions associated with energy consumption as electricity, transportation fuel or steam is based on U.S. data.

For estimating the LCI for the waste management processes, the Integrated SWM Decision Support Tool (ISWM DST) developed at North Carolina State University is used. It consists of a set of unit process models that estimate the LCI and cost associated with waste management. An optimization-based systematic search procedure is incorporated which aids in identifying good SWM strategies. The ISWM DST can be configured to generate strategies, which perform well according to a set of defined objectives. Also, to accommodate undefined goals and future decision maker preferences, an additional feature to develop alternative good strategies is implemented.

In addition to the environmental emissions, cost is also calculated for the solid waste management processes. The SWM alternatives and the results are evaluated from a community perspective and since the cost of the container production is borne by the industry, the community is not impacted.

3.3 Estimation of LCI

An inventory model was developed to calculate the environmental emissions relating to the manufacture and use of packaging materials. Data from US sources for the manufacturing and use processes for packaging materials is limited. Hence, in cases where data from US sources was unavailable, inventory data from a Danish Environmental Protection Agency (DEPA, 1998) was used. The inventory emissions from the DEPA study, where they were used, were adapted to reflect US conditions. This was done by first estimating the emissions relating to the production and use of Danish energy sources such as electricity, steam, fuels etc. These emissions were then extracted out from the Danish inventory and replaced with emissions, which would be released if the same type and amount of energy were consumed in US conditions. Production processes were assumed to be similar in Europe and the US (Keoleian and Spitzley, 1999).

Data for the emissions from the mining of virgin and recycled materials to the production of the common item were taken from an USEPA (2000) study. The USEPA data was available for both the primary materials and for some of the secondary materials such as corrugated board and LDPE. The USEPA data for the manufacture of materials consists of two separate inventories for the production of the material from virgin materials only and recycled materials only. These inventories can be combined linearly according to the ratio of virgin and recycled content used. This ratio is determined on the basis of the amount of packaging material recycled in the waste management. LCI data for the production of other secondary packaging materials such as cardboard, tinplate and paper used inventory data from the DEPA study. The same LCI database is used for the production of the transport packaging materials. The LCI for the processes from the production of the common item to the end of the packaging system’s useful life is taken from the DEPA study. The combined LCI for all these processes gives us the LCI for the upstream processes. It should be noted that the upstream LCI is estimated for the consumption of 1000 liters of beverage.

The percentage of aluminum and glass containers in the waste stream is given in Table 2. Based on characteristics of the community under consideration, the mass of glass and aluminum containers in the waste stream is calculated. From these results, the volume of beverage consumed by the community in glass and aluminum containers is estimated. The upstream inventory is then multiplied by the appropriate factor to arrive at the upstream LCI for the community.

The ISWM DST was applied to estimate the cost and environmental emissions for the downstream processes. A number of scenarios, which are described in the following section, are defined to simulate different communities. In each of the scenario the tool was restricted to choose a strategy from among a limited choice of unit processes and at a certain budget level. Under these conditions, the strategy, which performs best with respect to green house emissions, was selected. The output from the ISWM DST contains an inventory of cost and environmental emissions that are tracked. The LCI is distinguishable for the unit processes for waste management such as waste collection, transfer, separation, treatment, disposal, transportation and remanufacturing. Remanufacturing LCI is the LCI associated with the offsets gained when materials from the waste stream are recycled into new products. It is the difference between the inventory for production of new materials from virgin content and recycled content.

These offsets associated with the glass and aluminum packaging systems are accounted for in the upstream LCI. Hence, these offsets for the packaging systems under consideration are taken out to avoid double counting. This results in strictly the downstream, i.e., waste management, LCI for the community. The upstream and downstream LCI can then be combined to derive the total LCI for the system.

4. Case Study Scenarios and Results

The case study described in Section 2 was used to define a series of scenarios to investigate the relative environmental benefits between alternative beverage container packaging systems. This study focused on the primary packaging materials glass and aluminum. The scenarios were defined such that the results can provide insights to the following questions: how do the environmental effects associated with a shift in beverage container packaging material vary with different site-specific SWM goals for a municipality with a given characteristics; and how do alternative SWM strategies that meet the goals of a specific municipality affect the environmental implications of shifts in beverage container packaging systems. The environmental effects were compared in terms of differences in LCIs of a representative set of emissions associated with the production processes as well as the SWM processes. These effects were considered in increments, starting from existing conditions defined as base scenarios below. The variation of SWM related greenhouse gas emissions with different cost restrictions on SWM operations was first generated. Then a series of scenarios were defined to examine the incremental changes in emissions associated with waste processing when shifts in beverage container material are incorporated; i.e., when all beverage containers are made of either glass or aluminum. The production process related emissions were then included to obtain the net environmental effects for these scenarios. Finally, alternative SWM strategies that use maximally different unit processes to achieve the same waste management goals for the municipality were generated, and the net environmental effects were compared.

4.1 Base Scenarios

The ISWM DST, developed at NC State, was used to generate SWM strategies for the municipality described in Section 2. The ISWM DST was configured to generate SWM strategies with respect to waste management cost and the Green House gas Equivalents (GHEs), a measure of the global climate change potential. GHE is a weighted sum of the carbon dioxide, methane, and nitrogen oxide emissions.

To represent different current operating scenarios for the municipality modeled in this study, the ISWM DST was employed to find SWM strategies that yield the best GHE performance at different SWM cost constraints. The corresponding LCI of emissions of other 6pollutants (those included in Table 5) were also computed.

The variation of GHE with different SWM cost targets is shown in Figure 2. The choice of unit processes and mass flow for the SWM strategies corresponding to the two extreme scenarios, i.e., at the minimum cost and minimum GHE, are summarized in Table 6. Table 7 shows the SWM cost and the GHE values for all solutions plotted in Figure 2.

While a significant tradeoff between SWM cost and GHE is evident at lower levels of SWM cost, the incremental improvement in GHE reduction is insignificant beyond a cost of $60 million/yr. Examination of the waste flow in the SWM strategies at and above $50 million/yr, the diminishing rate of improvement in GHE with cost gives an explanation. Around $50 million/yr, some percentage of the waste collected as residuals is sent to a waste incinerator (with energy recovery). As more budget is available, the extra money is spent to recover more, although a very small amount, of the recyclables by processing the mixed waste first in a mixed waste MRF, and then incinerating the residual waste. This small addition of recyclable material recovery reduces the emissions slightly at a relatively high incremental cost.

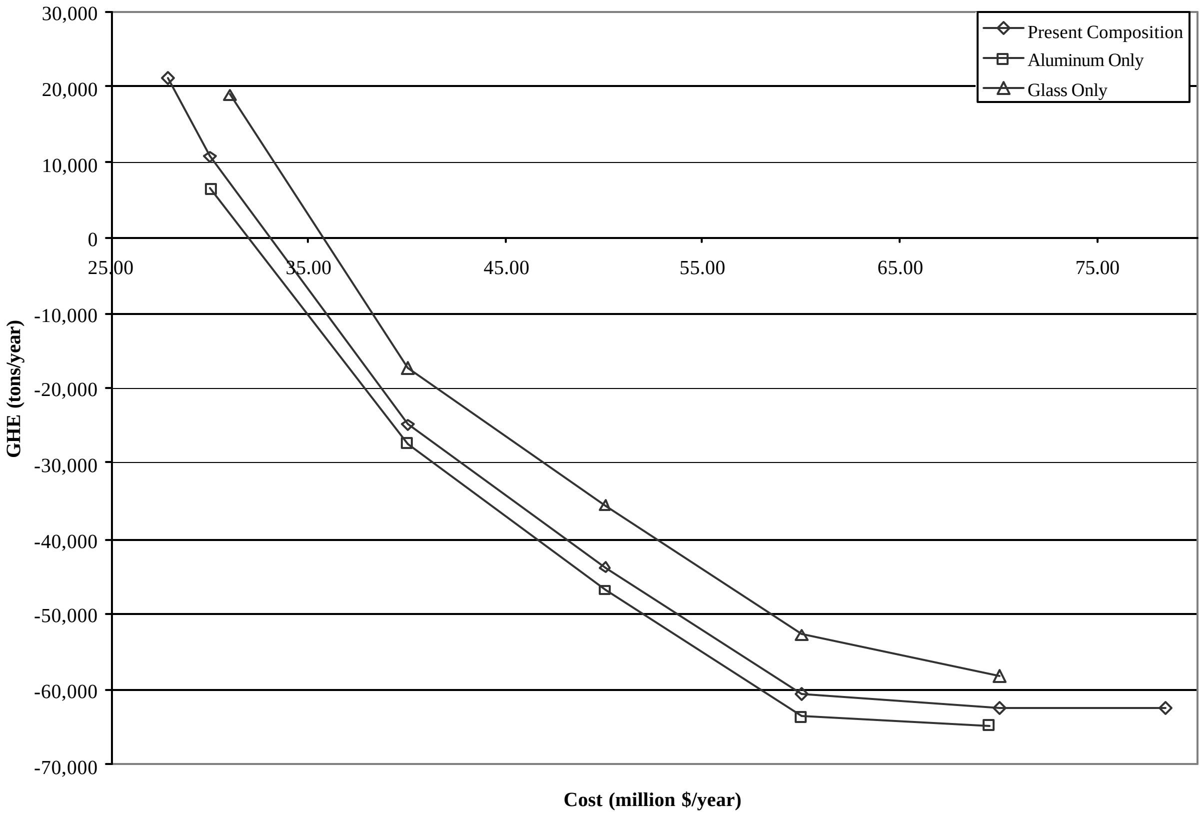

Fig 2 Variation of SWM Cost with GHE for existing conditions and after shifts in packaging systems (from aluminum to glass, and vice versa)

Table 6: Unit Processes and Mass Flows for the minimum cost and minimum GHE scenarios for the default composition

SWM Process		**Mass of Waste in Tons/year**	
		Minimum Cost	**Minimum GHE**
Residential Collection	Yardwaste	0	18100
	Commingled/MRF	0	14300
	Residual	206000	185000
	Recyclable Drop-Off	11300	0
Multifamily Collection	Recyclable Drop-Off	3760	0
	Pre-Sorted	0	5560
	Residuals	68800	67000
Commercial Collection	Pre-Sorted	49800	3600
	Residuals	141000	187000
Separation	Mixed Waste	0	252000
	Presorted	64800	9190
	Commingled	0	14300
Treatment	Combustion	0	437000
Disposal	Landfill	416000	374
	Ash-landfill	0	101000

Table 7: SWM Cost and GHE for the default composition, aluminum only and glass only scenarios.

Cost (in million $)	**GHE in tons/year**		
	Aluminum Only	**Default Composition**	**Glass Only**
30	33200	35000	36500
40	-797	-727	-643
50	-20200	-19600	-18800
60	-37400	-36800	-35900
70	-38500	-39000	-41100

4.2 Substitution Scenarios

Two sets of scenarios were considered in this analysis to evaluate the impact of packaging material substitution on the waste management LCI. The MSW stream composition was modified to reflect substitution of all aluminum beverage cans with glass bottles, and vice versa. This substitution was done on the basis of the volume of beverage contained in the containers being substituted. The corresponding changes in the secondary packaging materials were also reflected in the modified waste composition. The modified waste compositions for the affected items are listed in Table 8.

Table 8: Changes in waste composition due to shifts in packaging

	Aluminum Only	Default Composition	Glass Only
Cardboard	74900	75200	76200
Aluminum Cans	4470	3370	0
Glass - Clear	8310	14900	35200
Glass - Brown	3410	6160	14600
Glass - Green	2200	3850	8930
Paper	49500	49400	49300
CCCN Other	32800	32900	33000
Plastic	28600	28600	28600
CCNN Other	21700	21700	21800
Tinplate etc.	9340	9230	8880
CNNN Other	20500	20600	20700

The SWM strategies examined in the scenarios described in Section 4.1 were repeated with the new substitution scenarios. To simulate the effect of a shift in packaging systems on existing SWM strategies, the substitution scenarios were analyzed while restricting the SWM unit processes to those already selected in the base scenarios (described in the previous subsection). For example, the SWM unit processes selected for the $30 million/yr case were kept unchanged, and the waste flows were rearranged for a substitution scenario. The resulting variations in SWM cost and GHE are shown in Figure 3. These results in Figure 3 indicate that the waste management related GHE improves in all cases when the glass beverage containers are substituted by aluminum. As emissions offsets from recycled aluminum are significant, this observation is consistent with typical expectations.

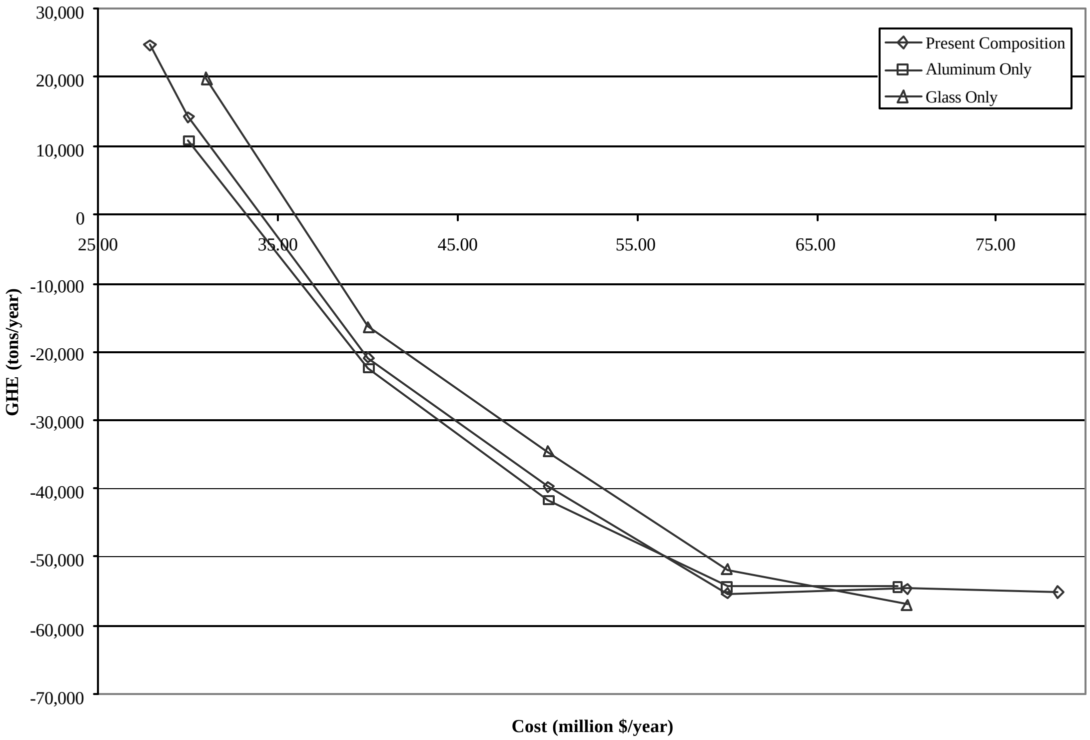

Fig 3: Variation of SWM GHE (without offsets for recycled materials) for existing conditions and after shifts in packaging systems (from aluminum to glass, and vice versa)

4.3 Integration of Upstream LCI

The scenarios analyzed in Section 4.2 were revisited to incorporate the upstream emissions associated with the production of the packaging materials. As ISWM DST incorporates the offsets from the recycled material in its LCI estimations, the first step is to discount these offsets. The resulting variations in discounted GHEs with SWM cost are shown in Figure 4. Then the upstream emissions are added. This is accomplished by first estimating the amounts of the affected packaging materials that are recycled in each SWM strategy were calculated. These amounts were then used as inputs to the upstream model to estimate the upstream LCI of emissions.

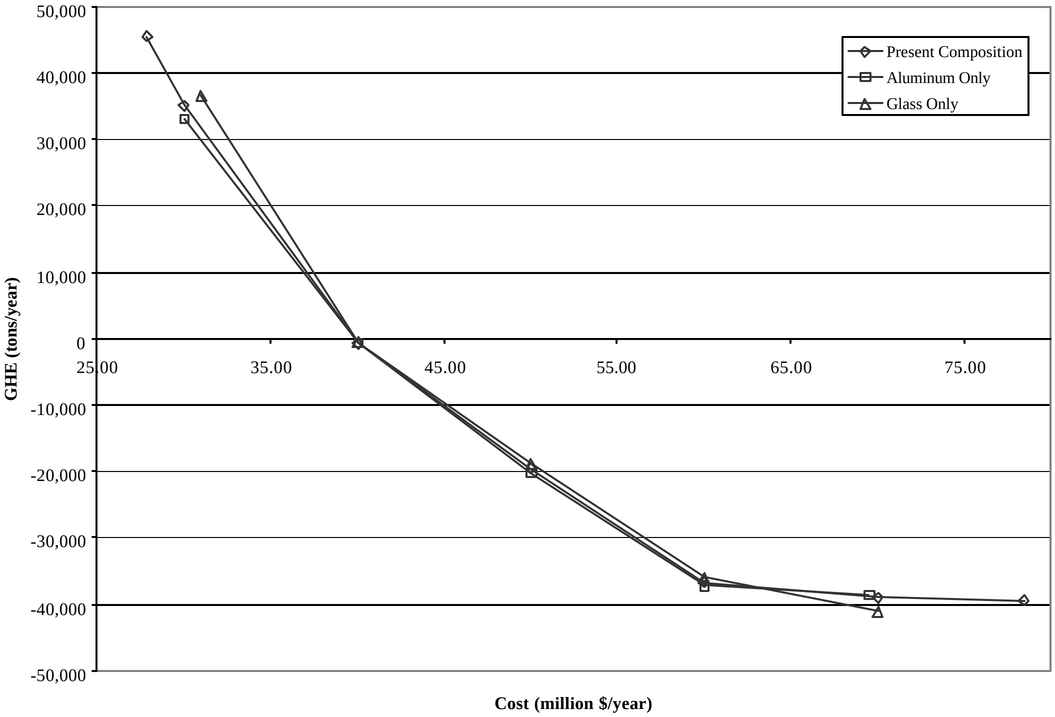

Fig 4 Variation of net GHE (including from both upstream and waste management processes) for existing conditions and after shifts in packaging systems (from aluminum to glass, and vice versa)

Comparing the results shown in Figures 3 and 4, the clear advantage of the aluminum-based container packaging system evident in Figure 2 does not prevail when the net emissions are considered in Figure 4 i.e. aluminum is more beneficial at lower levels of recovery of aluminum as a recyclable, and vice-versa. To understand these changes, the differences in emissions for all the major subprocesses associated with the strategies at $30 million/yr and $70 million/yr are summarized in Table 9.

From this table, it is evident that aluminum cans contribute to substantial offsets during remanufacturing. Glass bottles on the other hand do not have comparable remanufacturing offsets. The net emissions do not follow this trend when the beverage containers are shifted to aluminum. This can be explained by examining the waste flows in the SWM strategies. As it is most desirable to recover the aluminum cans via recycling, recycling collection and material recovery processes are included in the SWM strategies. To achieve higher levels of aluminum recycling, all waste is collected as mixed waste and is then processed at a mixed waste MRF to recover aluminum. This is the most cost-effective way to achieve the highest level of recovery of aluminum (since commingled or presorted recyclable collection or recycle drop-off options yield less recovery due to lower participation by the households). Since source separation is not occurring during mixed waste collection, all other waste items need to flow through the mixed waste MRF. This results in unnecessary handling, and therefore additional

Table 9: Comparison of differences in GHE due to shifts in packaging systems.

Packaging System	**Glass**	**Glass**	**Aluminum**	**Aluminum**
Budget Levels	31 million	70 million	30 million	70 million
Collection	1,260	1,220	1,210	1,160
Separation	1,600	774	1,410	3,610
Treatment	-2,820	-52,300	-8,700	-51,000
Disposal	21,700	88	18,200	69
Transportation (D/S)	232	218	204	334
Remanufacturing	-2,920	-8,200	-5,770	-19,000
SWM Total	**19,000**	**-58,200**	**6,540**	**-64,800**
Alum Remanufacturing	0	0	-4,370	-10,400
Glass Remanufacturing	-815	-1,180	0	0
Corrected Remanufacturing	-2,110	-7,020	-1,400	-8,570
Downstream	**19,800**	**-57,000**	**10,900**	**-54,400**
Glass Bottle Producton	8,320	7,660	0	0
Aluminum Can Production	0	0	11,200	4,780
Corrugated Board Production	420	395	395	371
LDPE Production	99	99	83	83
Other Processes	491	491	849	849
Transportation (U/S)	7,280	7,280	9,760	9,760
Upstream	**16,600**	**15,900**	**22,300**	**15,900**
Total	**36,500**	**-41,100**	**33,200**	**-38,500**

emissions, This results in unnecessary handling, and therefore additional emissions, at this MRF since most of the other potentially recyclable but combustible materials (e.g., paper and plastics) typically yield less net greenhouse gas emissions when combusted with energy recovery. Thus, the benefits from the use of aluminum for beverage containers are nullified by the increases in the additional emissions associated with the extra handling of other waste items. This is further confirmed by the mass flow when no aluminum was in the waste stream. In the absence of aluminum the mixed waste flows from collection directly to the waste incineration facility.

5. Summary and Conclusions

This paper presents a methodology to examine systematically the environmental impacts caused by shifts and substitutions in packaging systems. The focus of the illustrative study is on substitution of beverage container materials—glass and aluminum. The evaluation of environmental performance of the packaging materials includes LCI of manufacturing and use as well as waste management processes. Most packaging material studies consider typically a pre-selected solid waste management option to account for the LCI during the life of the material after it enters the municipal waste stream. Changes in the choice of packaging materials can potentially affect, however, the SWM process choices. Similarly, the SWM choices can potentially affect the raw material mix in the manufacturing processes. Therefore, it is necessary to understand and represent systematically and correctly these interrelationships.

This study attempts to adopt such an approach to examine the effects associated with substituting beverage container material. Two beverage packaging systems, i.e. glass bottles and aluminum cans, are considered. Since the secondary packaging materials are different depending on the primary material choice, changes in the primary as well as the secondary materials are modeled. A realistic case study is used to demonstrate the impacts of beverage container substitution. These impacts on the local SWM operation and the upstream manufacturing processes are estimated separately, and then the integrated effects are computed. Several scenarios were developed to examine how the impacts of packaging material shifts vary when the municipality is operating under different site-specific conditions.

Results show that a shift in beverage container packaging from glass to aluminum improves the LCI of green house gas emissions associated with the solid waste management processes. This was observed to be true for a range of different scenarios. However, when the upstream emissions were combined, the net emissions show a switching trend, i.e., aluminum is more beneficial at lower levels of recovery of aluminum as a recyclable, and vice versa. This can be explained by examining the waste flows in the SWM processes. To achieve higher levels of aluminum recycling, all waste is collected as mixed waste and is then processed at a mixed waste MRF to recover aluminum. This is the most cost-effective way to achieve the highest level of recovery of aluminum (since commingled or presorted recyclable collection or recycle drop-off options yield less recovery due to lower participation by the households). Since source separation is not occurring during mixed waste collection, all other waste items need to flow through the mixed waste MRF. This results in unnecessary handling, and therefore additional emissions, at this MRF since most of the other potentially recyclable but combustible materials (e.g., paper and plastics) typically yield less net greenhouse gas emissions when combusted with energy recovery. Thus, the benefits from the use of aluminum for beverage containers are nullified by the increases in the additional emissions associated with the extra handling of other waste items. This is further confirmed by the mass flow when no aluminum was in the waste stream. In the absence of aluminum the mixed waste flows from collection directly to the waste incineration facility.

Such insights into the interrelation of manufacturing and waste process may not be realized if a fixed waste management option is used in a study. The methodology proposed in the study can also be applied to other combinations of shifts in packaging systems. Although this study illustrates the method via a realistic case study, it is important to note that the amount and quality of data needed for such a study could be improved. The method, however, is broadly applicable in such comparative studies.

REFERENCES

Shapiro, K. (1993). Life-cycle Evaluation of Packaging Materials, *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment.* Arlington, VA, USA.

Kuta, C.C., Koch, D.G., Hildebrandt, C.C. and Janzen, D.C. (1995). Improvement of products and packaging through the use of life cycle analysis. *Resources, Conservation and Recycling,* 14, pp.185-198.

Spengler, T., Geldermann, J., Hahre, S., Sieverdingbeck, A., and Rentz, O. (1998). Development of a multiple criteria based decision support system for environmental assessment of recycling measures in the iron and steel making industry. *Journal of Cleaner Production*, 6, pp. 37-52.

Keoleian, G.A. and Spitzley, D.V. (1999). Guidance for Improving Life-Cycle Design and Management of Milk Packaging. *Journal of Industrial Ecology*, 3(1), pp.111-126.

Ayalon, O., Avnimelech, Y., and Shechter, M. (2000). Application of a comparative multidimensional life cycle analysis in solid waste management policy: the case of soft drink containers. *Environmental Science and Policy,* vol. 3, pp. 135-144.

Finnveden, G. (1999). Methodological aspects of life cycle assessment of integrated solid waste management systems. *Resources, Conservation and Recycling*. vol. 26, pp. 173-187.

Azapagic, A. and Clift, R. (1999). Life cycle assessment and multiobjective optimization. *Journal of Cleaner Production*, vol. 7, pp. 135-143.

Tillman, A.M., Ekvall, T., Baumann, H. and Rydberg, T. (1993). Choice of system boundaries in life cycle assessment. *Journal of Cleaner Production*, vol. 2, no. 1, pp. 21-29.

Widheden, J., Ekvall, T. and Nielsen, P.H. (1998). Life Cycle Assessment of Packaging Systems for Beer and Soft Drinks. *Danish Environmental Protection Agency, Environmental Project No. 401*, Denmark.

Harrison, K.W., Dumas, R.D., Solano, E., Barlaz, M.A., Brill, E.D. and Ranjithan, S.R. (2001). Decision Support Tool for Life-Cycle Based Solid Waste Management. *Journal of Computing in Civil Engineering*, vol. 15, no. 1, pp. 44-58.

Vaswani, S. (2000) Development of Models for Calculating the Life Cycle Inventory Development of Models for Calculating the Life Cycle Inventory of Methanol by Liquid Phase and Conventional Production Processes. Master's thesis. North Carolina State University.