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Life Cycle Design of Air Intake Manifolds

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Phase II: Lower Plenum of the 5.4 L F-250 Air Intake Manifold, Including Recycling Scenarios

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I. Notice

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II. Abstract

This life cycle design project was a collaborative effort between the Center for Sustainable Systems (formerly the National Pollution Prevention Center) at the University of Michigan and a cross-functional team at Ford Motor Company. The project team applied the life cycle design methodology to the design analysis of three alternatives for the lower plenum of the air intake manifold for use with a 5.4L F-250 truck engine: a sand cast aluminum, a lost core molded nylon composite, and a vibration welded nylon composite. The design analysis included a life cycle inventory analysis, a life cycle cost analysis, a product performance evaluation, and an environmental regulatory/policy evaluation.

The life cycle inventory indicated that the vibration welded composite consumed less life cycle energy (1,210 MJ) compared to the lost core composite (1,330 MJ) and the sand cast aluminum manifold (2,000 MJ). The manifold contribution to the vehicle fuel consumption dominated the total life cycle energy consumption (71-84%). The vibration welded composite also produced the least life cycle solid waste, 4.45 kg, compared to 5.56 kg and 12.68 kg for the lost core composite and sand cast aluminum, respectively. Waste sand from the sand casting process accounted for a majority (92%) of the solid waste from the aluminum manifold. End-of-life waste accounted for a significant portion (55-59%) of the total solid waste from the composite manifolds.

Recycling scenarios for aluminum and nylon were investigated. Potential fluctuations in the availability of secondary aluminum would have a significant effect on the life cycle energy use of the intake manifold. A decrease in recycled aluminum content from 100% to 85% will increase the life cycle energy by 10%. Utilizing available technology for incorporating 30% post consumer nylon into the vibration welded composite manifold would reduce life cycle energy use by 4%. Similar effects for both aluminum and nylon systems were shown in other inventory categories such as CO2, solid waste and several air and water pollutant emissions.

The life cycle costs were determined for the three alternative manifolds including the manufacturing costs, customer gasoline costs, and end-of-life management costs. Estimates provided by Ford indicate that the vibration welded composite is the least expensive alternative to manufacture, costing 64% less than the lost core composite, which is 20% less expensive than the sand cast aluminum manifold. Additionally, the cost of gasoline for the aluminum manifold is $7.31 more than for the composite manifolds, over a 150,000 mile vehicle life. The end-of-life management cost for the composite manifolds was $0.25, while the sand cast aluminum manifold received a $3.38 net credit due to the value of the recycled aluminum.

This project also provided several observations on the barriers to the life cycle design process including the availability and accessibility of necessary data and institutional barriers such as the need for clear policy guidance.

This report was submitted in partial fulfillment of Cooperative Agreement number CR822998-01-0 by the National Pollution Prevention Center at the University of Michigan under sponsorship of the U.S. Environmental Protection Agency. This work covers a period from April 14, 1997 to April 30, 1999; the life cycle design analysis was conducted between May 12, 1997 to August 1, 1997.

III. Table of Contents

IV. Acknowledgments

We wish to thank Ford and the members of the Ford life cycle design team for collaborating with the Center for Sustainable Systems. We wish to acknowledge DuPont and Ecobalance for providing inventory data for use in the study.

1. Project Description

This project examined the application of life cycle design (LCD) to the lower plenum of the air intake manifold for a 5.4 liter, Ford F-250 truck engine. This is the second air intake manifold project conducted with Ford Motor Company. The first, completed in 1996, examined alternatives for use with the 2.0 L, 1995 Contour engine (Keoleian and Kar 1997). This phase II project demonstrates the application of the phase I experience to the design analysis of a different manifold system.

In completing an initial inventory for this project, the project team indicated their interest in examining the potential effect that recycling would have on the study results. For this reason, additional analyses were conducted to examine the impacts that variations in recycled content would have on the intake manifold life cycle.

This project is one of a series of life cycle design demonstration projects that have been conducted with Dow Chemical Company, Ford Motor Company, General Motors Corporation, United Solar and 3M Corporation. An overview of the life cycle design framework is provided in Appendix D of this document. A list of Project Reports from other life cycle design demonstration projects is provided in Appendix E.

1.1 Objectives

The overall objective of this project is to demonstrate the capabilities and effectiveness of the life cycle design framework in enhancing business decisions during product planning and development. This is further divided into the following specific objectives:

1) Demonstrate the ability to apply life cycle design tools in an efficient and timely manner
    a) measure the time and human resources required to conduct the inventory and cost analyses
    b) identify barriers and opportunities to streamline the process
2) Analyze the decision making process to understand how life cycle issues are addressed
    a) identify the major internal and external requirements that influence design decisions and determine their relative importance in the decision making process
    b) identify the interrelationships between performance, cost and environmental analyses

1.2 Project Team

The success of this project is due largely to the support and expertise of the project team. The core project team was composed of representatives from the University of Michigan as well as representatives from Ford's V-Engine Operation Environmental Engineering, Scientific Research Laboratory, and Intake Manifold Design.

Two representatives from V-Engine Operation Environmental Engineering participated as members of the core team. A representative from V-Engine Operations was able to provide background on Ford's environmental policies and requirements as well as some knowledge of the environmental implications of several manufacturing processes. Another representative from V-Engine Operations served as the project facilitator. The responsibilities of the facilitator included establishing the core team, organizing meetings, and contacting information sources within Ford.

The Scientific Research Laboratory team member had experience with LCD as well as a working knowledge of the history of life cycle studies performed at Ford. This individual also provided information from Ford’s life cycle inventory databases.

The Intake Manifold Design Engineer provided the team with advanced knowledge of the manifold system, including the materials of construction, and manufacturing processes involved in production. Since this part is manufactured by a Tier 1 supplier, the design engineer was responsible for interacting with the suppliers to obtain the necessary data. Additionally, the design engineer was able to provide a complete performance evaluation of the alternative manifold designs.

The University of Michigan team members contributed to the project by educating team members on LCD methodology and tools, as well as developing the project plan, providing inventory data, system modeling, and writing the project report.

Members of the core project team are indicated below:

Ford Motor Company	University of Michigan
Fred Heiby, V-Engine Operation Environmental Engineer	Greg Keoleian, Research Director
Greg West, Intake Manifold Design Engineer	David Spitzley, Research Assistant
Mark Hall, V-Engine Operation Environmental Engineer	
Mia Costic, Scientific Research Laboratory Engineer	

The following Ford staff were instrumental in initiating this project:

- Wayne Koppe, Environmental Engineering Supervisor
- John Sullivan, Research Materials Supervisor
- Jim Mazuchowski, Intake Manifold Design Supervisor
- Bob Griffiths, Intake Manifold Design Supervisor
- Phil Lawrence, Environmental Quality Engineer

1.3 Project Timeline

The original project timeline called for the project to run for approximately 3 months (May 12th - July 18th). The project ran slightly longer than originally anticipated and was completed on August 1st. Data collection and modeling for the environmental and cost analyses required more time than expected. However, preliminary findings were reported to Ford management by the July deadline. Recycling scenarios were examined in a separate study which required one additional month for completion.

2. Methodology

2.1 Product System Definition

This project considered the lower plenum[1] of an air intake manifold for a 5.4 L Ford F-250 truck engine. Three types of manifolds were studied: aluminum, lost core composite, and vibration welded composite. The lost core composite is the manifold currently used in a majority of the 5.4L engines. The aluminum manifold is currently used in Ford's 5.4L natural gas vehicles. The vibration welded composite is not currently used in any vehicles, however, beginning with the 1999 model year a portion of the 5.4L engines will use this manifold. The manifolds were modeled using process data for vibration welding obtained from Ford. All three manifold alternatives are manufactured by a Tier 1 supplier and purchased by Ford.

The aluminum manifold, currently composed of 100% secondary aluminum, is manufactured using a sand casting process. This manifold requires no extra fittings, inserts or attachments of any kind. Attachment points are drilled and tapped directly into the cast aluminum part. The first type of composite manifold studied (lost core) is currently produced from glass fiber (33%) reinforced nylon 6,6 with no post-consumer recycled content, through the "lost core" molding process. Inserts must be added to this manifold after molding to allow attachment. A noise, vibration and harshness (NVH) tent must also be added to the manifold to insure proper acoustical performance. This tent is placed over the manifold during engine assembly. The other type of composite manifold studied (vibration welded) is produced through a two step process. First, the composite resin is injection molded to form the individual sections of the manifold. Then the manifold sections are bonded together through a procedure known as vibration welding. This manifold also requires the same inserts and NVH tent required by the lost core composite manifold.

Inserts in the composite manifolds could be made of either brass or steel. The effects of this material change on the manifold life cycle were considered. It was determined that due to differences in density the brass inserts would weigh approximately 7% more than the steel inserts. However, changing the mass of the inserts had a negligible effect on the overall manifold life cycle inventory. A preliminary study of the effects of changing insert material on manifold life cycle burdens indicated that manifolds with brass inserts had slightly lower burdens than those with steel. Based on these results only manifolds with brass inserts are examined in this report.

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[1] Although the product studied was the lower plenum of an intake manifold, this product is frequently referred to as a manifold in this report.

Once the base case study had been completed, scenarios for recycling of brass, aluminum and nylon were examined. Brass and aluminum are both commonly recycled and the current infrastructure supports the recycling of these materials from the end-of-life manifold back to the metal market as scrap (Sundberg 1996). This scrap is a source of secondary material for the auto industry. However, current infrastructure does not support the recycling of the end-of-life nylon composite from manifolds. Technology recently developed by a number of polymer manufacturers does allow recycling of post consumer carpet into nylon for use in automotive applications (Coeyman 1995),(Keller, Haaf, and Sylvester 1997),(Fairley 1994),(Hagberg and Dickerson 1997). Successful use of secondary nylon from carpeting has been demonstrated in the Ford Carpet to Car Parts project. Currently, this project incorporates recycled nylon into engine air cleaner housings for nearly 3 million Ford and Lincoln-Mercury vehicles each year (Ford 1997). This open loop system for nylon recycling was examined for manifolds in this study.

The recycling investigation addressed two separate issues in the manifold life cycle:

- The potential life cycle implications of changes in the supply of secondary metals on the intake manifold life cycle were examined. Producers of both the sand cast aluminum manifold and the brass inserts for the composite manifolds are known to use as much secondary material in production as possible (up 100% for aluminum and 99% for brass). However, producers must increase their use of primary materials when secondary sources are not available (Lessiter 1997). The recycling study addressed the potential effects that these slight increases in primary material use might have on the manifold life cycle.
- The study addressed the potential effects of increased availability of post consumer nylon in combination with Ford recycling requirements on the life cycle of composite manifolds.

2.1.1 Product Composition

The manifold compositions can be classified according to their body materials: aluminum or composite. The aluminum manifold is cast from a single material and requires no additional parts to meet Ford's component performance standards. The composite manifolds require both inserts and an NVH tent to perform acceptably. The NVH tent is composed of two pieces: an outer shell made from a synthetic rubber compound known as Multibase 8832, and an inner mat produced from polypropylene. Detailed product composition data are provided in Table 1.

Table 1. Manifold material composition

Sand Cast Aluminum Body		5.58 kg	
Total Aluminum Manifold			5.58 kg
Nylon-Glass (33%) Composite Body		2.24 kg	
Brass Inserts		0.03024 kg	
NVH Tent			
Multibase 8832 Outer		0.576 kg	
Barium sulfate	0.374 kg		
Styrene butadiene rubber (SBR)	0.101 kg		
Polypropylene	0.0505 kg		
Polyethylene	0.0505 kg		
Polypropylene Mat Inner		0.0454 kg	
Total Composite Manifold			2.89 kg

2.1.2 Process Flow Diagrams

Figures 1 - 3 show the life cycle process steps of three manifold systems. Closed loop recycling of metals is shown in these diagrams. The intake manifold system is a part of the vehicle life cycle, which includes other parts and components. In this study the metal from the shredded manifold is recycled back into a new manifold system. In practice the manifold is part of the larger scrap metal stream. Secondary metals from other sources, in the case of aluminum, or primary metals, in the case of brass, are required to replace a small fraction of the metal lost in the system. Closed loop recycling is shown in these Figures, although the percentage of closed loop recycling that takes place in the manifold life cycle is not known.

In the base case it was assumed that the nylon required for composite material production was produced from primary sources (natural gas, petroleum, etc.). In the second part of the study the effects of producing nylon from post consumer carpeting were examined. Production of nylon resin from post consumer carpeting requires several additional processing steps not shown in Figures 2 and 3, including: carpet collection, backing removal, and depolymerization (Keller, Haaf, and Sylvester 1997). The Ford experience with the engine air cleaner housings indicates that significant reductions in the amount of carpeting sent to landfill are possible using this process (Ford 1997). Based on the material production data used here, 0.75 kg of post consumer carpeting are used in the production of 1.0 kg of nylon-glass composite.

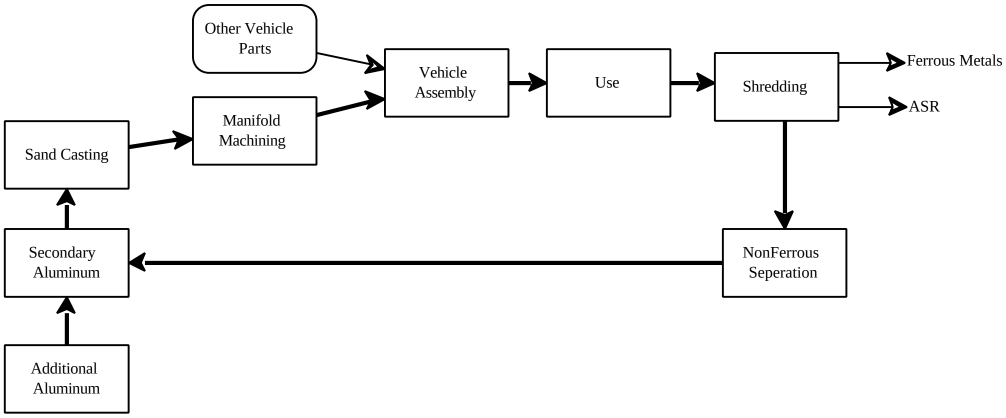

Figure 1. Process flow diagram for the aluminum manifold (closed loop recycling steps shown)

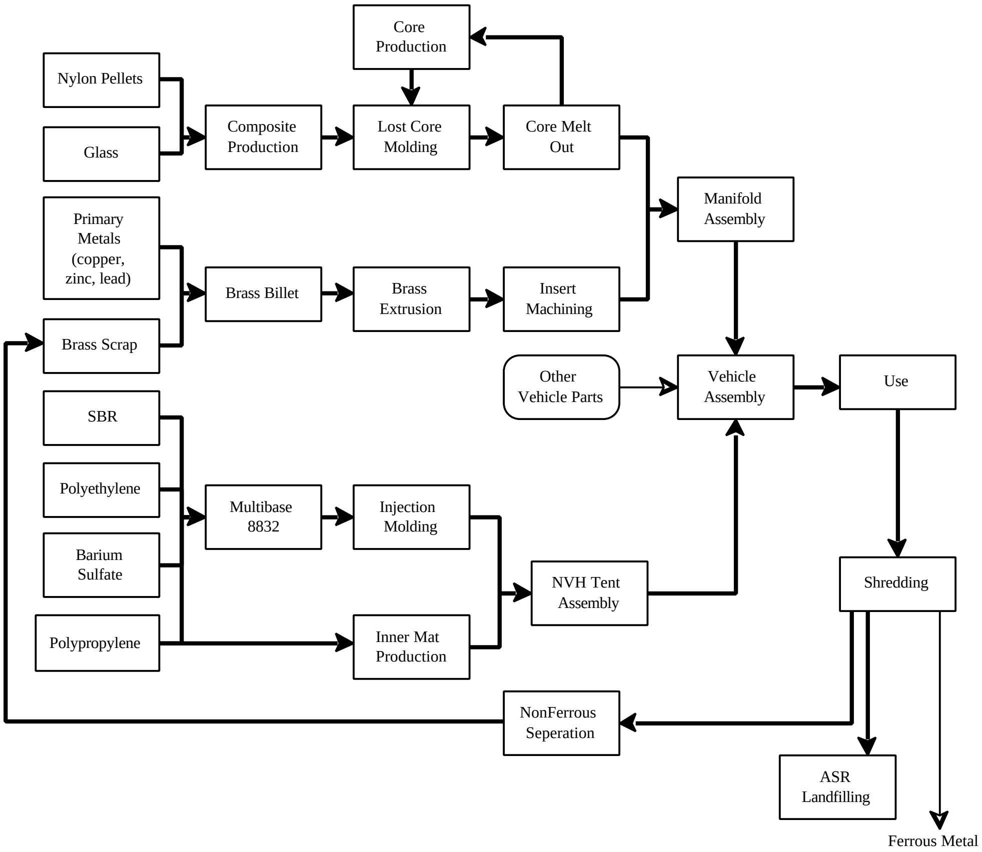

Figure 2. Process flow diagram for the lost core composite manifold

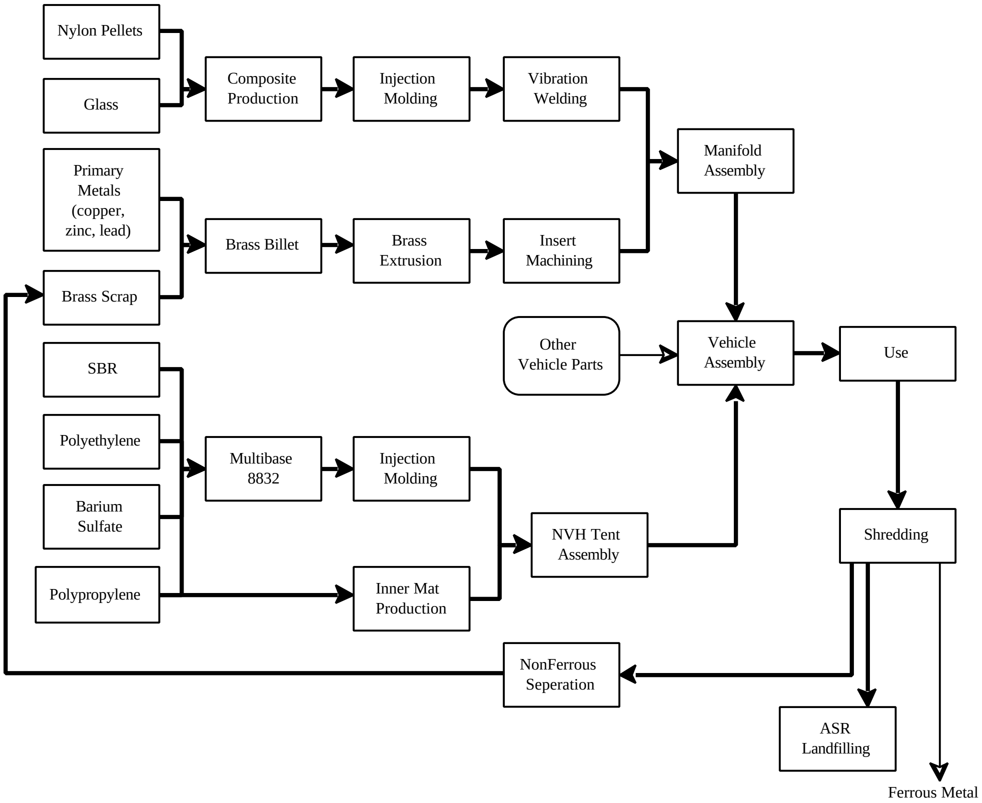

Figure 3. Process flow diagram for the vibration welded composite manifold

2.2 Inventory Analysis

2.2.1 Modeling Assumptions

The assumptions made to facilitate data collection and modeling enabled the project team to obtain results of a reasonable quality in a timely manner. Table 2 presents the boundaries and assumptions that provided a basis for data collection and system modeling.

Table 2. Boundaries and assumptions for the LCD study

Material Production	• Secondary aluminum is assumed to come from automotive or similar sources that require only limited separation and re-alloying. • In the base case brass inserts are assumed to be made from 99% secondary brass. The effects of changing this percentage were examined in the recycling study. • The Multibase 8832 supplier considers the composition of this material to be confidential, however it is known that this material consists of 65% barium sulfate. It is assumed that the remaining material composition is 17.5% styrene butadiene rubber, and 8.75% each of polypropylene and polyethylene. • The Multibase 8832 material is assumed to be a simple mixture of the components (SBR, PP, PE, and $BaSO_4$); impacts associated with potential melting and mixing of these materials to form Multibase are neglected.
Manufacturing	• Loss of tin bismuth core in lost core casting for composite manifolds is neglected due to a 99% recycle rate. • Start-up losses are assumed to be 2.6% for injection molding, and 5% for lost core molding as done in the previous project (Keoleian and Kar 1997). It is believed that these values could be less than 1% in some situations, however, no available data support this assertion. • The Tier 1 supplier currently landfills the core sand (24 lb.) from the sand casting process. Accordingly, in this project the core sand is assumed to be landfilled. Due to contamination, this sand can not be reused in casting. It is noted that core sand at other facilities has been successfully reused in construction applications such as cement. • Fitting the inserts in the manifold is neglected due to the relatively small amount of resources consumed during this process. • It is assumed that due to the similarity in melting points Nylon-6 injection molding (491° F) energy will serve as a reasonable surrogate for injection molding of Multibase 8832 (420-440° F). • Scrap generated from NVH tent outer molding was not inventoried but is expected to be negligible. • The fabrication (mat production) of the NVH tent inner component is neglected due to its small mass (0.1 lb.) and the lack of available energy and waste data. However, material production burdens of polypropylene are inventoried. • It is assumed that there are negligible environmental impacts associated with placing the NVH tent inner liner inside the outer cover. This procedure requires no fasteners and is most likely done by hand. • Environmental impacts of engine assembly are assumed not to vary among manifold systems.
Use	• A vehicle life of 150,000 miles (10 years) was assumed. • No warranty claims have been made against any of the manifolds considered, therefore, repair and replacement of manifolds was not included in the analysis. • Emissions and fuel use were calculated under the assumption that these values were linearly proportional with weight savings.
End-of-life	• It is assumed that no manifolds are removed from the vehicle prior to shredding. • An overall loss of 5% of metals is assumed in shredding and separation. • All non-metal materials are assumed to be disposed of in a non-hazardous waste landfill.

2.2.2 Data Collection and Analysis

Data for the inventory and cost analyses were collected from several data sources. In order to maintain consistent energy carrier data the Ecobalance DEAM™ (Data for Environmental Analysis and Management) database was used to provide energy data for all sources.

2.2.2.1 Material Production

Material production data from the DEAM™ database was used when available, however it was necessary to supplement this data with additional sources. Whenever an additional data source was used, the DEAM™ energy data was substituted for the existing energy source data to ensure consistency of the results. A list of the product materials used in the inventory and the corresponding data sources is shown in Table 3.

Table 3. Material production data sources

Aluminum (secondary)	DEAM™
Barium Sulfate	Ford
Brass Ingot (primary)	DEAM™
Brass (secondary)	(Keoleian and Kar 1997)
Nylon-Glass Composite	DuPont
Post Consumer Composite	DuPont
Polyethylene	DEAM™
Polypropylene	DEAM™
Styrene Butadiene Rubber (SBR)	Ford

2.2.2.2 Manufacturing

Manufacturing data come mainly from the previous LCD project on intake manifolds (Keoleian and Kar 1997) with upstream energy data supplied by the DEAM™ energy carrier modules. This data was supplemented with data from Ford on manufacturing steps unique to the systems studied here. Table 4 provides a complete list of the manufacturing processes and the sources for data. In some cases it was necessary to contact the Tier 1 supplier for data on a manufacturing process. In Table 4, Tier 1 information is listed with Ford as the source to preserve supplier confidentiality.

Table 4. Manufacturing process data sources

Aluminum Sand Casting	(Keoleian and Kar 1997), Ford
Brass Extrusion	(Keoleian and Kar 1997)
Composite Injection Molding	(PPI 1995)
Composite Lost Core Molding	(Keoleian and Kar 1997)
Composite Vibration Welding	Ford
Multibase 8832 Injection Molding	(PPI 1995)

2.2.2.3 Use

EPA emission testing and fuel economy data were used to determine the contribution of the intake manifold to the total vehicle use phase burdens. These data are presented in Tables 5 and 6. Also included in Table 5, are deterioration factors after 50,000 and

100,000 miles of travel. These data indicate an increase in vehicle emissions with increased miles driven.

Table 5. Lincoln Navigator[†] (5.4 L) EPA certification emission factors (provided by Ford)

	base (g/mi.)	Deterioration Factors‡	
	4,000 mi.	50,000 mi.	100,000 mi.
Carbon Monoxide (CO)	0.990	1.062	1.123
Nitrogen Oxides (NOx)	0.030	1.130	1.329
Total Hydrocarbon (THC)	0.082	1.000	1.102
Non Methane Hydrocarbon (NMHC)	0.078	1.056	1.144

[†] the Navigator and the F-250 are in the same engine family, data for the Navigator is used as a surrogate for F-250 emissions data.

‡Emissions at 50,000 and 100,000 miles are determined by multiplying the base emission factor (g/mi) by the deterioration factor (dimensionless)

Table 6. F-250 (5.4 L) Fuel economy (provided by Ford)

City (mi./gal)	13
Highway (mi./gal)	17

In order to determine the vehicle life time fuel consumption and emissions that should be allocated to the manifold, the relationship of fuel economy to changes in vehicle weight had to be calculated as follows.

$$r = \frac{\Delta FE}{\Delta M} \qquad \text{eq. 2-1}$$

where,

ΔFE	percentage change in vehicle fuel economy
ΔM	specified percentage change in vehicle mass (e.g. 10%)
r	is dimensionless

Ford determined that for a 10% change in the mass of the F-250 a 4.9% change in the fuel economy could be observed. Therefore, an r value of 0.49 was used in this project. Using this value, the amount of vehicle fuel consumption which is attributed to the manifold can be calculated using equation 2-2.

$$FC = r\left(\frac{0.45}{FE_h} + \frac{0.55}{FE_c}\right)L\frac{m_m}{M} \qquad \text{eq. 2-2}$$

where,

FC	Fuel consumption attributed to the manifold (gal)
FE_h	Vehicle highway fuel economy (17 mi./gal)
FE_c	Vehicle city fuel economy (13 mi./gal)
L	Total miles traveled over the vehicle lifetime (150,000 mi.)
m_m	Manifold mass, including all necessary inserts and parts (kg) (see Table 1 for values)
M	Vehicle Test Mass (2291 kg)

The lifetime vehicle emissions that were allocated to the manifold were calculated using the data in Table 5 and equations 2-3 and 2-4, below.

$$e_{v,i} = (1 + DF_{50,i} + DF_{100,i})\frac{e_{4,i}}{3} \qquad \text{eq. 2-3}$$

where,

i	Emission type (CO, NO_x, THC, or NMHC)
$e_{v,i}$	weighted vehicle emission factor for emission i (g/mi.)
$DF_{50,i}$	50,000 mile deterioration factor for emission i (see Table 5 for values)
$DF_{100,i}$	100,000 mile deterioration factor for emission i (see Table 5 for values)
$e_{4,i}$	Base emission factor measured at 4,000 miles (g/mi.) (see Table 5 for values)

Values for e_v are shown in Table 7, below. In equation 2-3 the three vehicle emission factors (e_4, DF_{50}, and DF_{100}) were weighted equally (1/3 each) to arrive at the total vehicle emission factors shown in Table 7. This was done to reflect the selected 150,000-mile vehicle life.

Table 7. Weighted vehicle emission factors (g/mi.)

Emission type (i)	Emission Factor (e_v) (g/mi.)
CO	1.051
NO_x	0.035
THC	0.085
NMHC	0.083

These values were used in equation 2-4 to calculate the lifetime vehicle emissions that could be attributed to the manifold.

$$e_i = re_{v,i}L\frac{m_m}{M} \qquad \text{eq. 2-4}$$

where,

e_i	Lifetime vehicle emissions that are allocated to the manifold (g)

Carbon dioxide (CO_2) emissions are the only vehicle emissions that were not determined using the above equation. These emissions are not tracked by the EPA testing system; however, they can be calculated based on the vehicle fuel consumption. Using the result of the vehicle fuel consumption calculation (eq. 2-2), shown above, the carbon dioxide emissions are determined using equation 2-5.

$$e_{CO_2} = \frac{44}{12}(2408FC - \frac{12}{28}e_{CO} - \frac{12}{13.9}e_{THC}) \qquad \text{eq. 2-5}$$

where,

e_{CO2}	Lifetime vehicle carbon dioxide emissions that are allocated to the manifold (g)

The constants in equation 2-5 are for unit conversion. These values are based on molecular weight, the density of regular gasoline (0.74 kg/L), and the carbon content of gasoline (86%) (DeLuchi 1991).

Fuel use information was also connected to DEAM™ data for fuel production in order to account for the upstream burdens of gasoline production and distribution. No other impacts or costs, such as off-cycle emissions or manifold maintenance were accounted for in the use phase.

2.2.2.4 End-of-life

The manifold end-of-life was modeled as a two-stage process. The two stages considered were manifold shredding and material separation. In the shredding stage the manifold is considered part of the vehicle hulk as it is fed through the shredder. The burdens from shredding are allocated to the manifold on a mass basis. The second stage, separation, is included only for the metal fraction of the manifold. Impacts associated with separation and recovery of a metal from mixed non-ferrous shredder product are allocated to the manifold in this stage. When applicable, closed loop recycling of metals is considered. The maximum percentage of manifold raw material that could, under the conditions of this study, be supplied by end-of-life manifolds is 81% for aluminum and 90% for Brass. However, no data is available on the percentage of manifold material that actually returns to the manifold system. These values include only end-of-life material and do not take into account other recyclable scrap generated throughout the life cycle.

In the current automotive retirement infrastructure, plastic materials are not recovered, but rather disposed of in landfills as part of the auto shredder residue (ASR) fraction. Hence, the nylon component of the composite manifold was considered waste at end-of-life.

2.3 Performance Analysis

Ford designers evaluate the performance of alternative products using a system similar to Kepner-Tregoe analysis (a full discussion of the Kepner-Tregoe decision making process can be found in (Kepner and Tregoe 1965)). In the Ford system each performance requirement category is assigned a weighting factor from 1 to 10. Then the alternative products are given a ranking, also 1 to 10, for each of the categories. Once an alternative has been given a ranking in a particular category, the ranking is multiplied by the corresponding weighting factor to determine the score for that category. Finally all scores for an alternative are summed to give a total score.

2.4 Cost Analysis

The costs to stakeholders at every stage of the life cycle were considered.

2.4.1 Material

Material cost is the cost for the raw materials used in manifold production. Generally, resin prices were found in Plastics Technology (Plastics Technology 1997) and metals prices come from the American Metal Market (American Metals Market 1997). The material costs are provided to indicate the relative contribution to the total life cycle cost.

2.4.2 Manufacturing

Manufacturing costs are proprietary and are not publicly available, however, estimates of the relative costs to Ford (for both the manifold and tent) were provided by Ford for use in this study. The manufacturing costs include the cost of materials in addition to labor and other fixed and variable manufacturing costs.

2.4.3 Use

The cost of gasoline was the only use phase cost evaluated. Lifetime cost of fuel was determined based on the national average price of gasoline for April 1997 (1.23 $/gal.) (EIA 1997) and the lifetime fuel consumption attributed to the manifold.

2.4.4 End-of-life

Five end-of-life costs were evaluated. Three of these were determined based on data from the American Plastics Council (APC)(APC 1994): transportation of hulks (i.e. scrapped vehicles) to a shredding facility, transportation of materials to a recovery facility, and landfill disposal cost. The remaining two costs, shredder and recovery facility operation, were determined from data published in the previous manifold study (Keoleian and Kar 1997). The value of material recovered at the end-of-life was also evaluated. Based on current infrastructure conditions metals are the only materials with a salvage value.

A total life cycle cost was calculated by subtracting the end-of-life value from the sum of the manufacturing, use and end-of-life costs of the manifold. This life cycle cost analysis does not account for externalities such as NOx, CO and HC emissions in the use phase or in other life cycle stages.

3. Results

3.1 Environmental Inventory

3.1.1 Base Case

The results of the base case inventory analysis for the total life cycle of the three manifold alternatives is shown in Table 8. Twelve inventory items were selected for this Table, the complete inventories for each manifold are available in Appendix A. The inventory analysis indicated that the aluminum manifold generally incurred greater burdens than the composite manifolds. This is due to the significantly heavier weight of the aluminum manifold and the effect this has on the use phase inventory, specifically emissions related to greater fuel consumption. On the other hand, the aluminum manifold produced fewer airborne emissions of lead and sulfur oxides than either of the composite manifolds. Differences in the energy sources used throughout the life cycle account for the observed differences in emissions. Over 60% of the energy used in the production of the aluminum manifold comes from natural gas, while both of the composite manifolds rely heavily on electrical energy from coal.

Table 8. Life cycle inventory profiles for alternative manifolds (select inventory items)

Manifold Material		Aluminum	Composite	
Manufacturing Process		Sand Casting	Lost Core Molding	Vibration Welding
Airborne Emissions				
Carbon Dioxide (CO_2)	g	139,000	82,100	73,300
Carbon Monoxide (CO)	g	215	135	132
Lead (Pb)	g	0.0002	0.0063	0.0035
Nitrogen Oxides (NO_x)	g	90.8	96.6	71.3
Sulfur Oxides (SO_x)	g	79.6	129	93.5
Waterborne Emissions				
BOD_5 (Biochemical Oxygen Demand)	g	23.4	15.2	15.1
COD (Chemical Oxygen Demand)	g	198	132	131
Dissolved Solids	g	1442	752	748
Suspended Solids	g	108	223	219
Total Solid Waste	kg	12.68	5.56	4.45
Energy Use	MJ	2,000	1,330	1,210

Figures 4 and 5, below show how the energy and solid waste values, from Table 8, are distributed across the life cycle. In Figure 5 the effect of the scrapped mold sand from the sand casting process can be seen in the high relative contribution of manufacturing to the total solid waste.

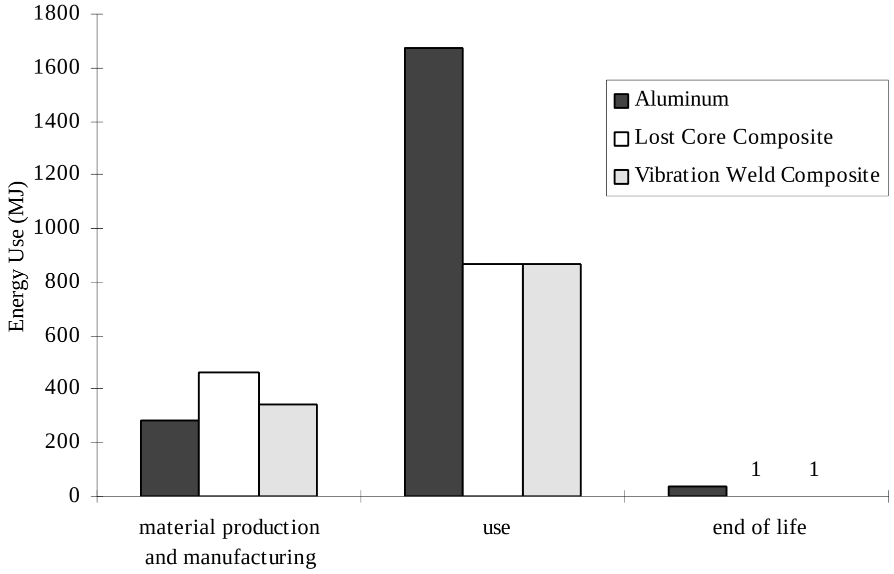

Figure 4. Distribution of energy use for the life cycle of intake manifolds (MJ)

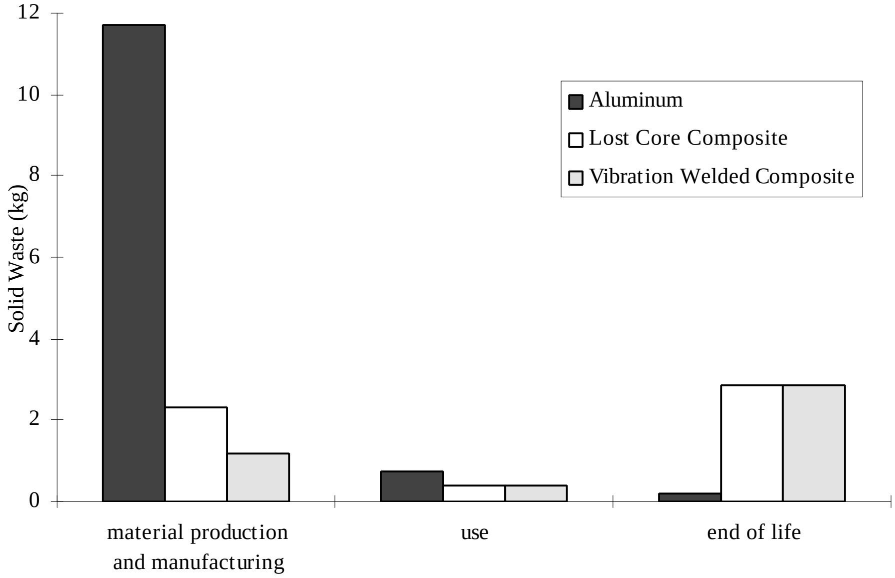

Figure 5. Distribution of solid waste for the life cycle of intake manifolds (kg)

3.1.2 Recycling Effects

Table 9 provides selected inventory results for the analysis of alternative recycling scenarios in the life cycle of air intake manifolds. The results of the initial life cycle inventory of air intake manifolds, shown in Table 8, indicated that in most cases the vibration welded manifold incurred lower burdens than the lost core molded composite. For this reason only the vibration welded manifold was considered in the recycling analysis. The complete inventories for the manifolds shown in Table 9 are available in Appendix B.

Table 9. Life cycle inventory profiles for alternative recycling scenarios (select inventory items)

Manifold Material		Aluminum	Composite
Recycled Content		85%	30% †
Manufacturing Process		Sand Casting	Vibration Welding
Airborne Emissions			
Carbon Dioxide (CO_2)	g	146,000	71,800
Carbon Monoxide (CO)	g	269	123
Lead (Pb)	g	0.0012	0.0038
Nitrogen Oxides (NO_x)	g	103	64.5
Sulfur Oxides (SO_x)	g	131	87.2
Waterborne Emissions			
BOD_5 (Biochemical Oxygen Demand)	g	23.4	14.3
COD (Chemical Oxygen Demand)	g	198	123
Dissolved Solids	g	1440	768
Suspended Solids	g	113	184
Total Solid Waste	kg	13.8	4.34
Energy Use	MJ	2190	1160

† 30% of the nylon material used in the production of the composite manifold is derived from post consumer carpeting.

The base case results can be compared to the results shown above to provide a better understanding of the effects that changes in recycled content have on the manifold life cycle. Base case results are combined with data from Table 9 to highlight the effects of recycled content on life cycle energy use and solid waste in Figures 6 and 7.

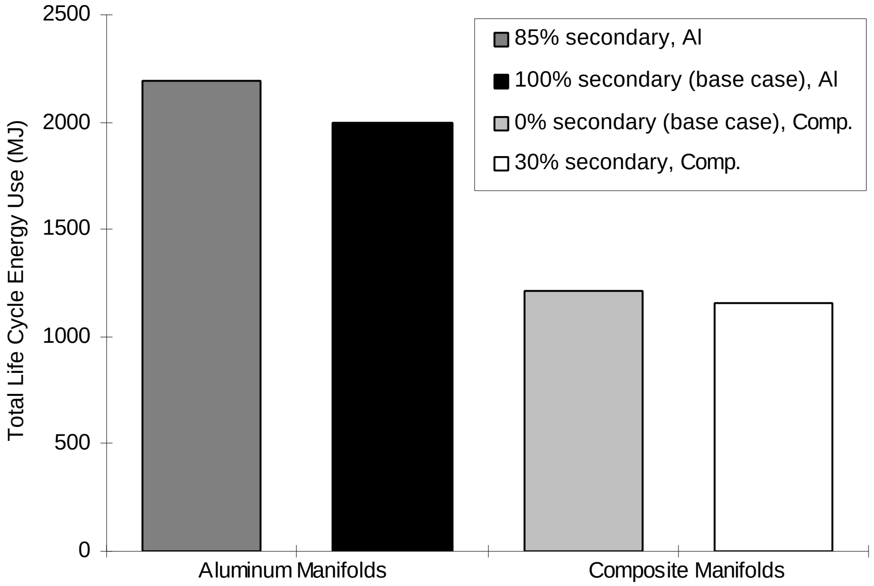

Figure 6. Life cycle energy use of manifolds with various recycled content. The secondary percentage provided for composite manifolds refers to the recycled content in the nylon used in composite production.

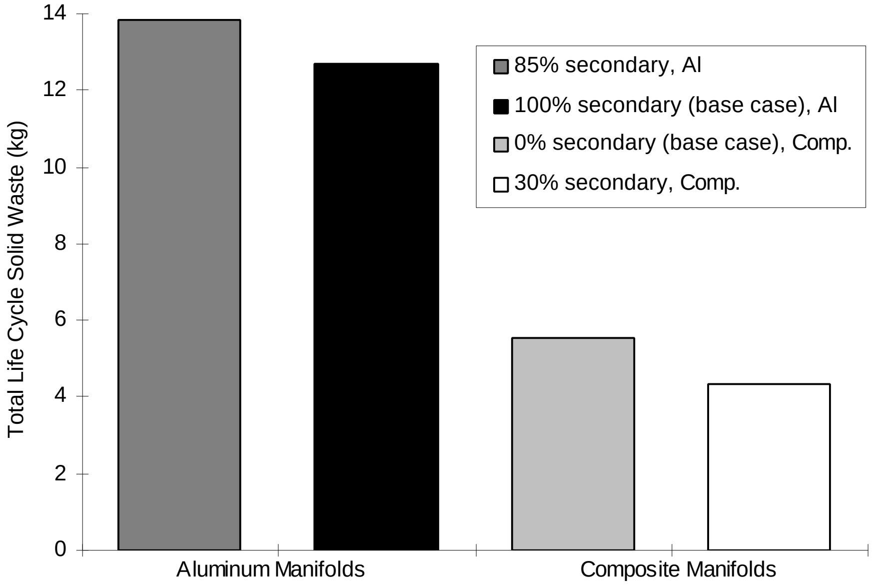

Figure 7. Life cycle solid waste of manifolds with various recycled content. The secondary percentage provided for composite manifolds refers to the recycled content in the nylon used in composite production.

The effects of changes in the fraction of recycled aluminum and nylon used in manifold production are shown in the above Figures and Table. The effect of changing the amount of recycled material in the brass inserts used in the composite manifold was also examined. It was observed that inserts produced from recycled brass generally incurred lower burdens than inserts produced from virgin ores. However, the net manifold life cycle effect of this change is negligible within the accuracy of this study.

3.2 Performance

The performance requirements used to evaluate alternative manifold designs are provided in Table 10. The rankings for each design are also indicated in this table. Performance rankings and total scores were determined by Ford and provided for use in the study. The individual requirement weightings used to determine the total scores were considered proprietary and are not included in this report. These weighting factors are used to help incorporate product objectives and priorities into the decision analysis. It is known that these rankings often take into account the manufacturing processes involved, e.g. the recyclability category includes the recyclability of ancillary manufacturing materials (sand for casting) in addition to product materials.

Table 10. Manifold performance rankings (as determined by Ford Motor Company)

	Aluminum Sand Cast	Composite Lost Core[‡]	Composite Welded[‡]
Airflow Performance	5	6	5
Weight	4	9	9
Fastener Compatibility	5	6	7
Material: Dimensional Stability	8	5	5
Recycleability	5	5	6
NVH Structural	10	5	5
NVH Acoustical	8	4	5
Manufacturing Flexibility	8	4	6
Component Integration	4	7	8
Material Scrap Rate	8	8	6
Expected Tolerances	6	6	5
Prototype Lead Time	8	4	6
Production Lead Time	5	3	8
Weighted Total[†] Score	407	415	448

[†] The total score is the sum of the weighted individual category scores. These scores are proprietary and are not shown here.
[‡] Composite manifolds are evaluated with out the NVH tent.

As seen in Table 10, above, the aluminum manifold received the highest unweighted ranking, or tied for the highest, in 7 of the 13 performance categories. The welded composite received the highest unweighted ranking in 5 categories, while the lost core composite led 4 categories. In the weighted results the welded composite received the highest overall score, followed by the other composite manifold with the aluminum manifold receiving the lowest score.

The values shown in Table 10 were provided for the base case manifolds. No data was available for the effects of varying recycled content on the performance of these manifolds. It is expected that increasing the recycled content of the composite manifold will eventually be limited by performance requirements.

3.3 Cost

The cost information for the manifolds studied is presented in Table 11. The manufacturing costs are proprietary and can not be shown. However, relative values based on the cost of the least expensive alternative (vibration welded composite) are presented. In this analysis the variable x represents the least expensive alternative and the other values are shown as factors of x. This means that in Table 11 the lost core composite and sand cast aluminum manufacturing costs are 1.57 and 1.95 times as much as those of the vibration welded composite manifold, respectively.

Table 11. Life cycle costs for manifolds

	Aluminum	Lost Core Composite	Vibration Welded Composite
End-of-life Value	(\$4.97)	(\$0.02)	(\$0.02)
Material Cost‡	\$6.04	\$13.32	\$13.02
Manufacturing Cost†	\$1.95x	\$1.57x	\$x
Use Phase Cost	\$15.16	\$7.85	\$7.85
End-of-life Cost	\$1.59	\$0.27	\$0.27
Life Cycle Cost	\$11.78 + 1.95x	\$8.10 + 1.57x	\$8.10 + x

† Manufacturing costs are proprietary and only relative values can be provided

‡ Material costs are shown for reference, they are not used to calculate the life cycle cost. Manufacturing costs include material costs.

The effect of changes in recycled content on the costs of intake manifolds was not examined in detail. However, previous experience, using resin supplied by Wellman Inc., indicates that the potential for cost savings through increasing recycled content in composites exists. The use of secondary nylon in the Windstar engine fan and shroud assembly is estimated to save $400,000 annually (Phelan 1996). The base case aluminum manifold, shown in Table 11, currently contains 100% secondary aluminum. The relatively high cost of primary aluminum (American Metals Market 1997) indicates that a cost analysis would favor maintaining the high levels of secondary aluminum currently used.

3.4 Requirements

Several internal and external environmental requirements affect the manifold design process. Examples of these, as published in the previous LCD report (Keoleian and Kar 1997), are given in Table 12.

Table 12. Internal and external environmental requirements (Keoleian and Kar 1997)

	Internal	External
Energy	• Corporate citizenship • Minimize facility energy (directive D101†: energy planning and control) • Meet platform fuel economy targets	• CAFE
Materials	• Ford targets for recycled content of plastic resin (D109†, A120†, manufacturing environmental leadership) • Substance use restrictions (HEX9‡) • Reduce part/vehicle weight	• Reduce materials used, increase materials recycled
Waste	• Protect health and environment (policy letter 17) • Recyclability targets (directive F-111†) • Reduce manufacturing waste (A-120†)	• Voluntary initiatives to reduce greenhouse emissions

†Ford directives and guidelines

‡Ford Engineering Specifications for Materials

This project identified some additional guidelines from the *Ford Worldwide Design Requirements for Recycling,* these include:

- Section 3.3.2: "30% recycled glass filled PA [nylon] in virgin PA compounds." The effects of this requirement on the manifold life cycle inventory were investigated as part of this study, as presented in section 3.1.2 above.
- Section 3.4.5: "Reduce NVH materials by stiffening sections rather than by use of deadeners"

Ideally one manifold would optimally meet or exceed all of these requirements, however, none of the manifolds studied outperformed all others with regard to all of the requirements. Due to the significantly lower weight of the composite manifolds they are generally more suitable for addressing the issues of fuel economy, weight reduction and greenhouse gas reductions. The aluminum manifold is produced, with high recycled content, from a single material which is highly recyclable. This means that the aluminum manifold addresses the material reduction and recycling requirements. The aluminum manifold does not require any NVH materials addressing the NVH material reduction requirement. Although much research has been conducted to eliminate NVH materials from the composite manifold systems, no feasible solution has yet been found.

4. LCD Process Observations and Decision Making

4.1 Process Observations

The original project goals were met in two and a half months, however, the recycling examination required an additional month for completion. An average of 42 person-hours/week (combined University of Michigan/Ford) were required for project completion.

The project tasks can be divided into three areas: LCI data collection and modeling, cost data collection and modeling, and determination of environmental and performance requirements. Each of these areas is discussed in detail below.

4.1.1 Inventory Data Collection and Modeling

A majority of the project time was spent on data collection and model development (estimated at 25 - 30 person hr./wk). Much of the inventory data required for this project was available from the previous manifold study and this served as a starting point for the data collection. The first category of data required for the inventory analysis was the product composition. Once the design engineer fully understood the product composition data requirements, these data were readily obtained with assistance from suppliers. Data also had to be collected for production of some materials and several of the manufacturing processes. A large portion of the time required (15+ hr./wk.) for the inventory section of the project was spent developing a database and model to facilitate future use of the data.

4.1.2 Cost Data Collection and Modeling

Cost data is often proprietary and is therefore difficult to collect in a short time period. Ford collected the manufacturing cost data used in this project. Initial data collection yielded data of insufficient quality for use in this study, some additional effort was required by the design engineer to collect useable manufacturing cost data. Other cost data were collected from published sources with little difficulty.

Cost data were incorporated into the inventory database and model to facilitate updating data and allow evaluation of cost in conjunction with environmental concerns.

4.1.3 Performance and Environmental Requirements

The performance requirements evaluated for this project were based on a list compiled for the previous manifold study. The design engineer reviewed this list and selected a final set of performance requirements.

A majority of the environmental requirements listed as part of this project came from the previous report. Those requirements which were not part of the previous project were retrieved from the Ford Corporate intranet by the environmental engineering representative. This aspect of the project was completed ahead of schedule.

4.2 Decision Making

Currently Ford does not have a procedure for incorporating LCD into the design program. This means that there is no consistent examination of the tradeoffs between environmental, cost and performance issues in design. When this examination is done there is no clear guidance for how the tradeoffs should be evaluated. However, Ford engineers are becoming more aware of life cycle tools and the tradeoffs involved in this type of analysis. Ford unveiled an employee education course on design for the environment (DFE) in January 1997 to address this concern. However, additional policy measures are necessary to facilitate considerations of LCD early in the design process.

It is often useful to facilitate life cycle design data interpretation by summarizing information for decision making. The section that follows provides some of the options available for presenting data to decision makers. Since no single ideal method for life cycle data aggregation is available, multiple methods are described.

Several methods for data summarization are available to designers and engineers. One simple method for presenting results to decision makers is a summary table, such as Table 13. This table, developed using the base case results, presents a desired criteria and the manifold which best satisfies the criteria. Using this method some of the tradeoffs implicit in design decision making can be identified. However, the number of criteria which can be effectively evaluated using this type of table is limited.

Table 13. Summary of manifold selection criteria

Criteria	Manifold Selection
• Manifold with the lowest total life cycle energy consumption:	Vibration welded composite (1,18 MJ)
• Manifold with the highest recycled content:	Sand cast aluminum (100%)
• Manifold with the highest end-of-life recyclability[†]:	Sand cast aluminum (100%)
• Manifold with the lowest total life cycle solid waste production:	Vibration welded composite (4.45 kg)
• Manifold with the lowest life cycle cost:	Vibration welded composite ($8.10 + x)

[†] Based on current available infrastructure and technology

Data aggregation is often useful when presenting results to decision makers. The results of an environmental analysis of design alternatives frequently includes a large number of speciated emissions and further aggregation often facilitates decision making. For example the criteria air pollutants, indicated in Tables 8 and 9, can be normalized using a number of methods (Rydberg 1995),(US EPA 1995),(Grimsted et al. 1994). One method that has been used (Guinée, de Haes, and Huppes 1993) to aggregate airborne emissions data is the units of polluted air analysis, also known as the critical volume approach. An analysis of the units of polluted air (UPA) produced by each manifold further clarified tradeoffs in atmospheric emissions. The complete UPA analysis is shown in Appendix C. This analysis determined that the vibration welded manifold, the lost core composite manifold and the sand cast aluminum manifold produced 2.38×10^7 m^3, 1.68×10^7 m^3, and 1.59×10^7 m^3 UPA, respectively. Results of this type, when combined with other life cycle results, further clarify the tradeoffs in decision making.

Life cycle design can also facilitate decision making by identifying areas for improvement and evaluating the potential benefits of a design change. This project identified the sand used in the sand casting of the aluminum manifold as a source of potential life cycle improvement. Current disposal of the casting sand results in 11 kg of solid waste per manifold. If this sand were recycled, with 90% material efficiency, the total life cycle solid waste of the aluminum manifold system could be reduced to 2.9 kg. Recycling the casting sand would affect the selection criteria shown in Table 13, sand cast aluminum would be the selected manifold for lowest total life cycle solid waste.

The results of this analysis can also be used to highlight the effects of changes in recycled content. As discussed earlier, Ford design guidelines specify that recycled material be used in nylon parts. Life cycle design data can be used to identify products that would achieve substantial benefit from this change. When evaluating the potential benefits of changes in recycled content it may be useful to first target systems for which minor changes would result in significant life cycle improvements. Results, such as those shown in Section 3.1.2 for the composite manifold, can be useful in identifying such systems.

5. Conclusions and Recommendations

5.1 Conclusions

This project applied the life cycle design framework to air intake manifolds. Environmental, cost, performance, regulatory, and policy data were successfully provided in less than three months.

The design analysis consisted of three basic components: environmental analysis, cost analysis, and performance analysis. Life cycle inventory analysis and life cycle cost analysis were specific tools used to evaluate design alternatives. The life cycle inventory analysis indicated the vibration welded composite manifold incurred fewer burdens in most categories. The aluminum manifold released fewer life cycle airborne emissions of sulfur oxides and lead than the other manifolds.

The vibration welded manifold consumed the least total life cycle energy. The life cycle energy consumption for the aluminum, lost core composite, and vibration welded composite were 2000 MJ, 1,330 MJ, and 1,210 MJ per manifold, respectively. The use phase energy accounted for a major fraction of this energy: 84% for the aluminum, 71% for the lost core composite, and 74% for vibration welded composite; which indicates the significance of manifold mass on life cycle energy. The life cycle energy of the vibration welded composite manifold can be further reduced to 1,160 MJ by utilizing post consumer recycled material in accordance with the Ford 30% recycled content guideline.

The nylon composite manifolds generated the least life cycle solid waste among alternatives: vibration welded composite manifold (4.5 kg); lost-core composite manifold (5.6 kg); and the aluminum manifold (12.7 kg). The solid waste profile had a different distribution across the life cycle. The use phase solid waste originating from the gasoline fuel cycle contributed only a small portion of the total solid waste. Material production and end-of-life dominated the solid waste values. A majority of the aluminum manifold life cycle solid waste (92%) resulted form the loss of sand in the casting process. Disposal of the composite as automotive shredder residue (ASR) at end-of-life contributed a majority of the composite manifolds' life cycle solid waste (55-59%).

The life cycle cost comparison between the manifolds indicated the vibration welded composite manifold offered a cost advantage over the other manifolds. Much of these cost savings can be accounted for by the low manufacturing cost of the vibration welded manifold. Manufacturing costs for the vibration welded manifold are 64% less than for the lost core manifold and 49% less than those of the sand cast aluminum. Manufacturing costs were a significant factor in determining the life cycle cost, contributing between 70% and 78% of the total life cycle cost. Consumer gas costs also accounted for some of the cost savings; the relatively lower weight of the composite manifolds offered a $7.31 savings on gasoline.

A total of 13 performance requirements were used to evaluate each design alternative. Each of the three manifolds satisfied basic performance requirements for manufacturing and vehicle operation. The Ford analysis of performance requirements indicated that the vibration welded composite manifold out performed the other manifolds.

This project revealed several organizational factors affecting the successful implementation of life cycle design projects. One significant factor affecting the success of this project was the level of knowledge of the project team. The experience gained on the previous life cycle design project and in the design for environment course offered by Ford helped increase the project team’s understanding of life cycle design which facilitated the timely completion of the project.

An air intake manifold is only one component of the powertrain system that is part of the total vehicle system. Consequently, it makes only a relatively small contribution to the overall environmental burdens of an automobile. More widespread application of the life cycle design methodology to other vehicle components and systems, however, could help identify opportunities for environmental improvement. This project served to demonstrate the efficient application of life cycle design to an automotive component. This will hopefully allow other parts, components, and higher level vehicle systems to be studied.

5.2 Recommendations

Overall, the 5.4 L vibration welded nylon composite manifold (lower plenum), for the F-250, demonstrated the best environmental, cost, and functional performance among the alternatives. Opportunities for improvement of this system exist in: 1) the recovery of the nylon composite in the end-of-life management stage; 2) increasing the recycled content of this manifold; and 3) eliminating the need for an NVH tent.

The efficiency and utility of future LCD studies will depend on the level of support for the process provided by corporations such as Ford. There are several actions that can be taken to facilitate LCD:

- Development of a database which provides life cycle practitioners access to part material composition data.
- Development of a model and corresponding database, readily available to designers, which includes emissions, waste, and energy factors. This inventory would have to be available for a number of materials and processes.
- Informing relevant manufacturing engineers and cost estimators of life cycle projects and provide them the opportunity for contributing to the project.
- Creation of policies that support the application of life cycle tools and methodologies in the decision making process.
- Implementation of educational activities, such as the DFE course currently offered by Ford, that provide education on life cycle issues as well as corporate environmental policies and guidelines.
- Providing access to expertise with in the company. It is necessary that individuals interested in performing life cycle studies have access to both individuals and data sets within the company.
- Development of an incentive system that encourages the designer to consider life cycle design, when applicable. This system is needed to commend individuals who successfully apply life cycle methods in the design process.

When considering these recommendations it is important to remember that life cycle design is only one of a number of tools available to designers and decision makers. These recommendations are intended to facilitate use of LCD in conjunction with other design tools.

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Appendix A

Complete Life Cycle Inventory

			Sand Cast Aluminum	Lost Core Composite	Vibration Weld Composite
Material Inputs	(r) Baryte (in ground)	kg	-	0.38418	0.38418
	(r) Bauxite (Al2O3, ore)	kg	-	5.71E-05	5.70681E-05
	(r) Boron (in ground)	kg	-	0.162522	0.158728
	(r) Clay (in ground)	kg	-	0.79968	0.781011
	(r) Coal (in ground)	kg	1.73885	4.24351	2.07345
	(r) Copper (Cu, ore)	kg	-	0.000250774	0.000250649
	(r) Fluorspar (in ground)	kg	-	0.0174047	0.0169984
	(r) Iron (Fe, ore)	kg	1.93283E-06	0.000360483	0.000360483
	(r) Iron-Manganese (ore)	kg	-	3.46E-10	3.4627E-10
	(r) Lead (Pb, ore)	kg	-	9.79E-06	9.78451E-06
	(r) Lignite (in ground)	kg	0.219617	-	-
	(r) Limestone (CaCO3, in ground)	kg	0.242385	0.426625	0.419596
	(r) Natural Gas (in ground)	kg	8.00409	4.87888	4.06049
	(r) Oil (in ground)	kg	33.6662	19.2907	19.1447
	(r) Sand (in ground)	kg	10.8904	-	-
	(r) Silica (in ground)	kg	-	0.336334	0.328482
	(r) Sodium Chloride (NaCl, in ground or in sea)	kg	0.00614404	0.000881419	0.000881419
	(r) Sulfur (in ground)	kg	-	0.000620598	0.000620598
	(r) Uranium (U, ore)	kg	5.70047E-05	1.13E-04	6.01753E-05
	(r) Zinc (Zn, ore)	kg	-	6.52E-05	6.51241E-05
	Argon (Ar)	kg	0.00509201	-	-
	Metallic Addition (unspecified)	kg	0.15289	-	-
	Recovered Matter: Aluminum Scrap	kg	1.16521	-	-
	Recovered Matter: Brass	kg	-	0.00278873	0.00277261
	Water Used (total)	liter	9.36309	6.74301	6.5368
Atmospheric Emissions	(a) Alcohol (unspecified)	g	-	0.153659	0.150072
	(a) Aldehydes	g	0.0205076	0.0239109	0.0169692
	(a) Ammonia (NH3)	g	0.0110073	0.536652	0.523967
	(a) Aromatic Hydrocarbons (unspecified)	g	0.0114321	-	-
	(a) Arsenic (As)	g	-	8.04E-04	0.000785601
	(a) Barium (Ba)	g	-	2.82E-07	2.7565E-07
	(a) Benzene (C6H6)	g	0.0121749	0.0373966	0.0365236
	(a) Boron (B)	g	-	1.16423	1.13705
	(a) Cadmium (Cd)	g	2.76555E-05	0.000347527	0.000134587
	(a) Carbon Dioxide (CO2, fossil)	g	139105	82055.7	73271.8
	(a) Carbon Monoxide (CO)	g	214.873	135.373	132.049
	(a) CFC 11 (CFCl3)	g	-	4.30E-05	4.20366E-05
	(a) CFC 12 (CCl2F2)	g	-	7.97E-04	0.00077871
	(a) Chromium (Cr)	g	-	0.007103	0.00693718
	(a) Copper (Cu)	g	-	0.00329278	0.00321591
	(a) Ethylbenzene (C8H10)	g	-	0.00193333	0.0018882
	(a) Fluorides (F-)	g	2.78725E-05	1.35954	1.32776
	(a) Formaldehyde (CH2O)	g	8.26046E-05	0.00220465	0.00203544
	(a) Halogenous Matter (unspecified)	g	5.70098E-07	-	-
	(a) Halon 1301 (CF3Br)	g	4.98836E-05	-	-
	(a) Hydrocarbons (except methane)	g	146.185	41.5777	32.2275
	(a) Hydrocarbons (total)	g	239.262	175.519	142.662
	(a) Hydrogen (H2)	g	-	5.17E-05	5.17165E-05
	(a) Hydrogen Chloride (HCl)	g	0.134638	0.517659	0.505738
	(a) Hydrogen Fluoride (HF)	g	0.0790364	0.00260196	0.00254485
	(a) Hydrogen Sulfide (H2S)	g	0.0165311	0.001046	0.001046
	(a) Lead (Pb)	g	0.000230388	0.00626779	0.00345981
	(a) Manganese (Mn)	g	7.32058E-05	0.00115953	0.00113246
	(a) Mercury (Hg)	g	0.000055823	0.00227247	0.00214729
	(a) Metals (unspecified)	g	0.0428446	0.0253861	0.00188312
	(a) Methane (CH4)	g	90.1763	132.365	108.895
	(a) Nickel (Ni)	g	0.00132807	0.00392782	0.00383612
	(a) Nitrogen Oxides (NOx as NO2)	g	90.83	96.5892	71.3088
	(a) Nitrous Oxide (N2O)	g	2.04004	94.559	92.0983
	(a) Organic Matter (unspecified)	g	0.0350547	0.0486775	0.0288246
	(a) Particulates (unspecified)	g	22.0899	53.4835	25.8852
	(a) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	3.49833E-05	0.627981	0.61332
	(a) Sulfur Oxides (SOx as SO2)	g	79.56	129.219	93.4886
	(a) Xylene (C6H4(CH3)2)	g	0.000837723	0.0069219	0.0067603
	(a) Zinc (Zn)	g	0.000386112	1.18E-05	1.15543E-05
Emissions to Soil	(s) Arsenic (As)	g	-	4.66E-06	4.54822E-06
	(s) Cadmium (Cd)	g	-	3.41E-11	3.33077E-11
	(s) Chromium (Cr)	g	-	2.66E-06	2.5957E-06
	(s) Cobalt (Co)	g	-	2.30E-07	2.24884E-07
	(s) Copper (Cu)	g	-	1.23E-08	1.20367E-08
	(s) Manganese (Mn)	g	-	2.87E-09	2.80244E-09

Appendix A
Complete Life Cycle Inventory

			Sand Cast Aluminum	Lost Core Composite	Vibration Weld Composite
	(s) Mercury (Hg)	g	-	4.66E-10	4.54822E-10
	(s) Nickel (Ni)	g	-	3.10E-05	3.03214E-05
	(s) Zinc (Zn)	g	-	3.27E-06	3.19294E-06
Waterborne Emissions	(w) Acids (H+)	g	0.00101102	0.0160693	0.0159973
	(w) aluminum2 (Al3+)	g	-	2.03E-07	-
	(w) Ammonia (NH4+, NH3, as N)	g	3.43987	1.93336	1.9227
	(w) AOX (Adsordable Organic Halogens)	g	0.000036279	-	-
	(w) Aromatic Hydrocarbons (unspecified)	g	0.0100415	-	-
	(w) Arsenic (As3+, As5+)	g	0.000706145	0.00486861	0.00475495
	(w) Barium (Ba++)	g	0.0537059	0.00486861	0.00475495
	(w) Benzene (C6H6)	g	-	0.00820844	0.00801681
	(w) BOD5 (Biochemical Oxygen Demand)	g	23.4289	15.1902	15.0728
	(w) Cadmium (Cd++)	g	3.07076E-05	4.89E-05	4.77793E-05
	(w) Chlorides (Cl-)	g	464.101	237.285	236.36
	(w) Chlorinated Matter (unspecified, as Cl)	g	1.90465E-05	2.05E-06	2.00076E-06
	(w) Chromium (Cr III)	g	6.28312E-06	0.000384717	2.02915E-05
	(w) Chromium (Cr III, Cr VI)	g	0.00360846	0.00755044	0.00737418
	(w) COD (Chemical Oxygen Demand)	g	198.238	132.127	131.05
	(w) Copper (Cu+, Cu++)	g	0.00174269	0.036691	0.0358344
	(w) Cyanides (CN-)	g	5.56494E-05	3.04E-07	2.97156E-07
	(w) Dissolved Matter (unspecified)	g	1441.62	751.595	748.392
	(w) Dissolved Organic Carbon (DOC)	g	0.00958802	-	-
	(w) Fluorides (F-)	g	0.0053057	0.0170349	0.00907704
	(w) Hydrocarbons (unspecified)	g	0.0293424	0.051559	0.0515442
	(w) Inorganic Dissolved Matter (unspecified)	g	6.27108	0.0414626	0.0414626
	(w) Iron (Fe++, Fe3+)	g	0.459978	4.55E-05	2.72623E-05
	(w) Lead (Pb++, Pb4+)	g	0.00211196	3.68E-05	3.59843E-05
	(w) Manganese (Mn II, Mn IV, Mn VII)	g	-	7.27E-08	7.09798E-08
	(w) Mercury (Hg+, Hg++)	g	2.68205E-06	1.13E-09	1.10719E-09
	(w) Metals (unspecified)	g	1.00871	0.5166	0.5166
	(w) Mobile Ions	g	1.2016	0.622292	0.622292
	(w) Nickel (Ni++, Ni3+)	g	0.00177508	1.87E-04	0.000182618
	(w) Nitrates (NO3-)	g	0.01609	0.00636402	0.00448244
	(w) Nitrogenous Matter (unspecified, as N)	g	0.0114862	0.00155905	0.00155905
	(w) Oils (unspecified)	g	11.9435	7.77127	7.68615
	(w) Organic Dissolved Matter (unspecified)	g	-	0.00415073	0.00415073
	(w) Phenol (C6H6O)	g	80.4359	41.6573	41.6572
	(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	g	0.0207308	0.00237523	0.00237432
	(w) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	0.000136046	-	-
	(w) Salts (unspecified)	g	-	163.463	159.647
	(w) Selenium (Se II, Se IV, Se VI)	g	-	1.96E-07	1.91576E-07
	(w) Sodium (Na+)	g	587.365	305.433	304.24
	(w) Sulfates (SO4--)	g	3.98083	0.00411705	0.00243549
	(w) Sulfides (S--)	g	0.000334933	1.60E-05	1.60321E-05
	(w) Suspended Matter (organic)	g	-	0.02597	0.02597
	(w) Suspended Matter (unspecified)	g	108.151	222.782	219.468
	(w) TOC (Total Organic Carbon)	g	-	0.376318	0.367533
	(w) Toluene (C7H8)	g	0.00134103	-	-
	(w) Water (unspecified)	liter	-	275.182	268.758
	(w) Water: Chemically Polluted	liter	0.00103032	0.0630869	0.00332745
	(w) Zinc (Zn++)	g	0.00358255	0.0376318	0.0367533
Material Outflows	Recovered Matter (total)	kg	0.331046	1.69E-05	1.68551E-05
	Recovered Matter (unspecified)	kg	-	1.69E-05	1.68551E-05
	Recovered Matter: Non Ferrous Metals	kg	0.331046	-	-
	Waste (FGD Sludge)	kg	0.055391	0.0734538	0.0306857
	Waste (hazardous)	kg	0.0761766	0.0395586	0.039462
	Waste (municipal and industrial)	kg	2.97358E-06	0.00746792	0.00746792
	Waste (total)	kg	12.6848	5.55875	4.44801
	Waste (unspecified)	kg	0.561681	1.33605	0.405271
	Waste: Automotive Shredder Residue (ASR, Non Metallic Materials)	kg	0.139481	2.85993	2.85993
	Waste: Mineral (inert)	kg	0.0604631	0.00341528	0.00341487
	Waste: Non Mineral (inert)	kg	3.86566E-05	-	-
	Waste: Non Toxic Chemicals (unspecified)	kg	-	0.000934474	0.000934474
	Waste: Slags and Ash (unspecified)	kg	0.0914176	0.857346	0.838457
Energy Inputs	E Feedstock Energy	MJ	1489.43	774.632	770.231
	E Fuel Energy	MJ	508.38	556.534	438.929
	E Non Renewable Energy	MJ	1992.86	1325.02	1206.6
	E Renewable Energy	MJ	4.68109	6.14299	2.42876
	E Total Primary Energy	MJ	1997.54	1331.16	1209.03

Appendix B

Complete Life Cycle Inventory for Manifolds with Variations in Recycled Content

			Sand Cast 85% secondary Aluminum	Vibration Weld 30 % secondary Composite
Material Inputs	(r) Baryte (in ground)	kg	-	0.38418
	(r) Bauxite (Al2O3, ore)	kg	3.60522	5.70681E-05
	(r) Boron (in ground)	kg	-	0.158707
	(r) Clay (in ground)	kg	-	0.780715
	(r) Coal (in ground)	kg	3.21266	2.16335
	(r) Copper (Cu, ore)	kg	-	0.000250649
	(r) Fluorspar (in ground)	kg	-	0.0169929
	(r) Iron (Fe, ore)	kg	1.6429E-06	0.000360483
	(r) Iron-Manganese (ore)	kg	-	3.4627E-10
	(r) Lead (Pb, ore)	kg	-	9.78451E-06
	(r) Lignite (in ground)	kg	0.304258	-
	(r) Limestone (CaCO3, in ground)	kg	0.411357	0.419728
	(r) Natural Gas (in ground)	kg	8.18724	3.3786
	(r) Oil (in ground)	kg	34.8448	18.6918
	(r) Sand (in ground)	kg	10.8904	-
	(r) Silica (in ground)	kg	-	0.328543
	(r) Sodium Chloride (NaCl, in ground or in sea)	kg	0.0581833	0.000881419
	(r) Sulfur (in ground)	kg	-	0.000620598
	(r) Uranium (U, ore)	kg	0.000126985	6.33751E-05
	(r) Zinc (Zn, ore)	kg	-	6.51241E-05
	Argon (Ar)	kg	0.00432821	-
	Calcium Fluoride (CaF2)	kg	0.0246827	-
	Metallic Addition (unspecified)	kg	0.129957	-
	Recovered Matter: Aluminum Scrap	kg	0.173629	-
	Recovered Matter: Brass	kg	-	0.00277261
	Sulfur Dioxide (SO2)	kg	0.0190465	-
	Water Used (total)	liter	-	13.583
Atmospheric Emissions	(a) Alcohol (unspecified)	g	-	0.10505
	(a) Aldehydes	g	0.020472	0.0171531
	(a) Ammonia (NH3)	g	0.0238653	0.368979
	(a) Aromatic Hydrocarbons (unspecified)	g	0.0630325	-
	(a) Arsenic (As)	g	-	0.000741497
	(a) Barium (Ba)	g	-	1.92955E-07
	(a) Benzene (C6H6)	g	0.0272372	0.0255665
	(a) Boron (B)	g	-	1.13705
	(a) Cadmium (Cd)	g	0.000279623	0.000097694
	(a) Carbon Dioxide (CO2, fossil)	g	146110	71766.5
	(a) Carbon Monoxide (CO)	g	268.618	123.238
	(a) CFC 11 (CFCl3)	g	-	2.94256E-05
	(a) CFC 12 (CCl2F2)	g	-	0.000545097
	(a) Chromium (Cr)	g	-	0.00632868
	(a) Copper (Cu)	g	-	0.00282656
	(a) Ethylbenzene (C8H10)	g	-	0.00132174
	(a) Fluorides (F-)	g	0.800757	1.32742
	(a) Formaldehyde (CH2O)	g	8.25693E-05	0.00143932
	(a) Halogenous Matter (unspecified)	g	2.3698E-06	-
	(a) Halon 1301 (CF3Br)	g	0.000332957	-
	(a) Hydrocarbons (except methane)	g	155.698	32.0613
	(a) Hydrocarbons (total)	g	285.875	135.781
	(a) Hydrogen (H2)	g	-	5.17165E-05
	(a) Hydrogen Chloride (HCl)	g	0.793701	0.379579
	(a) Hydrogen Fluoride (HF)	g	0.137828	0.00263099
	(a) Hydrogen Sulfide (H2S)	g	0.0165311	0.001046
	(a) Lead (Pb)	g	0.0012038	0.00378338
	(a) Manganese (Mn)	g	0.000365414	0.000792722

Appendix B

Complete Life Cycle Inventory for Manifolds with Variations in Recycled Content

			Sand Cast 85% secondary Aluminum	Vibration Weld 30 % secondary Composite
	(a) Mercury (Hg)	g	0.000151619	0.00230716
	(a) Metals (unspecified)	g	0.250266	0.00188035
	(a) Methane (CH4)	g	105.567	86.6743
	(a) Nickel (Ni)	g	0.00926248	0.00329654
	(a) Nitrogen Oxides (NOx as NO2)	g	103.081	64.4775
	(a) Nitrous Oxide (N2O)	g	2.07807	64.6888
	(a) Organic Matter (unspecified)	g	0.0350395	0.0289343
	(a) Particulates (unspecified)	g	42.5497	22.795
	(a) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	0.0388029	0.716319
	(a) Sulfur Oxides (SOx as SO2)	g	131.11	87.1588
	(a) Xylene (C6H4(CH3)2)	g	0.000837723	0.00473221
	(a) Zinc (Zn)	g	0.00244663	8.08802E-06
Emissions to Soil	(s) Arsenic (As)	g	-	3.18375E-06
	(s) Cadmium (Cd)	g	-	2.33154E-11
	(s) Chromium (Cr)	g	-	1.81699E-06
	(s) Cobalt (Co)	g	-	1.57419E-07
	(s) Copper (Cu)	g	-	8.42569E-09
	(s) Manganese (Mn)	g	-	1.96171E-09
	(s) Mercury (Hg)	g	-	3.18375E-10
	(s) Nickel (Ni)	g	-	0.000021225
	(s) Zinc (Zn)	g	-	2.23506E-06
Waterborne Emissions	(w) Acids (H+)	g	0.000859365	0.0153164
	(w) aluminum2 (Al3+)	g	-	-
	(w) Ammonia (NH4+, NH3, as N)	g	3.51087	1.8832
	(w) AOX (Adsordable Organic Halogens)	g	0.000241709	-
	(w) Aromatic Hydrocarbons (unspecified)	g	0.0607187	-
	(w) Arsenic (As3+, As5+)	g	0.00540071	0.00356001
	(w) Barium (Ba++)	g	0.385765	0.00356001
	(w) Benzene (C6H6)	g	-	0.00584676
	(w) BOD5 (Biochemical Oxygen Demand)	g	23.4218	14.297
	(w) Cadmium (Cd++)	g	0.000217538	3.34455E-05
	(w) Chlorides (Cl-)	g	512.558	237.934
	(w) Chlorinated Matter (unspecified, as Cl)	g	7.32317E-05	1.40053E-06
	(w) Chromium (Cr III)	g	6.28312E-06	2.02486E-05
	(w) Chromium (Cr III, Cr VI)	g	0.0271668	0.00772288
	(w) COD (Chemical Oxygen Demand)	g	198.231	123.468
	(w) Copper (Cu+, Cu++)	g	0.0133367	0.0396274
	(w) Cyanides (CN-)	g	0.000327168	2.13772E-07
	(w) Dissolved Matter (unspecified)	g	1440.99	767.674
	(w) Dissolved Organic Carbon (DOC)	g	0.0117842	-
	(w) Fluorides (F-)	g	0.0079369	0.00955967
	(w) Hydrocarbons (unspecified)	g	0.0293295	0.0515375
	(w) Inorganic Dissolved Matter (unspecified)	g	37.3985	0.0414626
	(w) Iron (Fe++, Fe3+)	g	1.28014	2.81948E-05
	(w) Lead (Pb++, Pb4+)	g	0.0149139	2.52339E-05
	(w) Manganese (Mn II, Mn IV, Mn VII)	g	-	4.18443E-06
	(w) Mercury (Hg+, Hg++)	g	6.59435E-06	7.75035E-10
	(w) Metals (unspecified)	g	1.61698	0.516394
	(w) Mobile Ions	g	1.20107	0.622019
	(w) Nickel (Ni++, Ni3+)	g	0.0135586	0.000127832
	(w) Nitrates (NO3-)	g	0.103169	0.00482397
	(w) Nitrogenous Matter (unspecified, as N)	g	0.0766494	0.00155905
	(w) Oils (unspecified)	g	13.5063	7.53348
	(w) Organic Dissolved Matter (unspecified)	g	0.00165199	0.011452
	(w) Phenol (C6H6O)	g	80.4093	41.6386

Appendix B

Complete Life Cycle Inventory for Manifolds with Variations in Recycled Content

			Sand Cast 85% secondary Aluminum	Vibration Weld 30 % secondary Composite
	(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	g	0.158526	0.00236288
	(w) Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	g	0.0175101	-
	(w) Salts (unspecified)	g	-	111.753
	(w) Selenium (Se II, Se IV, Se VI)	g	-	1.34103E-07
	(w) Sodium (Na+)	g	587.106	305.179
	(w) Sulfates (SO4--)	g	20.3896	0.00272906
	(w) Sulfides (S--)	g	0.00218934	1.60321E-05
	(w) Suspended Matter (organic)	g	-	0.02597
	(w) Suspended Matter (unspecified)	g	112.554	183.934
	(w) TOC (Total Organic Carbon)	g	0.722017	0.257273
	(w) Toluene (C7H8)	g	0.00837947	-
	(w) Water (unspecified)	liter	-	188.131
	(w) Water: Chemically Polluted	liter	1.73076	0.00332042
	(w) Zinc (Zn++)	g	0.0273391	0.040498
Material Outflows	Recovered Matter (total)	kg	0.315109	0.00054531
	Recovered Matter (unspecified)	kg	0.0220589	1.68551E-05
	Recovered Matter: Non Ferrous Metals	kg	0.281389	-
	Waste (FGD Sludge)	kg	0.055367	0.03072
	Waste (hazardous)	kg	0.10996	0.0394489
	Waste (municipal and industrial)	kg	0.00105203	0.0151365
	Waste (total)	kg	13.8482	4.33545
	Waste (unspecified)	kg	0.561449	0.407912
	Waste: Automotive Shredder Residue (ASR, Non Metallic Materials)	kg	0.139481	2.85993
	Waste: Mineral (inert)	kg	-	0.173866
	Waste: Non Mineral (inert)	kg	-	-
	Waste: Non Toxic Chemicals (unspecified)	kg	-	0.000934474
	Waste: Slags and Ash (unspecified)	kg	-	0.622598
Energy Inputs	E Feedstock Energy	MJ	1518.91	782.363
	E Fuel Energy	MJ	672.142	376.856
	E Non Renewable Energy	MJ	2140.01	1156.25
	E Renewable Energy	MJ	50.7751	2.8344
	E Total Primary Energy	MJ	2190.79	1159.09

Appendix C
Units of Polluted Air

Units of polluted air were calculated using the National Ambient Air Quality Standards (NAAQS) shown in Table C-1.

Table C-1. National Ambient Air Quality Standards (NAAQS)[†] for US EPA criteria air pollutants[‡]

Air Pollutant	*NAAQS (mg/m^3)*	*Type of Average*
carbon monoxide	*10*	*8-hour*
lead	*1.5*	*maximum quarterly average*
nitrogen oxides	*100*	*annual arithmetic mean*
sulfur oxides	*80*	*annual arithmetic mean*
particulates	*50*	*annual arithmetic mean*

[†] *Source: (US EPA 1996)*

[‡] *As defined by the Clean Air Act, not including ozone.*

The values in Table C-1 were used to calculate units of polluted air as follows.

$$UPA = E_i/S_i \qquad \text{(eq. C-1)}$$

where,

UPA	Units of Polluted Air (m^3)
S_i	NAAQS for emission i (mg/m^3)
E_i	Total life cycle emissions of species i (mg)

Table C-2 presents the results of the units of polluted air analysis for the base case manifolds.

Table C-2. Total life cycle emissions and units of polluted air for alternative manifolds.

	Sand Cast Aluminum		*Lost Core Composite*		*Vibration Welded Composite*	
	emissions (g)	*UPA (m^3)*	*emissions (g)*	*UPA (m^3)*	*emissions (g)*	*UPA (m^3)*
CO	*215*	*21,500,000*	*135*	*13,500,000*	*132*	*13,500,000*
Pb	*0.0002*	*133*	*0.0063*	*4,200*	*0.0035*	*2,333*
NO_x	*90.8*	*908,000*	*96.6*	*966,000*	*71.3*	*713,000*
SO_x	*79.6*	*995,000*	*129.2*	*1,615,000*	*93.5*	*1,168,750*
Particulates	*22*	*442,000*	*36*	*720,000*	*40*	*800,000*
Total UPA (m^3)		*23,800,000*		*16,800,000*		*15,900,000*

References

US EPA. 1996. *National Air Quality and Emissions Trends Report, 1995*, EPA 454/R-96-005. United States Environmental Protection Agency, Office of Air Quality, Research Triangle Park, NC.

Appendix D. Life Cycle Design Framework

Primary elements of the life cycle design framework are (Keoleian, Koch, and Menerey 1995):

- Product life cycle system
- Goals
- Principles
- Life cycle management
- Development process

Product Life Cycle System

Life cycle design and management requires an accurate definition of the product system, including both spatial and temporal boundaries. The product system can be organized by life cycle stages and product system components. Life cycle stages include materials production, manufacturing and assembly, use and service, and end-of-life management as shown in Figure D-1.

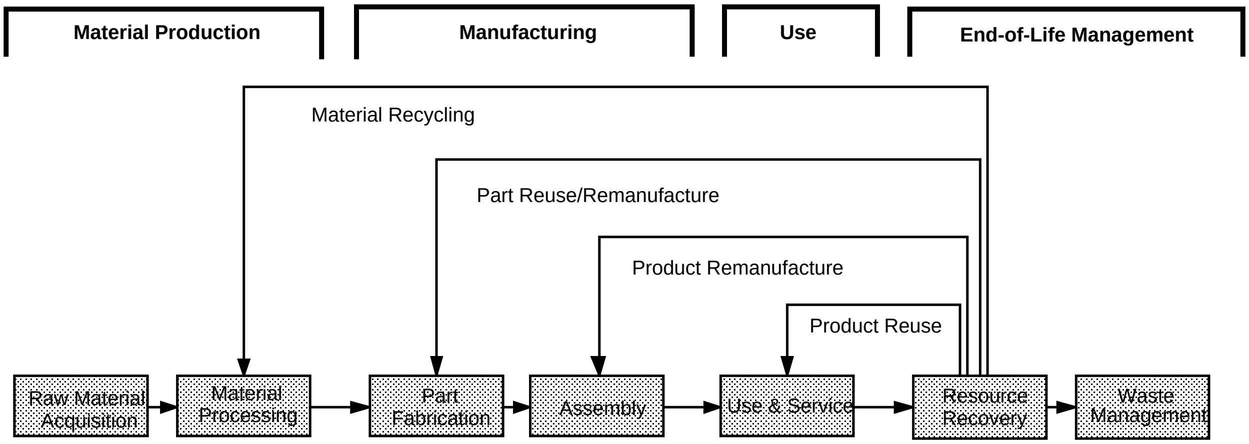

Figure D-1. Product Life Cycle System

Product, process and distribution components further characterize the product system for each life cycle stage as shown in Figures D-2 and D-3. This organization in contrast to LCA convention can better accommodate product and process design functions. The time frame for a design project ranges between a short term horizon that may emphasize incremental improvements in the product system or a long range view that explores next generation designs.

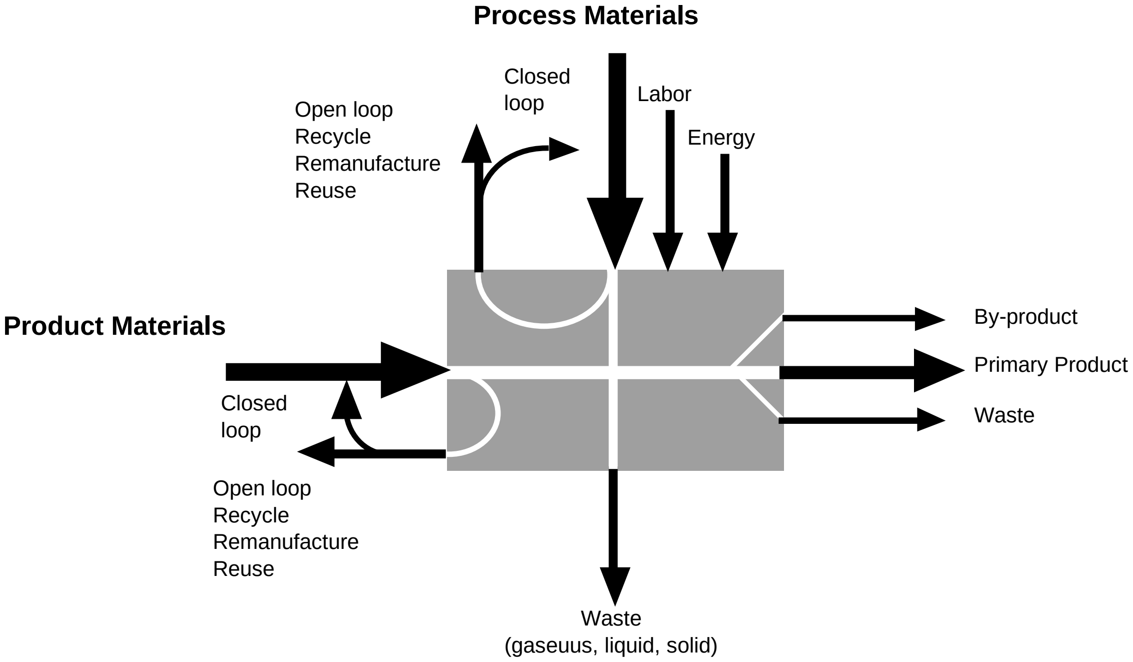

Figure D-2. Flow Diagram Template for Life Cycle Subsystem

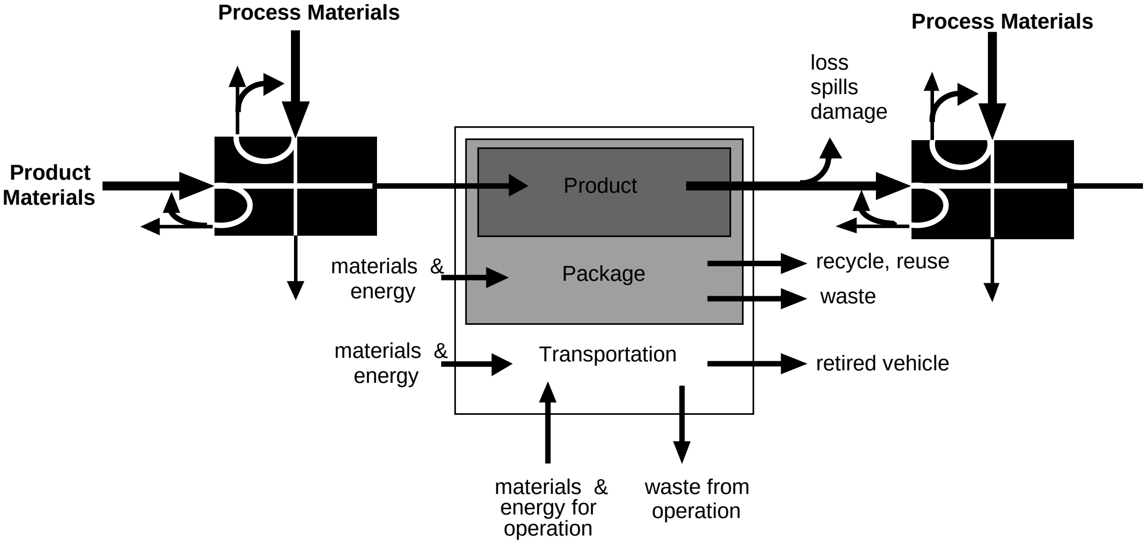

Figure D-3. Distribution Component Flow Diagram

Goals

The broad goal of life cycle design is to design and management products that are ecologically and economically sustainable. Necessary conditions for sustainability include: sustainable resource use (conserve resources, minimize depletion of non-renewable resources, use sustainable practices for managing renewable resources), pollution prevention, maintenance of ecosystem structure and function, and environmental equity. All of these conditions are interrelated and highly complementary. Economic sustainability requires that the product system meet basic cost, performance, legal and cultural criteria.

The specific environmental goal of life cycle design is to minimize the aggregate life cycle environmental burdens and impacts associated with a product system. Environmental burden include resource inputs and waste outputs which can be classified into impact categories according to life cycle impact assessment methods. (Guinée et al. 1993; SETAC 1993a; Weitz and Warren 1993) General impact categories include resource depletion and ecological and human health effects. No universally accepted method for aggregating impacts is available.

Principles

There are three main themes for guiding environmental improvement of product systems in life cycle design: *systems analysis* of the product life cycle; *multicriteria analysis* of environmental, performance, cost, and legal requirements and issues (see specification of requirements section); and *multistakeholder participation and cross-functional teamwork* throughout the design process. The following principles relating to each of these themes have been derived from our empirical research. Many of these principles of life cycle design are already considered best design practice.

Systems Analysis

Systems analysis focuses on understanding the behavior of individual components of a system and the relationships between the collection of components that constitute the entire system. In addition the relationships between the system under study and higher order/larger scale systems should be analyzed. Both time and space dimensions must be addressed.

1. The product life cycle is a logical system for product management and design because it encompasses the total physical flow of product materials through the economy.
2. Successful design initiatives should establish clear system boundaries for analysis. The scope of a design activity can be restricted to smaller system boundaries such as individual life cycle stages or process steps, but this will inherently limit the opportunities for improvement.
3. Studying the relationship between product materials and related process/distribution components - systems that transform/transport the product material along the life cycle - is critical towards improving the product system design.
4. The breadth of system boundaries depends on the vision of the organization; less responsible firms do not address environmental issues much beyond the manufacturing domain whereas more ecologically responsible corporations will address the full product life cycle. The broader perspective may not yield immediate economic benefits but should lead to long term success.

Multiobjective Analysis

A successful design will satisfy multiple objectives including performance, cost, legal and environmental requirements. Many design requirements will overlap and reinforce each other while others conflict and limit design possibilities.

1. Specifying design requirements for both guiding improvement and evaluating alternatives is a critical to efficient product design and management. Clearly defined requirements that are both internal and external to an organization reduce uncertainty in decision making.
2. Understanding the interactions and conflicts between performance, cost, legal, and environmental requirements serves to highlight opportunities as well as vulnerabilities. In some cases, environmentally preferable designs may not be adopted because they do not show a direct cost advantage to the manufacturer, are not supported by regulations, or do not demonstrate performance advantages.
3. Unless more specific guidance can be offered through well-established corporate environmental policies and goals or national environmental policies or goals design teams must rely on. their personal knowledge and experience to make complex tradeoffs. Tradeoffs often exist among environmental criteria, such as minimizing waste, energy and emissions as well as between environmental, cost, performance and legal criteria. Judgment is ultimately required to weight and rank criteria.

Multistakeholder Participation

The stakeholders that control the life cycle of a product can be considered part of a virtual organization. Some stakeholders share a common goal for enhancing the overall economic success of the product, while maximizing their own individual profit. Minimizing life cycle burdens, however, may not be a priority. Identifying the actors that control the life cycle of a product and their interests is a first step in achieving better life cycle management of a product.

1. Harmonizing the often diverse interests of stakeholders (suppliers, manufacturers, customers, waste managers, regulators, investors) into a product design that is technically, economically, socially and ecologically feasible/optimal is a fundamental challenge of design.
2. Partnerships are helpful in implementing changes that affect more than one stage or activity in the life cycle.
3. Initiatives to reduce life cycle environmental burdens will be limited in their effectiveness by the degree to which stakeholders recognize this a common goal for product design and management.

Life Cycle Management

Life cycle management includes all decisions and actions taken by multiple stakeholders which ultimately determine the environmental profile and sustainability of the product system. Key stakeholders are users and the public, policy makers/regulators, material and waste processors, suppliers, manufacturers, investors/shareholders, the service industry, and insurers. The design and management decisions made by the manufacturer of the end-use product may have the greatest influence over the life cycle environmental profile of a product system. It is useful to distinguish between environmental management by internal and external stakeholders. A major challenge for product manufacturers is responding to the diverse interests of external stakeholder groups.

The environmental management system (EMS) within a corporation is the organizations structure of responsibilities, policies, practices, and resources for addressing environmental issues. Several voluntary EMS standards and guidelines have been developed (BS7750, ISO 14,001, GEMI). Although EMS activities have emphasized proactive measures in addition to regulatory compliance, traditionally these systems have only addressed the manufacturing domain of the corporation (Marguglio 1991) and did not cover end-of-life management or material acquisition processing stages.

Life Cycle Development Process

The product development process varies widely depending on the type of product and company and the design management organization within a company. In general, however, most development processes incorporate the key activities shown in Figure D-4. For life cycle design this process takes place within the context of sustainable development and life cycle management.

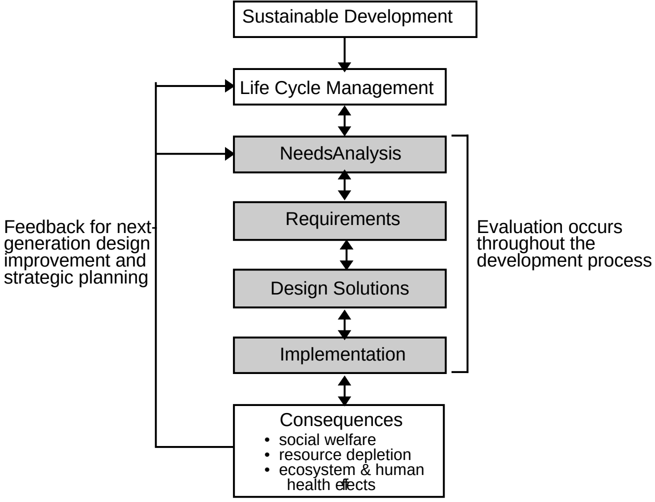

Figure D-4. Life Cycle Development Process

The life cycle design framework emphasizes three important design activities: specifying requirements to guide design improvements, selecting strategies for reducing environmental burden, and evaluating design alternatives.

The specification of requirements to guide design and management decisions is a fundamental activity for any design initiative (Gause and Weinberg 1989). Techniques for assisting development teams in establishing environmental design criteria have not been widely implemented. A multilayer requirements matrix has been developed as a tool to identify, organize, and evaluate environmental, cost, performance, legal and cultural design criteria (Keoleian and Menerey 1993; Keoleian and Menerey 1994; Keoleian, Koch, and Menerey 1995). DFX or Design for X strategies (Gatenby and Foo 1990) such as design for recyclability, disassembly, and remanufacturability have been more widely promoted. Life cycle assessment tools for evaluating product systems (Vigon et al. 1993; Heijungs et al. 1992; Guinée, de Haes, and Huppes 1993; SETAC 1993b; SETAC 1991) have probably received the most attention in the last two decades. The practical application of LCA tools by product development engineers, however, is limited (Keoleian and Menerey 1994; White and Shapiro 1993). It is the refinement and application of these three types of design and analysis tools that will lead to the most effective implementation of life cycle design and DFE.

Specification of Requirements

Specification of requirements is one of the most critical design functions. Requirements guide designers in translating needs and environmental objectives into successful designs. Environmental requirements should focus on minimizing natural resource consumption, energy consumption, waste generation, and human health risks as well as promoting the sustainability of ecosystems. A primary tool of life cycle design is the multicriteria matrices for specifying requirements shown in Figure D-5. Other tools for guiding designers include design checklists and guidelines.

The matrices shown in Figure D-5 allow product development teams to study the interactions and tradeoffs between environmental, cost, performance and legal requirements. Each matrix is organized by life cycle stages and product system components. Elements can then be described and tracked in as much detail as necessary. Requirements can include qualitative criteria as well as quantitative metrics.

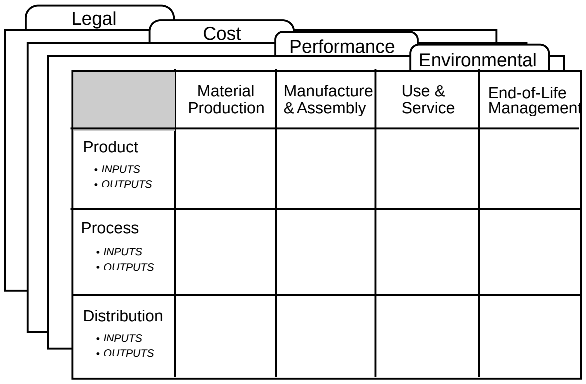

Figure D-5. Multicriteria Requirements Matrix

Design Strategies

Selecting and synthesizing design strategies for meeting the full spectrum of requirements is a major challenge of life cycle design and management. General strategies for fulfilling environmental requirements are product oriented (product life extension, remanufacturability, adaptability, serviceability, and reusability); material oriented (recycling, substitution, dematerialization); process oriented; and distribution oriented (optimize transportation and packaging). An explanation of each strategy is provided in the *Life Cycle Design Guidance Manual* (Keoleian and Menerey 1993).

Design Evaluation

Analysis and evaluation are required throughout the product development process as well as during strategic planning by management. Approaches for design evaluation range from comprehensive analysis tools such as life cycle assessment (LCA) to the use of single environmental metrics. LCA tools can be broadly classified as SETAC related methodologies (Vigon et al. 1993; Heijungs et al. 1992; SETAC 1993b), semi-quantitative matrix evaluation tools (Graedel, Allenby, and Comrie 1995; Allenby 1991), and other techniques such as the Environmental Priority Strategies (EPS) system (FSI 1993). If environmental requirements for the product system are well specified, design alternatives can be checked directly against these requirements. Several tools for environmental accounting and cost analysis are also emerging (US EPA 1989) (White, Becker, and Goldstein 1992) (US EPA 1995) (SNL 1993). Cost analysis for product development is often the most influential tool guiding decision making. Key issues of environmental accounting are: measuring environmental costs, allocating environmental costs to specific cost centers, and internalizing environmental costs.

In principle, LCA represents the most accurate tool for design evaluation in life cycle design and DFE. Many methodological problems, however, currently limit LCA's applicability to design (Keoleian 1994). Costs to conduct a LCA can be prohibitive, especially to small firms, and time requirements may not be compatible with short development cycles (Sullivan and Ehrenfeld 1992) (White and Shapiro 1993). Although significant progress has been made towards standardizing life cycle inventory analysis, (SETAC 1991) (Heijungs et al. 1992) (Vigon et al. 1993) (SETAC 1993b) results can still vary significantly (Svensson 1992) (Curran 1993). Such discrepancies can be attributed to differences in system boundaries, rules for allocation of inputs and outputs between product systems, and data availability and quality issues.

Incommensurable data presents another major challenge to LCA and other environmental analysis tools. A large complex set of inventory data can be overwhelming to designers and managers who often lack environmental training and expertise. The problem of evaluating environmental data remains inherently complicated when impacts are expressed in different measuring units (e.g., kilojoules, cancer risks, or kilograms of solid waste). Furthermore, impact assessment models vary widely in complexity and uncertainty.

Even if much better assessment tools existed, LCA has inherent limitations in design and management, because the complete set of environmental effects associated with a product system can not be evaluated until a design has been specified in detail (Keoleian 1994). This limitation indicates the importance for requirements matrices, checklists and design guidelines which can be implemented during conceptual design phases.

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Appendix E

Life Cycle Design Reports

The following list provides reference information for other LCD reports available from the National Technical Information Service (**NTIS:** www.ntis.gov or 800-553-6847) or the **EPA**'s National Service Center for Environmental Publications (www.epa.gov/ncepi or 800-490-9198).

Report Title		Report Number	Available From
Life Cycle Design Guidance Manual: Environmental Requirements and the Product System			
	full report	EPA/600/R-92/226	EPA
		PB 93-164507AS	NTIS
	summary report	EPA/600/SR-92/226	EPA
Life Cycle Design Framework and Demonstration Projects: Profiles of AT&T and AlliedSignal			
	full report	EPA/600/R-95/107	EPA
Life Cycle Design of Amorphous Silicon Photovoltaic Modules			
	full report	PB 97-193106	NTIS
	summary report	EPA 600/SR-97/081	EPA
Life Cycle Design of Milk and Juice Packaging Systems			
	full report	PB 98-100423	NTIS
	summary report	EPA 600/SR-97/082	EPA
Life Cycle Design of a Fuel Tank			
	full report	PB 98-447856INZ	NTIS
	summary report	EPA 600/SR-97/118	EPA
Life Cycle Design of In-Mold Surfacing Films			
	full report	EPA 600/R-01/058	EPA
Life Cycle Design of Air Intake Manifolds: Phase I: 2.0 L Ford Contour Air Intake Manifold			
	full report	EPA 600/R-99/023	EPA

Additional Information

Additional information on life cycle design publications and research can be found on our website (http://css.snre.umich.edu) under the heading *Research*.