International Journal of Environmentally Conscious Design & Manufacturing, Vol. 10, No. 3, 2001-2002
Printed in the U.S.A.

DETERMINING THE FEASIBILITY OF USING A STANDARDIZED INVENTORY DATABASE FOR CALCULATING ENVIRONMENTAL IMPACT OF PRODUCTS

JONATHAN D. LINTON
DEPARTMENT OF MANAGEMENT
POLYTECHNIC UNIVERSITY
401C DIBNER, SIX METROTECH CENTER
BROOKLYN, NY 11201

A study environmental impact data for metals and polymers is conducted to consider the stability of the data. It was found that the variation in environmental impacts for materials data may vary by orders of magnitude. Therefore, academe, policy makers, industry, and other interested parties must calculate impacts for the entire lifecycle of a product for decision making purposes. If environmental impacts are based on average data or other data that is not specific to the product under question for most purposes the tremendous variability will leave the calculation meaningless. Variables considered in this analysis include: time, process variability, input variability, recycling of materials, product design, and location.

INTRODUCTION

During the design process, costs and environmental impacts that occur during the entire lifecycle of a good or service are rarely considered. Research into the relationship of design decisions and environmental impacts have found that design for the environment is complex, because environmental impacts are frequently incomparable (see [1,2]) and the impacts of different design options are not readily available[3]. Research to reduce the incomparability of options, includes [4-11]. A more preferable way to gain an understanding of the environmental impact of a product system is commonly referred to as Lifecycle Assessment [12]. The life cycle assessment involves determination of the resource requirements and environmental impacts that occur at every step of the supply chain used for the creation of either a good or service. Not only do life cycle assessments provide information that can be used to compare products, but the information can be used to determine which stages of the supply chain offer the greatest opportunities for reduction of a product's environmental impact. Although the life cycle assessment is useful, there have been few lifecycle assessments of products. Unfortunately, the time and expense of collecting environmental impact data is great. Two solutions have been suggested to counter this problem. In some cases an abbreviated version of the lifecycle analysis has been conducted in an attempt to obtain most of the value that an assessment could provide, while limiting the time and cost typically associated with a full assessment [13-17]. The other suggestion to increase the accessibility of life cycle assessment is to create a series of standard life cycle assessments for engineering materials and processes that would be reused for all products. Prior to creating or using a database or decision support system comprised of standardized life cycle assessments for materials and processes, it is necessary to examine the reliability and sensitivity of such an approach. This paper examines the reliability and sensitivity of the use of standardized impacts for engineering materials and manufacturing processes. (The use and disposal-phase of life cycle assessment are not considered in this investigation.) The investigation was conducted as part of a project to obtain a better understanding of and create better accessibility to life cycle assessments.

Prior to producing a decision support system (DSS) of standardized materials for life cycle analysis an analysis of a sample of data must be conducted to determine whether the data is suitable for the purpose of making decisions related to design or other purposes. Such a study also allows for a better understanding of what precautions and limitations may be required when using a lifecycle impact decision support system to analyze design concepts.

This investigation determined that there is too much variability in environmental impact data for a tool based on the supplied data to provide useful guidance. Consequently, it is suggested that life cycle analyses be used as a learning exercise conducted by firms on an as required basis. The variability of the impacts of materials and processes are up to two orders of magnitude. Plus or minus two orders of magnitude is too much variability to use this data to simplify the process of determining a product's life cycle impact. Any information provided by such a tool would be so misleading that it is more likely to cause confusion than to assist in decision making. Support for these conclusions follow.

RESEARCH METHODOLOGY

Data collected for a life cycle analysis DSS was provided for analysis. Because in most cases the data provided was a single value (see Figure 1), additional data was collected. Data provided and data collected was compared to determine if different sources provide consistent information. Additional study of the literature was conducted to identify other factors that may have a significant impact on the stability of the data.

Material/ Process	Energy	Quantity	Comment	Source
ABS	4433 kWh	1,000 lbs.	Theoretical	[18]
HIPS	4630 kWh	1,000 lbs.	Theoretical	[18]
PVC	5021 kWh	1,000 lbs.	Theoretical	[18]
Aluminum	34,014 kWh	1,000 lbs.	Primary metal	[19]
Copper	13,605 kWh	1,000 lbs.	.050% copper ore	[19]
Injection Molding	0.11 – 0.17 kWh	1 kg	Theoretical	[20]
Injection Molding	0.4 – 2 kWh	1 kg	Practical	[20]
Injection Molding	0.4 - .8	1 kg	Efficient values	[20]

Figure 1. Data intended for incorporation into multi-lifecycle environmental impact tool that was provided for analysis of robustness.

FACTORS EFFECTING ENVIRONMENTAL IMPACTS: GENERAL

There are a number of factors that must be considered when attempting to conduct a lifecycle analysis or create an environmental impact inventory for the manufacture of a product. These factors include: time, variability of process, variability of input, importance of various pollutants, recycled material, design, location, and where boundaries for the analysis are set. In order to determine the precision of environmental impact data, we must understand how significant the effect of each factor is. Consequently, each factor is considered separately.

Effect Of Time

With the passage of time, innovation can result in significant changes to current practice and learning can result in improvements with the way in which current practice is conducted. The question under consideration is c*an and do environmental impacts change significantly over time?*

Evidence suggests that a range of industries and firms are gradually reducing their environmental impacts as a result of the use of new technologies and practices (see Figure 2). Average annual decreases between four and fourteen percent can be inferred from these results. However, the possibility of improvements does not guarantee improvements [21,22,23]. Consequently, we must consider that the environmental impact associated to a product may either be unaffected, partially affected or completely affected by changes in practice over time. Over five years, the time-related uncertainty associated with data that we were initially confident of will be as great as 70%. If impact reduction follows the same pattern as a learning curve [21,22,23] the effect of time will be similar during the short and medium term, but diminish over long periods of time.

Company or Industry	Time Period	Decrease in impact	Average Decrease (per year)	Source
Newark AFB	1985 to 1994	94% ozone depleting chemicals	10%	[24]
Nortel	1993 to 1997	55% greenhouse gases	14%	[25]
Nortel	1993 to 1997	50% water use	13%	[25]
Nortel	1993 to 1997	49% energy use	12%	[25]
Nortel	1993 to 1997	26% hazardous waste	7%	[25]
Metal Fabrication	1988 to 1993	31% total air emissions	6%	[26]
Textiles	1988 to 1994	42% solid waste	7%	[27]
Pulp and Paper	1988 to 1993	22% chemicals	4%	[28,29]

Figure 2. Examples of decreases in impact over time.

Variability Of Process

Frequently, there are alternative manufacturing processes available. The use of different processes for transforming materials and manufacturing products is significant. For example, in the steel industry batch, continuous casting and mini mills have significantly different input requirements for comparable end products. Even if the same process is used to manufacture a product there can be substantial differences in resource inputs required and the environment impacts created, due to the age and condition of equipment and differences in practice. The effects of process variability must be quantified. Even if the equipment in use is comparable there can be great differences in the total impact of a process depending on how it is managed. For example, casting facilities receive materials in different forms. If metal is delivered molten, the energy required to convert molten metal into solid bars and then back into a liquid form is eliminated. Differences in process design, like the supply of molten metal, can greatly modify the amount of energy required to produce a product.

The effect of process must also be considered for the production of energy. Not only are there differences in the efficiency of electrical generation facilities [30], but there are differences in the use of pollution control technology [31].

Variability Of Input

Differences in raw material use can result in tremendous differences in resource depletion and pollutant generation. The quantity of ore required to produce a unit of metal depends on the percentage of the metal present in the ore. Variability of input is also of great importance when considering the quantity of waste generated through energy use. Depending on the quality of fuel stock used, air emissions can vary greatly [31].

Importance Of Other Pollutants

The data provided by for the analysis, is limited to energy use. It is important to initially consider a wide range of environmental impacts. Attempts have been made to use energy consumption as an indication of environmental effect [7]. Unfortunately, energy consumption is only indicative of a small number of air pollutants such as carbon dioxide, sulphur oxides, and nitrogen oxides. Important environmental issues, such as ozone depletion, are overlooked if energy is used as an indicator of environmental impact. Another concern is that over time the relative importance of different environmental concerns change. (The change in perception of the threat of ozone lay depletion over time is a good example [32].) If material inventory's focus on energy, every time there is an increase in concern for a specific pollutant or material a new material inventory will be required. However, if an impact inventory indicates a wide range of pollutants then how specific materials, processes, and products are affected by growing concern over a specific environmental issue are obvious.

Recycling Material

Recycling of material is generally less resource intensive than production of virgin material. Consequently, the impact of a product can be greatly modified by substituting virgin material with recycled material. Unfortunately, the recycling rate of different materials is a function of both location [33,34,35,36] and time. Consequently, one must use great care in making generalizations about the actual impact of material used in a product.

Effect Of Design

Modifications to product design can increase the life of a product, thereby reducing lifecycle impact. Changes in design can also make a product more efficient to manufacture and result in reduced resource depletion. A typical example is the use of an increase in our knowledge of stress, strain, and alloy properties to reduce the thickness of the walls of many newer products. Design changes, such as this, reduce the amount of material required to perform the same function, thereby reducing product impact.

Location

Location is of interest when assessing environmental impact for a variety of reasons. The environmental impact of energy use is a function of location [37,38]. Location is also important when assessing the use and availability of raw materials [38]. The relative locations of raw materials, processing, and customers all effect the amount of transportation used during the life of the product. Location is also important when assessing the environmental impact of the transportation, since the impact of a mode of transportation varies with location, age of fleet, efficiency of a particular vehicle, difference in pollution standards, and differences in the amount of time required to move between two locations [31,39,40].

Other Issues Associated To Transportation

The transportation mode is an important factor. There is a substantial difference in environmental impact depending on whether one moves a product by ship, train, truck, automobile and airplane. Unfortunately, there is also a great variation in the emissions within individual modes of transit. For example, the emission level of automobiles manufactured in the same model year can vary by a factor of twenty times [39].

Where Bounds For Analysis Are Set

One can modify the outcomes of an analysis by choosing different boundaries or by limiting the study to a specific set of impacts. For example, if consumption of paper is studied as part of a lifecycle analysis of printers, the findings suggest that efforts to reduce the environmental impact of the printer has a relatively trivial effect on overall system impact [41,42]. This finding is a result of the relatively large environmental impact of paper production. One must use caution with this type of analysis, since it can be argued that without printers the impacts associated with paper production would be eliminated. Consequently, the printer is environmentally undesirable and requires fundamental design changes. This is interesting, since it is inconsistent with the conclusions of the analyses. Unfortunately, this advice does not assist with setting logical barriers. However, certain impacts have been found to be trivial and can be ignored.

The impact of capital equipment and workers has been found to be negligible [43]. A calculation of the effect on capital equipment used for processing polymers found that if the equipment had an extremely short life (one year); the equipment would increase processing energy requirements by only 0.5%[43]. For most products the energy associated with capital equipment production will be negligible.

The effect of human activity will also be negligible. The total energy attributable to work is only about 80 MJ/day [43]. This figure includes a commute of 24 miles (40 km). If one divides this against the production associated with a production worker on a daily basis, the value is insignificant. Having discussed the general effect of a variety of factors, the overall effect on a lifecycle analysis is considered by further examining the data provided for analysis.

ANALYSIS OF ENVIRONMENTAL IMPACTS BASED ON DATA PROVIDED

Comparison of data intended for use in a life cycle impact analysis tool is compared with data from other sources in figures 3 (polyvinylchloride), 4 (high impact polystyrene), 5 (acrylonitrile butadiene styrene), 6 (aluminum), 7 (copper), and 8 (injection molding). Unsurprisingly, the data provided differs, in some cases substantially, from other sources. The dfferent impacts reported in difference sources reflect differences that have been discussed in general terms already. Now the effect of different factors will be considered in relation to the materials under study.

Effects Of Time

Over time reductions in environmental impact occur due to both incremental and discontinuous change. The data considered in Figures 3 through 8 span a twenty-year period. Consequently, the average yearly improvement of four to fourteen percent shown in Figure 2 implies a reduction in impact level between 80 and 280% over a twenty-year period. The effect of time on the data presented in this study explains a variance in results of an order of magnitude between the data sources in Figures 3 through 8.

Variability Of Process

Process variability can result in significant differences in environmental impact. Variability in process is a factor in the manufacture of material and product. In Figure 3, the difference in impact for three currently used alternatives for the manufacture of PVC is shown. In the case of aluminum, the Hall-Heroux process is currently used for smelting. However, there are a number of alternative processes that would significantly affect the impact of smelting. Alternatives include the ALCOA [51,52], Toth [53] monochloride [53] and direct reduction [54] processes.

Impact	Suspension Process[44]	Emulsion Process [44]	Bulk Polymerization Process [44]	CRT Study[45]	Supplied [18]
Energy (MJ)	**64.9**	**74.9**	**66.8**	**25.0**	**39.8**
Dust	3,900	5,400	3,900	7.7	
CO	2,500	1,600	2,700	7.2	
CO_2	1,747,000	2,741,000	1,944,000		
SO_x	13,000	26,000	20,000	56.5	
NO_x	15,000	19,000	16,000	25.5	
HCl	240	300	230		
Hydrocarbon	19,000	26,000	20,000	130	
Metals	3	3	3	.0094	
Organics	510	1389	720	1.6	
COD	*1,100*	*1,200*	*1,100*	*17*	
BOD	*80*	*60*	*80*	*5.5*	
Acid as H	*170*	*130*	*110*	*12*	
Dissolved solids	*1,400*	*760*	*500*	*36*	
Suspended solids	*2,000*	*4,200*	*2,400*	*7.5*	
Na^+	*4,800*	*2,000*	*2,300*		
Metals	*200*	*220*	*200*	*3.6*	
Nitrogen	*3*	*2*	*3*		
Cl^-	*42,000*	*39,000*	*40,000*	*5.6*	
SO_4^-	*1,500*	*4,000*	*4,300*	*.19*	
Oil	*50*	*50*	*50*	*2.2*	
Dissolved organics	*1,400*	*1,000*	*1,000*		
Other organics	*3*	*4*	*10*	*.13*	
Mineral waste	***60,000***	***110,000***	***66,000***		
Mixed industrial waste	***2,000***	***1,300***	***1,800***	***119***	
Slag/ash	***12,000***	***210,000***	***47,000***		
Inert waste	***11,000***	***11,000***	***14,000***		
Regulated waste	***3,500***	***3,500***	***1,200***		
Bauxite	**220**	**150**	**220**		
Salt	**675,000**	**695,000**	**690,000**		
Sand	**1,000**	**770**	**1,200**		
Iron ore	**370**	**230**	**400**		
Limestone	**15,000**	**6,700**	**1,600**		
Water	**20,000,000**	**6,700,000**	**1,900,000**		

Figure 3. Environmental impact of manufacture of one kilogram of polyvinyl chloride (PVC) from different sources. All data, except energy, expressed in kg. Legend: resources required in bold font, air impacts in regular font, water impacts in italic font, solid waste in bold italic font.

Impact	General Purpose Polystyrene [46]	High Impact Polystyrene (HIPS) [46]	Expandable Polystyrene [46]	CRT Study[45]	Supplied [18]
Energy (MJ)	**88.3**	**90.7**	**82.1**	**36.7**	**36.7**
Dust	1,700	2,000	2,000	7.6	
CO	1,100	1,200	960	7.2	
CO_2	2,600,000	2,800,000	2,400,000		
SO_x	11,000	12,000	11,000	62	
NO_x	12,000	12,000	11,000	26	
HCl	26	35	25		
Methane	11,000	11,000	11,000	22	
Hydrocarbon	2,800	3,800	4,700	22	
Hydrogen	10	10	8		
Metals	9	10	66		
Organics	1	24	3	1.7	
COD	*370*	*360*	*710*	*22*	
BOD	*51*	*45*	*150*	*8.5*	
Acid as H	*43*	*45*	*40*	*13*	
Phenol	*5*	*6*	*5*	*.15*	
Suspended solids	*290*	*340*	*690*	*9.5*	
Dissolved solids	*110*	*150*	*110*		
Hydrocarbon	*92*	*120*	*90*		
Na^+	*490*	*600*	*610*		
Metals	*430*	*430*	*330*	*3.6*	
Nitrogen	*18*	*18*	*20*		
Cl^-	*5,600*	*4,700*	*3,500*		
SO_4^-	*160*	*160*	*120*	*.21*	
Oil	*69*	*70*	*61*	*2.4*	
Dissolved organics	*31*	*37*	*50*		
Other organics	*2*	*2*	*4*		
Mineral waste	***18,000***	***27,000***	***26,000***		
Mixed industrial waste	***1,800***	***2,200***	***2,100***	***17***	
Slag/ash	***3,400***	***4,600***	***4,300***		
Inert waste	***2,300***	***2,000***	***8,000***		
Unspecified	***17***	***18***	***17***		
Construction	***29***	***28***	***28***		
Metals	***11***	***10***	***16***		
Regulated waste	***830***	***800***	***1,000***		
Bauxite	**960**	**1,000**	**1,100**		
Salt	**1,800**	**2,100**	**1,900**		
Sand	**110**	**160**	**120**		
Iron ore	**820**	**840**	**730**		
Limestone	**1,300**	**25,000**	**1,700**		
Calcium sulphate	**16**	**15**	**12**		
Sulphur	**53**	**81**	**93**		
Water	**174,800,000**	**185,400,000**	**175,500,000**		

Figure 4. Environmental impact of manufacture of one kilogram of high impact polystyrene (HIPS) data from different sources. All data, except energy, expressed in kg. Legend: resources required in bold font, air impacts in regular font, water impacts in italic font, solid waste in bold italic font.

Impact	SAN Styrene [47]	ABS [47]	CRT Study [45]	Supplied [18]
Energy (MJ)	**89.6**	**95.2**	**35.2**	**32.1**
Dust	1,700	3,000	7.1	
CO	3,800	3,800	7.2	
CO_2	2,800,000	3,100,000		
SO_x	7,600	10,000	61	
NO_x	9,200	11,000	25	
HCl	28	58		
Methane	11,000	12,000	22	
Hydrocarbon	3,400	4,200	34	
Hydrogen	89	140		
Metals	3	4		
Organics	183	660	1.7	
COD	*1,200*	*2,200*	*29*	
BOD	*18*	*33*	*11*	
Acid as H	*44*	*45*	*13*	
Phenol	*3*	*7*	*.14*	
Suspended solids	*320*	*2,400*	*9.1*	
Dissolved solids	*980*	*1,100*	*36*	
Hydrocarbon	*67*	*68*		
Na^+	*730*	*1,100*		
Metals	*600*	*1,500*	*3.7*	
Nitrogen	*542*	*511*	*.11*	
Cl^-	*2,700*	*4,500*		
SO_4^-	*1,100*	*8,500*	*.20*	
CO_3^{--}	*200*	*180*		
Oil	*69*	*93*	*3.5*	
Dissolved organics	*30*	*34*		
Other organics	*2*	*3*	*.0059*	
Mineral waste	***26,000***	***77,000***		
Mixed industrial waste	***1,100***	***4,200***	***6.2***	
Slag/ash	***5,600***	***12,000***		
Inert waste	***1,100***	***3,400***		
Unspecified	***19***	***6,800***		
Construction	***24***	***18***		
Metals	***9***	***65***		
Regulated waste	***4,100***	***10,000***		
Bauxite	**670**	**600**		
Salt	**2,200**	**6,200**		
Sand	**110**	**600**		
Iron ore	**880**	**900**		
Limestone	**1,800**	**18,000**		
Bentonite	**220**	**200**		
Clay	**16**	**16**		
Dolomite	**10**	**10**		
Fluorspar	**4**	**4**		
Gravel	**3**	**8,500**		
Nitrogen	**47,000**	**310,000**		
Olivine	**7**	**8**		
Oxygen	**43**	**41**		
Potassium	**7**	**4,500**		
Magnesium		**1,200**		
Talc		**21,000**		
Shale	**62**	**280**		
Calcium sulphate	**22**	**98**		
Sulphur	**4,000**	**9,300**		
Water	**166,100,000**	**169,300,000**		

Figure 5. Environmental impact of manufacture of one kilogram of high impact acrylonitrile butadiene styrene (ABS) data from different sources. All data, except energy, expressed in kg. Legend: resources required in bold font, air impacts in regular font, water impacts in italic font, solid waste in bold italic font.

Impact	Aluminum [38]	Aluminum [38,48]	Aluminum [38,49]	Recycled Aluminum [38]	Aluminum [38]	CRT Study[45]	Supplied [19]
Energy (MJ)	**103**	**91.6**	**71.5**	**11.1 to 18.5**	**222 to 264**	**98**	**270**
CO	790,000	790,000	790,000			790,000	
CO_2	837,000	837,000	837,000			650,000	
Particulate	45,000	45,000	45,000				
Metals	254,800	1,038,800	1,507,240			70,000	
Waste water	*25,000*	*25,000*	*18,866,680*				
Red Mud	***1,899,240***	***8,972,920***	***3,848,264***				
Carbon Anode						***510,000***	
Cryolite						***30,000***	
Al-fluoride						***40,000***	
Fluorine						***20,000***	
Bauxite	**3,767,120**	**6,620,880**	**5,011,720**				
Fluorine	**20,000**	**20,000**	**20,000**				
Fluorspar	**52,000**	**52,000**	**52,000**				
Petrocoke	**467,000**	**467,000**	**467,000**				
Pitch	**93,000**	**93,000**	**93,000**				
Sodium Hydroxid	**93,440**	**238,480**	**17,000**			**77,000**	
Sodium Carbonate			**147,000**				
Sulfuric Acid	**66,000**	**66,000**	**66,000**				
Starch		**29,400**	**117,600**				
Limestone	**76,440**	**98,000**	**143,080**			**76,000**	
Water	**5,338,000**	**5,338,000**	**5,338,000**				

Figure 6. Environmental impact of manufacture of one kilogram of aluminum data from different sources. All data, except energy, expressed in kg. Legend: resources required in bold font, air impacts in regular font, water impacts in italic font, solid waste in bold italic font.

Differences in environmental impact, caused by the manufacturing process is also shown to be significant. In Figure 8, a factor of twenty is shown as the potential range for the injection molding of polymers. Differences in defect rate can also have a significant impact on the environmental impact. In aluminum die casting, defect rates can range from a fraction of a percent to a few percent. (The impact caused by this is smaller than the magnitude of defects would suggest, since the defective parts are recycled.) The elimination of process steps is not only desirable from a cost and time perspective, but frequently results in a reduction in environmental impacts. For example, an aluminum casting facility that receives aluminum in a molten form requires 1MJ less energy for processing, than if aluminum is received in the form of solid bars. This energy constitutes between 0.4 and 10% of the energy required to produce aluminum from ore. Furthermore, between 30 and 60% of the energy used for manufacturing polymer was in the form of fuel, as opposed to feedstock. The energy provided by fuel is only consumed if it is used to cause the formation of new substances. Consequently, much of the fuel energy has the potential to be recaptured using heat exchanges or used for other purposes that require lower temperatures.

Variability of process can account for a difference in an order of magnitude of an environmental impact under consideration. The effect of process variability on the data presented in this study explains a variance in results of an order of magnitude between the data sources in Figures 3 through 8.

Variability Of Input

The amount of material and effort for obtaining a metal is a function of the quality of the ore. The alumina content of bauxite may range from 26-60% [49], depending on where it is mined. The copper content of mined ore ranges from 0.3% to 5% [38]. Certain environmental impacts are inversely related to ore quality. Other environmental impacts are a function of other materials found in the ore and are independent of ore purity. The effect of impacts resulting from undesired materials present in the ore also is an issue for fuel sources, like the sulfur content of coal.

Coal and other fossil fuels are frequently used as an energy source. SOx is a byproduct of the combustion of coal. However, SOx generation depends both on the type of coal and the effort taken to reduce SOx emissions.

Based on the differences in input quality the environmental impact can frequently vary by an order of magnitude or more for the same material. Based on the examples of aluminum and copper, environmental impacts may range from ½to 1/16th as a result of differences in inputs. The effect of input variability on the data presented in this study explains a variance in results of an order of magnitude between the data sources in Figures 3 through 8.

Impact	Copper [38]	Copper [50]	Recycled Copper [50]	Supplied [19]
Energy (MJ)	**29.4**	**100 to 200**	**14 to 40**	**108**
Dust	334,000			
CO	790,000			
CO_2	837,000			
SO_x	1,302,000			
Particulate	45,000			
Metal ions	*700*			
Waste water	*25,000*			
Mineral waste	***160,700,000***			
Slag/ash	***3,221,000***			
Unspecified	***6,000***			
Fluorspar	**52,000**			
Copper ore	**164,820,000**			
Sand	**820,000**			
Steel balls	**157,000**			
Limestone	**652,000**			
Floatation reagent	**12,000**			
Sulfuric acid	**66,000**			
Petrocoke	**467,000**			
Fluorine	**20,000**			
Pitch	**93,000**			
Sodium hydroxide	**17,000**			
Water	**5,338,000**			

Figure 7. Environmental impact of manufacture of one kilogram of copper data from different sources. All data, except energy, expressed in kg. Legend: resources required in bold font, air impacts in regular font, water impacts in italic font, solid waste in bold italic font.

Impact	PP Injection Molding [43]	PVC Injection Molding [43]	Supplied [20]	Supplied [20]	Supplied [20]
Energy (MJ)	**44.3**	**37.1**	**.40 to .61**	**1.4 to 7.2**	**1.4 to 2.8**
Dust	8,650	2,000			
CO	1,844	1,100			
CO_2	2,600,000	300,000			
SO_x	21,420	10,000			
NO_x	17,260	4,000			
HCl	305	60			
Hydrocarbon	14,030	200			
Metals	7	3			
COD	*14*	*2,140*			
BOD	*6*	*220*			
Acid as H	*2*	*2*			
Suspended solids	*600*	*900*			
Dissolved solids	*2*	*4*			
Hydrocarbon	*5*	*42*			
Metals	*1*	*10*			
Nitrogen		*30*			
Cl^-	*2*	*2*			
Oil	*1*	*2*			
Mineral waste	***114,300***	***26,800***			
Mixed industrial waste	***4,100***	***1,300***			
Slag/ash	***34,300***	***7,200***			
Inert waste		***2,800***			
Unspecified	***11,000***	***211,100***			
Regulated waste		***100***			
Salt		**100**			
Iron ore		**3400**			
Limestone		**800**			
Water		**35,482,200**			

Figure 8. Environmental impact of manufacture of one kilogram of polymer using an injection molding process, data from different sources. All data, except energy, expressed in kg. Legend: resources required in bold font, air impacts in regular font, water impacts in italic font, solid waste in bold italic font.

Importance Of Other Pollutants

Figures 3 through 8 demonstrate that there is a wide range of impacts in terms of both resource depletion and emission of pollutants. Any modeling of lifecycle impact must state whether analysis will be constrained by magnitude of impact, type of impact or both. The cataloging of impacts for material and process should be made as inclusive as possible to minimize the likelihood of having to collect omitted data at a later date.

Recycling Materials

Recycling rates of metals vary tremendously. Copper recycling has been reported in the past as 25% for the United States [35], 26.5% for the European Union [36], and as 42% for West Germany [33]. Recycling rates for aluminum vary more widely than for copper. The average recycling rate for aluminum in Europe is 17.5%, with a range of between 5 and 93% [34]. As a result of the wide range of recycling rates it is evident that the material used to manufacture a product may have a low or high recycled material content. This content difference is significant, since recycled aluminum and copper require 5-7% [38] and 7-40% [50], respectively, of energy compared to virgin material. Consequently, energy consumption and air pollution associated with the production of recycled metals can easily be an order of magnitude lower than virgin material.

In the case of polymers, recycling is not so attractive. The recycling of polymers is energy intensive and polymers properties vary greatly. However, polymers that are a shape or part of an assembly that is useful may offer value since they offer environmental impact reduction in terms of both material production and reducing the manufacturing effort required to produce a new product.

Recycled metals can offer a reduction in environmental impact as much as 100% for certain resources and emissions. Based on the two examples considered, aluminum and copper, recycling of metals results in savings in energy use from ½to 1/20th. The effect of recycling material on the data presented in this study explains a variance in results of an order of magnitude between the data sources in Figures 6 and 7.

Effect Of Design

There is a trend towards miniturization and dematerialization. Therefore, new designs tend to require less material and result in environmental impacts with a lower magnitude. For example, demand for semiconductor silicon lags growth in electronic sales. Products based on semiconductor silicon have grown substantially. However, a high rate of miniturization of circuitry and an increase in production yields ensures that overall demand for semiconductor silicon is relatively stable. Effect of design on a product varies greatly; certain products have greater potential for miniturization. Impacts of differences in design may be minimal or an order of magnitude or more.

Location

The effect of location on environmental impact of material and product transportation is not considered here. Not enough information has been provided to estimate the distance and transportation mode(s) that a product may travel. However, there are other location-related issues that can and should be considered. Environmental legislation and control is a function of location. In the case of aluminum smelting, the regulations regarding allowable fluorine emissions vary greatly from country to country. As a result, aluminum-fluoride consumption and emissions varies by more than an order of magnitude, if difference in location is considered [38]. The effect of energy production is another important factor.

Air emissions resulting from energy production are strongly related to changes in location. If one considers the fuel segment of energy used for polymers and assumes that it is provided by electrical energy the level of certain air pollutants may vary by two orders of magnitude as a function of location (see Figure 9). In Figure 9, the level of air pollutants is considered for states that are the most efficient and inefficient in terms of air pollutants generated [30,37]. The levels of pollutant generated are then compared to the level of pollutant for the manufacture of the polymer (see Figures 3 through 5). Figure 9 illustrates the significant difference that location can have on pollution caused by electricity by showing that impact of the polymer on air emissions could be increased by up to twenty-eight times. Since electricity supplies a fraction of the energy used for polymer production, actual impact of location is lower. However, consideration must be given to type of fuel oil, grade of coal, and pollution control equipment in use.

Differences in location result in variability of over an order of magnitude for certain environmental impacts. The effect of location on the data presented in this study explains a variance in results of an order of magnitude between the data sources in Figures 3 through 8.

Material	SO_x	NO_x	CO_2
PVC	3.4 to 1,600 %	3.0 to 890 %	6.2 to 2,000 %
HIPS	4.3 to 2,000 %	4.3 to 1,300 %	5.0 to 1,600 %
ABS	6.0 to 2,800 %	5.4 to 1,600 %	5.2 to 1,700 %

Figure 9. Demonstration of the effect that location has on the level of specific air emissions. Data expressed as a percentage of air emission expressed in figures 3 to 5. States selected for analysis represent most and least efficient locations for the production of air pollutants. States considered are California, North Dakota, Oregon, Vermont, Washington, and Wyoming [30,37].

RECOMMENDATIONS

Time, process variability, input variability, recycling of materials, product design, and location are all factors that can have values that have a range of greater than an order of magnitude. Guidelines for lifecycle analysis assessment suggests that data should be rated using a green, yellow, red system which correspond to uncertainties of 10, 25 and 50% respectively [55]. Since the analysis of the materials has identified six separate factors that may differ by an order of magnitude these guidelines may appear to be irrelevant. However, this variation in impact level is reflected by the lack of specificity of the data collected. Consequently, it is necessary for detailed data to be collected every time a lifecycle analysis is desired. It is not feasible to use a generalized impact database to assist and support lifecycle decision making, unless the decision makers are willing to accept values that have a precision of ± two orders of magnitude.

This is not to suggest that lifecycle analysis is not worthwhile. Lifecycle analysis offers useful information on the environmental efficiency of products and processes. Lifecycle analysis can assist in identifying opportunities to reduce waste. (Hence, an environmental analysis may identify candidates for substantial cost reduction.) But, impact assessment is very sensitive to a number of factors. Consequently, impact inventories must be collected each time a product or process is to be studied. If analysis is conducted using a database that was not specifically collected for the product or process under study, the data should only be considered accurate to ± two orders of magnitude of the stated value.

INDUSTRIAL COLLABORATION

This particular project did not involve industrial collaboration. All data and analysis is based on printed information.

REFERENCES

1. Fava, J., F. Consoli, R. Denison, K. Dickson, T. Mohin, and B. Vigon (Eds.). 1993. *A Conceptual Framework for Life-Cycle Impact Assessment.* Society of Environmental Toxicology and Chemistry: Pensacola, Florida.

2. Linton, J. D., "Evaluating the environmental impact of product and production processes: Overcoming the dilemma of incomparable impacts," Working Paper, Center for Policy Studies, New Jersey Institute of Technology, 1998.

3. Melnyk, S., ac cited in "Take-back legislation", *Circuits Assembly*, 8(2), pp. 26-7.

4. Ahbe, S., A. Braunschweig, and R. Müller-Wenk, *Methodik für oekbolianzen auf der basis ökologischer optimierung*, Schriftenreihe Umwlet Nr. 133, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland, 1990.

5. Bringezu, S., F. Hinterberger, and H. Schütz., "Integrating sustainability into the system of national accounts: The case of interregional material flows", *International effect Symposium Models of Sustainable Development. Exclusive or Complementary Approaches to Sustainability*. Paris, France, 1994.

6. Hertwich, E. G., W. S. Pease, and C. P. Koshland, "Evaluating the environmental impact of products and production processes - A comparison of six methods," Working paper, Department of Environmental Health Science, University of California: Berkeley, 1996.

7. Kalisvaart, S., and J. Remmerswaal, "The MET Points Method - a single figure environmental performance indicator," *Proceedings of Conference on Integrating Impact Assessment into LCA*, SETAC. Brussels, 1994.

8. Krotscheck, C., *Der Sustainable Process Index.* Dis., Institute of Chemical Engineering, Technische Universität Graz, Austria, 1995.

9. Rees, W. E., "Revisiting carrying capacity: Area based indicators of sustainability, Veranstaltungreihe Strategien der Nachhaltigkeit, Institut für Verfahrenstechnik, Technische Universität Graz, Austria, 1994.

10. Srinivasan, M., T. Wu, and P. Sheng, "Development of a scoring index for the evaluation of environmental factors in machining processes: Part 1 - Health Hazard Score Formulation," *Transactions of NAMRI/SME* 23: 115-22, 1995.

11. Steen, B. and S.-O. Ryding. *The EPS Environmental Accounting Method: An application of environmental accounting principles for evaluation and valuation of environmental impact in product design*, Swedish Environmental Research Institute, Göteborg, Sweden., 1991

12. Block, M., *Implementing ISO 14000*, Quality Press: Milwaukee, 1997.

13. Eagen, P. and L Weinberg, "Development of a streamlined, life-cycle, Design for the Environment (DFE) tool for manufacturing process modification: A Boeing defense and Space group case study", *IEEE Symposium on Electronics and the Environment*, pp. 188-191, 1997.

14. Korpalski, T.,"Pragmatic use of priority life cycle assessment elements to help drive product stewardship", *IEEE Symposium on Electronics and the Environment*, pp. 207-210, 1994.

15. Nissen, N. F., H. Griese, A. Middendorf, J. Muller, H. Potter, and H. Reichl, "Environmental assessment of electronics: A new model to bridge the gap between full life cycle evaluations and product design", *IEEE Symposium on Electronics and the Environment*, pp. 182-187, 1997.

16. O'Connor, F. and D. Blythe, "Designing environmental considerations in to products – A novel qualitative life cycle approach", *IEEE Symposium on Electronics and the Environment*, pp. 192-197, 1997.

17. Brinkley, A., S. Ching, J. R. Kirby, O. D. Pitts, C. C. Sloop, and I. Wadehra, "Assessing green pen computer designs: Product and program metrics", *IEEE Symposium on Electronics and the Environment*, pp. 48-51, 1997.

18. *A Research Report…Plastics: Resource and environmental profile analysis*, Manufacturing Chemists' Association, 1974.

19. "'Green' metals conserve resources," *Manufacturing Engineering*, 116 (1), p. 30, 1996.

20. "Good housekeeping can save energy for injection molders," *Modern Plastics* 74(11), p. 64, 1997.

21. Abernathy, W.J., and K. Wayne, "Limits of the learning curve", *Harvard Business Review*, 5, pp. 109-119, 1974.

22. Andress, F.J., "The learning curve as a production tool", *Harvard Business Review*, 1, 1954.

23. Hirschmann, W.B., "Profit from the learning curve", *Harvard Business Review*, 1, 1964.

24. Linton, J.D., *Report on Technical and Managerial Innovation*, Report ADA332448, http:/www.dtic.mil:80/ozone/fulltext.html.

25. *1997 Progress Report on Environment, Health and Safety*, Nortel Networks: Mississauga, 1998.

26. EPA, *Profile of the Fabricated Metal Products Industry*, EPA/310/R-95/007, Washington DC, September 1995.

27. US AEP, *Clean Technologies in U.S. Industries, Focus on Textiles*, Washington D.C., September 1997.

28. US AEP, *Clean Technologies in U.S. Industries, Focus on Pulp and Paper*, Washington D.C., September 1997.

29. EPA, *Profile of the Pulp and Paper Industry*, EPA/310/R-95/015, Washington DC, September 1995.

30. Linton, J.D., "Evaluating the environmental impact of product and production processes: Overcoming the dilemma of incomparable impacts", Center for Policy Studies Working Paper 98-07, New Jersey Institute of Technology, 1998.

31. United Nations Environment Programme (UNEP) and the World Health Organization (WHO), "Air pollution in the world's megacities", *Environment*, 36(2), pp. 4-13, 25-27, 1994.

32. United Nations Environmental Programme (UNEP), *The Impact of Ozone-Layer Depletion*, UNEP: Nairobi, 1992.

33. Bundesverband der Deutschen Industrie e. V., *Industrie und Öcologie*, Bundesverband der Deutschen Industrie e. V.: Koln, Germany, 1994.

34. Renaux, G., *Packaging in the single European market*, Club de Bruxelles: Brussels, Belgium, 1992.

35. United States Bureau of Mines, *Minerals Yearbook; Volume I: Metals and Minerals*, United States Government Printing Office: Washington, DC, 1991.

36. Metallgesellschaft AG, *Metal Statistics 1982-1992*, Metallgesellschaft AG:Frankfurt am Main, 1993.

37. DOE (Department of Energy), *Electric Power Annual 1989*. Energy Information Administration. Department of Energy: Washington, DC, 1991.

38. Ayres, R.U. and L.W. Ayres, *Industrial Ecology: Towards closing the materials cycle*, Edward Elgar: Cheltenham, UK, 1996.

39. Beaton, S.P., G.A. Bishop, Y. Zhang, L.L. Ashbaugh, D.R. Lawson, and D.H. Stedman, "On-road vehicle emissions: Regulations, costs, and benefits", *Science*, 268, pp. 991-3.

40. Shiomi, E., H. Nonura, G. Chow, and K. Niiro, "Physical distribution and freight transportation in the Tokyo metropolitan area", *Logistics and Transportation Review*, 4, pp. 335-353, 1993.

41. Pollock, D. and R. Coulon, "Life cycle assessment of an inkjet print cartridge", *IEEE Symposium on Electronics and the Environment*, pp. 154-160, 1996.

42. Calkins, P., "Life cycle assessment at Xerox corporation", *Fifth International Congress of Environmentally Conscious Design and Manufacturing*, Rochester, 1998.

43. Bousted, I., *Eco-profiles of the European plastics industry, Report 10: Polymer conversion*, Association of Plastic Manufacturers in Europe (APME): Brussels, Belgium, 1997.

44. Bousted, I., *Eco-profiles of the European polymer industry, Report 6: Polyvinyl chloride*, Association of Plastic Manufacturers in Europe (APME): Brussels, Belgium, 1994.

45. Badwe, D. J., *Multi-lifecycle Assessment of Cathode Ray Tubes,* Unpublished Masters Thesis, New Jersey Institute of Technology, 1997.

46. Bousted, I., *Eco-profiles of the European plastics industry, Report 4: Polystyrene*, 2nd edition, Association of Plastic Manufacturers in Europe (APME): Brussels, Belgium, 1997.

47. Bousted, I., *Eco-profiles of the European polymer industry, Report 11: Co-Polymers of acrylonitrile-butadiene-styrene (ABS) and styrene-acrylonitrile (SAN)*, Association of Plastic Manufacturers in Europe (APME): Brussels, Belgium, 1997.

48. Lübkert, B., Y. Virtanen, M. Muhlberger, I. Ingham, B. Vallance, and S. Alber, *Life cycle analysis: International database for ecoprofile analysis (IDEA),* Working paper (WP-91-30), International Institute for Applied Systems Analysis, Laxenburg, Austria, 1991.

49. Hall, E.H., W.H. Hanna, L.D. Reed, J. Varga Jr., D.N. Williams, K.E. Wilkes, B.E. Johnson, W.J. Mueller, E.J. Bradbury, and W.J. Frederick, *Evaluation of the theoretical potential for energy conservation in seven basic industries,* Final Report (PB-244,722), Battelle Laboratories: Columbus, Ohio, 1975.
50. Forrest, D. and J. Szekeley, "Global warming and the primary metals industry", *Journal of Metallurgy,* 43(12), pp. 23-30, 1991.

51. Jarrett, N., personal communication, ALCOA Corporation, Pittsburgh, 1982, cited in Ayres, R.U. and L.W. Ayres, *Industrial Ecology: Towards closing the materials cycle*, Edward Elgar: Cheltenham, UK, 1996.

52. Jarrett, N., personal communication, ALCOA Corporation, Pittsburgh, 1994, cited in Ayres, R.U. and L.W. Ayres, *Industrial Ecology: Towards closing the materials cycle*, Edward Elgar: Cheltenham, UK, 1996.

53. Pearcy, J.G., and W.G. Davenport, "Evaluation of alternative methods of aluminum production", *Journal of Metals*, 7, p. 28, 1974.

54. Bruno, M.J., *Production of aluminu-silicon alloy and ferrosilicon and commercial purity aluminum by the direct reduction process*, final technical report (CONS-5089-16 UC95f), Aluminum Company of America ALCOA Labratories: ALCOA Center, PA, 1982.

55. Raynolds, M.A., M.D. Checkel, and R.A. Fraser, "Uncertainty, sensitivity, and data quality assessment for life cycle value assessment (LCVA)", Society of Automotive Engineers (SAE) Technical Paper Series, number 980479, SAE: Warrendale, PA, 1998.