



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

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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 *can 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 different impacts reported in different 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	<i>1,100</i>	<i>1,200</i>	<i>1,100</i>	17	
BOD	<i>80</i>	<i>60</i>	<i>80</i>	5.5	
Acid as H	<i>170</i>	<i>130</i>	<i>110</i>	12	
Dissolved solids	<i>1,400</i>	<i>760</i>	<i>500</i>	36	
Suspended solids	<i>2,000</i>	<i>4,200</i>	<i>2,400</i>	7.5	
Na ⁺	<i>4,800</i>	<i>2,000</i>	<i>2,300</i>		
Metals	<i>200</i>	<i>220</i>	<i>200</i>	3.6	
Nitrogen	<i>3</i>	<i>2</i>	<i>3</i>		
Cl ⁻	<i>42,000</i>	<i>39,000</i>	<i>40,000</i>	5.6	
SO ₄ ⁻	<i>1,500</i>	<i>4,000</i>	<i>4,300</i>	.19	
Oil	<i>50</i>	<i>50</i>	<i>50</i>	2.2	
Dissolved organics	<i>1,400</i>	<i>1,000</i>	<i>1,000</i>		
Other organics	<i>3</i>	<i>4</i>	<i>10</i>	.13	
Mineral waste	<i>60,000</i>	<i>110,000</i>	<i>66,000</i>		
Mixed industrial waste	<i>2,000</i>	<i>1,300</i>	<i>1,800</i>	119	
Slag/ash	<i>12,000</i>	<i>210,000</i>	<i>47,000</i>		
Inert waste	<i>11,000</i>	<i>11,000</i>	<i>14,000</i>		
Regulated waste	<i>3,500</i>	<i>3,500</i>	<i>1,200</i>		
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	
<i>COD</i>	<i>370</i>	<i>360</i>	<i>710</i>	<i>22</i>	
<i>BOD</i>	<i>51</i>	<i>45</i>	<i>150</i>	<i>8.5</i>	
<i>Acid as H</i>	<i>43</i>	<i>45</i>	<i>40</i>	<i>13</i>	
<i>Phenol</i>	<i>5</i>	<i>6</i>	<i>5</i>	<i>.15</i>	
<i>Suspended solids</i>	<i>290</i>	<i>340</i>	<i>690</i>	<i>9.5</i>	
<i>Dissolved solids</i>	<i>110</i>	<i>150</i>	<i>110</i>		
<i>Hydrocarbon</i>	<i>92</i>	<i>120</i>	<i>90</i>		
<i>Na⁺</i>	<i>490</i>	<i>600</i>	<i>610</i>		
<i>Metals</i>	<i>430</i>	<i>430</i>	<i>330</i>	<i>3.6</i>	
<i>Nitrogen</i>	<i>18</i>	<i>18</i>	<i>20</i>		
<i>Cl</i>	<i>5,600</i>	<i>4,700</i>	<i>3,500</i>		
<i>SO₄</i>	<i>160</i>	<i>160</i>	<i>120</i>	<i>.21</i>	
<i>Oil</i>	<i>69</i>	<i>70</i>	<i>61</i>	<i>2.4</i>	
<i>Dissolved organics</i>	<i>31</i>	<i>37</i>	<i>50</i>		
<i>Other organics</i>	<i>2</i>	<i>2</i>	<i>4</i>		
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 ⁻²	1,100	8,500	.20	
CO ₃ ⁻²	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	<i>25,000</i>	<i>25,000</i>	<i>18,866,680</i>				
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				
Petrocokoe	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. SO_x is a byproduct of the combustion of coal. However, SO_x generation depends both on the type of coal and the effort taken to reduce SO_x 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 1/2 to 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			
<i>Metal ions</i>	<i>700</i>			
<i>Waste water</i>	<i>25,000</i>			
<i>Mineral waste</i>	<i>160,700,000</i>			
<i>Slag/ash</i>	<i>3,221,000</i>			
<i>Unspecified</i>	<i>6,000</i>			
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			
<i>COD</i>	<i>14</i>	<i>2,140</i>			
<i>BOD</i>	<i>6</i>	<i>220</i>			
<i>Acid as H</i>	<i>2</i>	<i>2</i>			
<i>Suspended solids</i>	<i>600</i>	<i>900</i>			
<i>Dissolved solids</i>	<i>2</i>	<i>4</i>			
<i>Hydrocarbon</i>	<i>5</i>	<i>42</i>			
<i>Metals</i>	<i>1</i>	<i>10</i>			
<i>Nitrogen</i>		<i>30</i>			
<i>Cl</i>	<i>2</i>	<i>2</i>			
<i>Oil</i>	<i>1</i>	<i>2</i>			
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 $\frac{1}{2}$ to $\frac{1}{20}$ th. 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 \pm 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 \pm 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.

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