A Streamlined Life-Cycle Assessment Tool for the Production of Printers

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Abstract

The research presented in this paper examined the impact assessment and improvement analysis steps in the life-cycle assessment of the production of a printer. The impact assessment step assesses the possible impacts on human health; ecological quality and natural resources attributed to the inventory data such as the energy and resource usage, as well as environmental emissions produced during the life-cycle of the product. Various scoring criteria have been developed, which are weighted accordingly using the analytical hierarchy process method. The criterion scores and weights are combined to obtain a single figure of environmental merit for each component. The improvement analysis step appraises the needs and opportunities to reduce the environmental burden associated with resource use and environmental emissions throughout the life cycle of the product. The individual component scores are combined into a final environmental score representing the overall environmental quality of the printer. A software tool has been developed to perform the necessary computations. This final figure has environmental and commercial importance. It is useful in bench-marking a product against that of competitors', and also in assessing improvements to environmental quality due to changes to the product and its related processes or activities.

Keywords

Life-cycle Assessment, Environmental Impacts, Analytical Hierarchy Process, Manufacturing

1. Introduction

Life-Cycle Assessment (LCA) /1,2/ refers to a methodology for evaluating the environmental effects occurring throughout the entire life-cycle of a product, process or activity, encompassing the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth. Life-cycle studies have been performed for the past 20 years. However, there is currently still no single correct way to perform an LCA. The impact assessment step is still in the early stages of development following a Society for Environmental Toxicology and Chemistry (SETAC) workshop in early 1992, while the improvement analysis has not been discussed widely.

The results of an LCA indicate when the selection of one product over another, or when a modification made to the system has the desired end result of decreasing environmental impacts from all the life-cycle stages. In addition, when apparent improvements are made without considering possible secondary effects, unwanted shifting of burdens to another part of the system can occur. Thus, a key concept behind LCA is to identify these unwanted shifts between media (air, water, and solid waste).

2. Review of Existing LCA Applications

To conduct of an LCA demands considerable effort on the part of the investigator if accepted professional guidelines for study quality are to be met. It can be noted that the development of the methodology for LCA is highly theoretical, whereas the collection of data has a direct connection with practice. Software takes a position in between. It contains the formalised methodology and the suitability of the data within the theoretical framework. Thus, software may act as a bridge between theory and practice.

Today's typical LCA users are a mixture of LCA experts and individuals with skills in other disciplines who want to be able to evaluate their products, processes, or activities in a life-cycle context. Since LCA is being used more as a decision support tool in application methods such as Design-for-Environment or Pollution Prevention engineering, LCA software must mesh at a certain level with the tools typically used in these disciplines. LCA is rarely used alone. Thus, the compatibility of LCA software with other information system components and software tools is an issue with most users. However, the current generation of LCA software does not fully exploit the capabilities of the technology.

Most of the current LCA inventory analysis software is based on commercial spreadsheet programs. The most basic execution of this level of LCA inventory software uses the adorned spreadsheet as the input data template, computational engine and output form. A simple database on materials and processes may be included in a section of the spreadsheet so that users are not required to input anything more than basic functional unit and product descriptions. The database can be modified or augmented only with difficulty.

Two primary LCA impact assessment methodologies have been used in the impact assessment software, namely the critical volume approach and the conversion of inventory values (per functional unit) to monetized or quasi-monetized units. In the former case, relevant values for the regulatory levels are embedded in the software with or without user control or specification. In the latter case, the functional unit value-based data is transferred to a spreadsheet set-up to convert the mass values to impact metrics. Calculation of the aggregated impacts is then carried out.

Improvement assessment software has features that allow side-by-side comparisons of alternative systems. This feature allows the user to choose the most environmental friendly product, process or activity from among comparisons. The user can analyse the element that contributes to the greatest burden in order to reduce the effects to the environment.

A critical evaluation of this software shows that the method to calculate the impacts to the environment is still not standardized. Various software companies use different approaches to assign the impacts produced by the usage and processing of the materials. In addition, the method by which they obtain their scores of the impact to the environment is typically not disclosed. This can be misleading as these values may differ for different countries.

LCA methods for identifying, evaluating, and selecting among alternative opportunities for improving the energy, resource, and environmental release profile of a product or process are still developing. The complexity of the products involved and the multi-national nature of the manufacturing operations have limited the application of LCA in industries.

3. A Streamlined Life-Cycle Assessment Tool – PLCAT

Current available LCA tools typically require users to have considerable knowledge of the environmental issues involved or to seek out professional expertise to interpret the design implications of the results. For non-expert users, this is an undesirable feature. The PLCA (Pre-LCA) method, which was evolved in this study, is to place minimal burden on the designer to interpret the results. Furthermore, the PLCA method can be used as a prelude to a full LCA or as a stand-alone tool, depending on the product application and the type of decision that is being supported.

The software tool that has been developed in this study, entitled "PLCAT", is straightforward and easy to understand. It is designed for users who do not wish to spend large amount of time learning to use programs that are complicated and data-input intensive. PLCAT provides a preliminary study of the effects on the environment produced by the manufacture of a product. The user can compare different products by executing the program again and noting down the overall environmental score at the end of the program execution. In this way, designers would know which types of products are more environmentally friendly. Future products can be designed with the green feature in mind.

In PLCAT, weights of the criteria are calculated using the Analytical Hierarchy Process (AHP) method. First, the user has to input information on the amount of compounds that are emitted to the environment, ant the energy used. These would be processed by the built-in database to assign criterion scores for the process or product. Scores of the criteria range from 0.0 to 1.0 for most criteria. In this research, a score of 0 is most environmentally friendly. It may also exceed 1.0 in some cases. Criterion score of 0.0 has the least impact on the environment while a score of 1.0 has the most impact on the environment. Scores exceeding 1.0 are most undesirable. The criterion scores would then be combined to obtain an overall environmental score for the product.

4. OVERVIEW OF METHODOLOGY

Figure 1 shows the flowchart of the methodology adopted in this study to develop PLCAT.

4.1. Goal Definition and Scoping

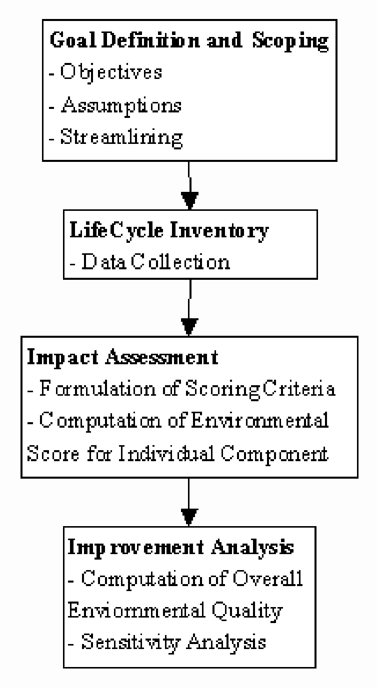

Figure1. Flowchart of Methodology.

The objective of this study is twofold. A streamlined life-cycle assessment is to be performed for the production of a printer, in particular, developing criteria to assess the environmental impacts associated with the resource consumption and environmental emissions at the various stages of the product life-cycle. The result of the study should be represented by a single figure indicative of the environmental merit of the printer. This figure would be useful in analyzing the needs and opportunities for improving the environmental aspects of the product. The assumptions made in this study are as follows:

Capital Equipment. In most systems, the inputs and outputs attributed to capital equipment are allocated among the multitude of products manufactured throughout the life-cycle of the capital equipment. As a result, the resource usage and environmental emissions attributed to capital equipment are mostly small, and are generally excluded.

Personnel Issues. At most sites, there may be personnel-related effluents due to the manufacturing process, canteen trash, energy use, air conditioning emissions, water pollution from sanitary facilities, etc. Inputs and outputs also occur when transporting personnel to and from home and work. In most situations, the personnel-related resource consumption and environmental emissions are small as compared with that involved in the direct manufacturing process of a product. Moreover, these personnel issues would most likely occur regardless of whether the product was produced or not. Hence, the resources used and environmental emissions due to personnel issues are not considered in this study.

Improper Disposal of Wastes. It is assumed that wastes are properly disposed into the municipal solid waste system or the wastewater treatment system. Illegal dumping, littering and other improper waste disposal methods are not considered as methods for solid waste disposal.

Foreign and Domestic Data. As a compromise, when no domestic data is available, practices occurring in other countries are assumed to be the same as for their domestic counterparts. Data is most readily adopted from the United States, Canada, Western Europe and Japan as these countries are acknowledged to possess the most accurate and readily available data on resource use and environmental releases.

The scope of the study has been streamlined in two ways, firstly, by focusing on parts composed of a particular material group and, secondly, on selected life-cycle stages of parts belonging to this material group. Focusing on parts composed of a particular material group allows for progress through the entire methodology of assessing the inventory data collected for the selected parts according to impact assessment criteria. The aim being familiarization with and improvement on the procedures. Once a viable assessment technique has been established, this may be extended to other parts of the printer, such as parts made of metal. The assessment is further streamlined by focusing on the manufacturing stage and recycle/waste management stages of the product life-cycle.

4.2. Life-Cycle Inventory (LCI)

This phase of the study entails an inventory of the energy and resource consumption, as well as environmental emissions produced during selected stages of the life-cycle of the product (the manufacturing stage - material manufacture and product fabrication steps). The data has been collected through interviews and correspondence with vendors. Literature research contributed data to supplement that obtained from vendors.

4.3. Impact Assessment (IA)

Possible impacts on human health, ecological quality and natural resources (summarily referred to as "the environment") due to the inputs and outputs at various life-cycle stages are assessed at this phase. Various criteria have been analyzed and formulated to assign an environmentally-related score to the individual inventory data and associated impacts. The AHP method is used to assign weights to the criteria representative of their relative importance. The weight sand criterion scores computed for the criteria are then combined to produce an environmental score representative of the environmental merit of the component.

4.4. Improvement Analysis

At this step, the component environmental scores computed previously are combined into an environmental score representative of the overall environmental quality of the printer. This final figure would be useful in appraising the needs and opportunities to improve the environmental aspects of the product and its related processes and/or activities. As the assumptions made in the course of the assessment can significantly affect the results, sensitivity analysis should be performed on the results in order to examine the effects of making changes to the system.

5. Life-Cycle Inventory and Impact Assessment

The LCI phase of the study entails an inventory of the energy and resource consumption, as well as environmental emissions produced during selected stages of the life-cycle of the product. Product-specific data has been collected through interviews and correspondence with vendors. Industry-average data were obtained through literature research.

The IA step assesses the possible impacts on human health, ecological quality and natural resources attributed to the LCI data collected at various life-cycle stages. Information on the possible impacts due to the data collected in the IA phase have been obtained through literature research, information gathered on the Internet, and through interviews and correspondence with persons involved in related fields. The IA phase may be thought of as comprising of two main sections, firstly, the development of IA criteria and, secondly, the computation of an environmental score for individual components.

5. Development of Impact Assessment Criteria

Various criteria were analyzed and formulated to assign an environmentally-related criterion score to the inventory data and associated impacts. Each criterion has been formulated with the goal of quantifying as accurately as possible the particular inventory data or related impact under consideration. This in turn would allow for a more objective environmental score to be computed for each criterion. In addition, the criteria are based product-specific as well as industry-average information.

5. Computation of Environmental Score for Individual Parts

For each plastic component, based on the criteria, an environmental score is computed for the individual LCI data and associated impacts. The AHP method is employed to weigh the criteria according to the relative importance attached to each criterion by the user. The computed environmental scores and assigned weights are then combined to obtain an environmental score representing the environmental merit for the component.

6. Impact Assessment Criteria

A set of IA criteria has been identified for the LCA of a printer production. These criteria have been analyzed to formulate the methods of determining a criterion environmental score to a component for that particular criterion. In this research, a criterion score of 0 is most environmentally friendly. It may also exceed 1.0 in some cases. Criterion score of 0.0 have the least impact on the environment while a score of 1.0 has the most impact on the environment. Scores exceeding 1.0 are most undesirable where environment is concerned. The criteria scores would then be combined for the product so that an overall environmental score can be found for each component.

6.1. Energy Usage - Process Energy

The values for the ***energy usage - process energy*** criterion are taken to be similar to the net process energy for all processes involved in the production of the plastic resin /3/. Figure 2 shows the chart that has been formulated for calculating a criterion score for this criterion.

To illustrate, the net processing energy/process energy per unit weight of ABS and Polycarbonate (PC) are 8280 BTU/lb and 9200 BTU/lb respectively. Assuming that for two plastic components belonging to the same assembly, one component composes of 1 lb of ABS and the other component, 2 lbs of PC. The process energy required for each component is 8280 and 18400 BTU respectively. An environmental score of 1.0 is assigned to the component composed of PC as it has the higher process energy value. An environmental score of 0 would represent a material **with zero process** energy (ideal). A linear relationship is assumed to plot the graph in Figure 2. The score corresponding to the process energy for the ABS component is read off this graph.

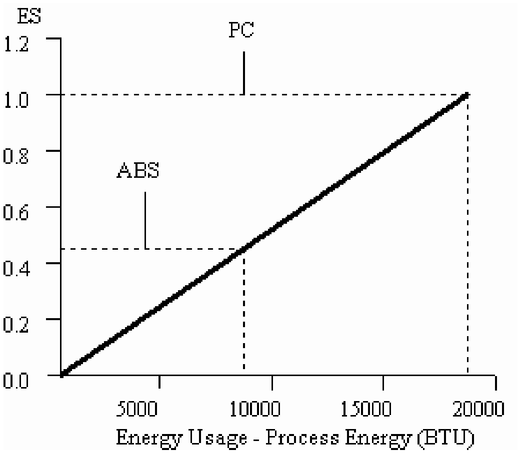

Figure 2. Graph of ES vs Process Energy.

6.2. Energy Content of Material Resources

Net heat of fuel combustion values are equivalent to the energy content of material resources. The energy content of material resources is also known as the fuel-related inherent energy or the latent energy of materials /3/. It accounts for those products that consume raw materials whose alternative use is as a fuel/energy resource. The inherent energy is a measure of the energy implications of the decision to forego the use of it as fuel /1/. Plastics are derived from petroleum and natural gas. As the actual plastic materials contain energy, an energy value is assigned to the plastic material in addition to the other types of basic energy forms associated with plastic production. This additional energy value is equivalent to the fossil fuel combustion value of petroleum and natural gases.

For the components under consideration, a scoring system similar to that for the previous criterion has been formulated for this criterion. Having accounted for the weight of the material used in each component, an environmental score of 1.0 is assigned to the component made of material having the highest energy content of material resources. This is representative of the highest opportunity cost as a result of making use of the resources. An environmental score of 0 would represent zero energy content of material resources. A linear relationship is assumed and a graph of environmental score versus energy content of material resources can be plotted. The score corresponding to the energy content of material resources for components composed of other materials can be read off this graph.

6.3. Airborne Emissions

The criterion for airborne emissions is derived based on the Environment Ministry of Singapore's National Emission Standards for Air Pollutants. An environmental score of 1.0 is assigned to the regulatory standard for the particular airborne emission being considered. Similarly, a score of 0 is assigned to represent an ideal of zero emissions.

6.4. Inhalation Risks

Many regulatory agencies have evaluated the health data and published dose-response values for many chemicals /4/. Unit risk values are the probability of contracting cancer if one is exposed to 1 microgram per cubic metre (a "unit" exposure) of the chemical for a 70-year life-time. The AELs (acceptable exposure level) are the levels at which direct health effects could occur in the most sensitive populations.

6.4.1. Carcinogenic Chemicals

The range of acceptable cancer risks is from 1×10^{-4} (100 in 1,000,000) to 1×10^{-7} (0.1 in 1,000,000) per EPA guidance. However, most agencies use 1×10^{-6} (1 in 1,000,000) as a point of departure for decision making, i.e., a practical *de facto* bright-line standard of 1 in 1,000,000. For carcinogenic chemicals, the risk screening procedure is given by equation (1). RS is the risk score, Q is the emission rate in pounds per year, URV represents the unit risk value, and 1700 is the conversion and dispersion factor.

$$RS = Q \times URV \times 1700 \ (1) \qquad (1)$$

From equation (1), the resultant RS is equal to the risk per 1,000,000. If RS equals 10, the risk is equivalent to 10 in 1,000,000. Generally, when the risk is less than 1 in 1,000,000, no further action to reduce the risk is required. If the risk is 10 in 1,000,000, some form of risk reduction process is required to reduce the risk to below 1 in 1,000,000. If the risk is greater than 100 in 1,000,000, immediate action is required.

Based on the above risk characterisation, the graph in Figure 3 is formulated. An environmental score of 0 is assigned to a risk of less than 1 in 1,000,000. A score of 0.1 is assigned to a risk of 10 in 1,000,000, and a score of 1.0 is assigned to a risk of 100 in 1,000,000. An exponential relationship between the environmental score and the risk score is assumed, as shown in Figure 3.

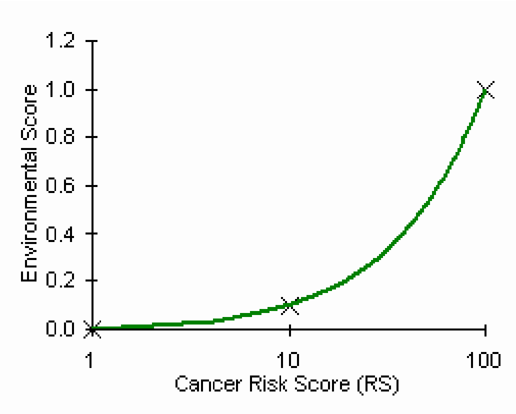

Figure 3. Graph of ES vs Cancer Risk Score (Carcinogenic Chemicals).

This assumption emphasises that higher scores are associated with greater risks to human health. Thus, a cancer risk score exceeding 100 in 1,000,000 would be penalised with an environmental score greater than 1.

6.4.2. Non-Carcinogenic Chemicals

For non-carcinogenic chemicals, the risk screening equation is given by equation (2) and equation (3) for chronic and acute effects respectively.

$$RS = (Q/AEL) \times 150 \text{ for chronic effects (2)} \qquad (2)$$

$$RS = (Q/AEL) \times 1500 \text{ for acute effects (3)} \qquad (3)$$

RS is the risk score, and Q is the emissions in pound per year for chronic effects, and pounds per hour for acute effects. AEL is the acceptable exposure level, and 150 and 1500 are the conversion and dispersion factor. From these equations, if RS exceeds 10, it indicates that the AEL is likely to be exceeded. If it is less than 10, the AEL is not likely to be exceeded. When the concentration of the chemical is less than the AEL, there will be no health effect. If the concentration is slightly or much greater than the AEL, the health effect will occur. Thus, an environmental score of 0.1 is associated with an RS less than 10. An environmental score of 0.9 is assigned to an RS exceeding 10. This results in the ‘step’ graph being formulated as shown in Figure 4.

6.5. Global Warming Factor

Global Warming Potentials (GWP) of major Greenhouse Gases (GHGs) are shown in Table 1 /5/.

Gas	**Annual Growth Rate as of 1990 (%/year)**	**Contribution to Global Warming** **1880-1990 (%)**	**Lifetime (years)**	**Global Warming Potential**
CO_2	0.5	66	120	1
CH_4	0.9	15	10	21
N_2O	0.25	3	150	290
CFC-11	4	4	60	3700

CFC-12	4	5	130	7600
Others		7	No Estimates	
HCFC-22			15	1500
HCFC-123			1.6	87
HCFC-134a			16	1300
HCFC-143a			41	2900
HCFC-152a			1.7	140

Table 1. Global Warming Potential Values of Major Greenhouse Gases

A set of scores can be calculated based on the GWP values. For example, for a particular process, 15 units of CO_2, 10 units of CH_4 and 5 units of N_2O with GWP 1, 21 and 290 respectively are emitted. The scoring system that has been devised for this criterion is shown in Table 2. The scores are influenced strongly by the magnitudes of the GWPs of GHGs being considered. This should be taken into consideration during the ranking of the criteria, so that the environmental impact of the GHGs is assigned the appropriate level of importance.

GHG	GWP	No of Units, Q	GWP x Q	Fraction (Score)
CO_2	1	15	15	15/1675 = 0.009
CH_4	21	10	210	210/1675 = 0.125
N_2O	290	5	1450	1450/1675= 0.866
Total			1675	1.000

Table 2. Scoring System for Greenhouse Gases

6.6. Waterborne Emissions

The criterion for the waterborne emissions is derived based on the Environment Ministry of Singapore's Allowable Limits for Trade Effluent Discharge to Sewer/Watercourse/Controlled Watercourse. Similar to the scoring system that has been formulated for the airborne emissions criterion, an environmental score of 1.0 is assigned to the allowable limit for the type of trade effluent and discharge category being considered. A score of 0 is assigned to represent an ideal of zero trade effluent discharge.

6.7. Industrial Scrap to Part Weight Percent

The industrial scrap to part weight percentages for the four plastic components of the input tray assembly of a printer at the injection moulding stage are given in Table 3 /6/.

Part	Short Weight (part & runner) in grams	Industrial Scarp to Part Weight Percent – runner wt. vs part wt.	Comment
Tray-Main	325	0	No scrap due to moulding method used
Plate-Presure	186.25	7	-

Cover-Input	113	8	-
Guide-Paper	27	16	-

Table 3. Input Tray Assembly – Industrial Scrap to Part Weight (%)

The scoring system formulated for this criterion involves assigning an environmental score of 1.0 to the component with the highest industrial scrap to part weight percent as a reference value. A score of 0 represents a lower (ideal) limit of zero industrial scrap to part weight percent. A linear relationship is assumed between these two variables (score and criterion), and a straight-line graph is obtained from which other components can be scored accordingly.

6.8. Product Disassembly Potential

The Design for Assembly (DFA) index is derived by rating the ease of assembly of a part according to certain criteria and assigning penalties to those parts which do not meet the criteria. A higher DFA index means that a part is easier to assemble. In general, a part, which is easier to assemble, is also potentially easier to disassemble. Therefore, a higher DFA index generally indicates the potential ease with which a part may be disassembled.

For all the components listed in a printer, the "Kicker 1–Output" has the highest DFA index of 110. This component is the easiest to assemble and should potentially be the easiest to disassemble. This component would therefore require fewer resources for assembly and disassembly, thus encouraging separation and appropriate disposal of the plastic component (such as through recycling). Hence, an environmental score of 0, indicative of greater environmental merit, is assigned to this component. An environmental score of 1.0 is assigned to the component with the lowest DFA index, indicative of the lowest product disassembly potential (and environmental merit). A linear relationship is assumed between the environmental score and product disassembly potential, from which the scores associated with the product disassembly potential of the other components can be derived.

6.9. Waste to Energy Value

The waste to energy value is taken as the product heat of combustion /3/. The greater the amount of energy produced when the waste is burnt, the more environmentally desirable this is, assuming the energy released is properly utilised.

To illustrate the scoring system that has been formulated for this criterion, if two components are made of 1lb of ABS and 1.5lb of PC respectively, the respective waste to energy values would be 18045 BTU and 30075 BTU. An environmental score of 0 is assigned to the component that is composed of the material with the highest waste to energy value, in this case PC. The worst case scenario of zero waste to energy value is assigned a score of 1.0. A linear relationship is assumed. A graph of score versus waste to energy value is obtained showing a negatively sloped straight line passing through the above two points. As shown in Figure 5, the score corresponding to the waste to energy value of ABS can be read.

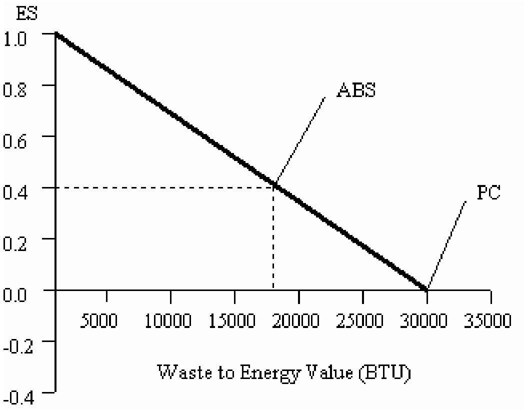

Figure 5. Graph of ES vs Waste to Energy Value.

6.10. Waste Disposal Factor

In different areas of the world, different choices are made concerning the solution of plastic waste problems. Plastic wastes are mainly dumped in US. In Japan, a larger proportion of the plastic waste is incinerated. In the Netherlands, the bulk of the plastic waste is dumped or incinerated (about 90%), while the Dutch public and the political agenda prefer prevention and recycling /7/. Based on the 1995 Dutch Government Policy on polymer waste, the targets for polymer waste and polymer packages (expressed in kilotonnes) are shown in Table 4.

Waste Disposal Option		1986		2000	Percentage Change
Prevention	-	(0%)	-	(0%)	0%
Re-use & Recycling	55	(10%)	200	(35%)	+25%
Incineration	160	(30%)	240	(45%)	+15%
Dumping	325	(60%)	100	(20%)	-40%
Total	540	(100%)	540	(100%)	-

Table 4. 1995 Dutch Government Policy - Targets for Polymer Waste & Polymer Packages

From Table 4, it appears that the preferred waste disposal option is prevention, followed by re-use and recycling, incineration and lastly dumping. Based on the magnitude of the percentage change of the various waste disposal options, a scoring system shown in Table 5 is adopted.

Waste Disposal Option	Percentage Change	Rank	Score
Prevention	0%	0	0/3 = 0
Re-use & Recycling	+25%	1	1/3 = 0.33
Incineration	+15%	2	2/3 = 0.67
Dumping	-40%	3	3/3 = 1.0

Table 5. Scoring System for Polymer Waste Disposal Options

Therefore, parts that can be re-used/recycled are assigned a low environmental score relative to parts which have to be disposed of by incineration or dumping.

6.11. Post-Consumer Recycle Percentage

Post-consumer plastics that are 100% divertible from the general municipal waste stream are assumed to be candidates for recycling in a secondary or tertiary sense. Therefore, they are considered to have maximum potential as DPWs (divertible plastic waste) /3/. An environmental score of 0 is assigned to the 100% of post-consumer plastics associated with having full potential as DPWs. A worst case scenario of minimum potential as DPWs would be associated with 0% of post-consumer plastics, and is assigned an environmental score of 1.0. A linear relationship between the percentage of post-consumer plastics recycled and the score is assumed as shown in Figure 6. The score corresponding to a given post-consumer recycle percentage can be read off the graph.

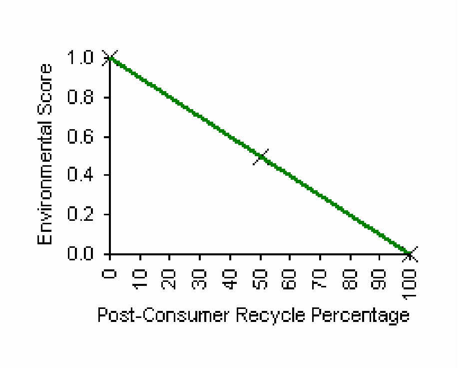

Figure 6. Graph of ES vs Post-Consumer Recycle Percentage.

7. Computation of Environmental Score for Individual Component

For each plastic component, based on the various criteria, an environmental score is computed for the LCI data and the associated environmental impacts. The AHP method is employed to weigh the criteria according to the relative importance attached to each criterion by the user. These computed environmental scores and assigned weights are next combined to produce an environmental score representing the environmental merit of the component.

Determination of weights of criteria in a hierarchical structure is an important and formidable task. In a general setting, the weights may be determined by an analysis of available quantitative data, by an analysis of available qualitative information, or by a subjective assessment of available qualitative information. When the quantitative data is insufficient or not available, the weights have to be determined based on the available information or expert opinion. In such cases, the use of theoretical methods or frameworks for determining weights is preferred to simply making a subjective assessment. Saaty' s method /8, is one such framework for the determination of weights based on qualitative information or expert opinion. This method is known as the eigenvector method. The method utilizes a technique known as the pair-wise comparison. Through pair-wise comparisons of the criteria, a matrix of numbers is formed. Each number in the matrix is a mapping of the judgement in a pair-wise comparison to a scale of importance shown in Table 6. The scale recommended is from 1 to 9. By enforcing a constraint of consistency in the results of pair-wise comparisons, a procedure was developed for determining weights of the criteria in a hierarchical structure. This procedure involves finding an eigenvector which satisfies the consistency constraint. The elements of the eigenvector obtained are the wanted weights.

Assuming that there are *n* criteria to evaluate a printer consisting of *m* number of components, the process of pair-wise comparisons will require a total number of $n(n\text{-}2)/2$ judgements. According to Saaty, the relative importance of one criterion over another may be measured in terms of some linguistic descriptors listed in Table 6

Intensity of importance	Definition
1	Equal importance

3	Weak importance of one over another
5	Essential of strong importance
7	Demonstrated importance
9	Absolute importance

Table 6. Intensity of Importance for AHP Matrix

When a pair of criteria are compared, the relative dominance of one criterion over the other is judged and a proper descriptor is assigned. In order to process the result of the pair-wise comparison (or judgement), a discrete value of 1 to 9 is used to map these descriptors into numbers. Thus, the end product of the pair-wise comparison process is a matrix of scaling numbers, which is called the pair-wise comparison matrix (PCM).

Theoretically, a PCM is a reciprocal matrix that has positive elements and has the reciprocal property. Let *A* be a PCM given by equation (4).

$A = a_{11}\ a_{12} \ldots a_{1n}$

. . . .

. . . .

. . . .

$a_{n1}\ a_{n2} \ldots a_{nn}$

(4)

For $1 \leq i \leq n$ and $1 \leq j \leq n$,

$a_{ij} = 1 / a_{ji}$ (5) (5)

Each element a_{ij} of a PCM may be considered as a ratio of weights. For example, if the ‘true’ weights of all the criteria are known, then the result of a pair-wise comparison (criterion *i* vs criterion *j*) will simply be the ratio of the weight of criterion *i* to that of *j*. This may be expressed symbolically as equation (6).

$a_{ij} = w_i / w_j$ (6) (6)

w_i and w_j are the weights of criterion *i* and *j* respectively. Once the PCM has been constructed, the problem of determining the weights becomes that of finding an eigenvector *W* to satisfy equation (7).

$A\ W = \lambda_{max}\ W$ (7) (7)

W is the eigenvector whose elements are the weights of the criteria considered, and λ_{max} is the largest eigenvalue of the matrix A. The eigenvector W is usually expressed as equation (8), and that these weights are often normalized to ensure uniqueness and that $\sum w_i = 1$.

$$W = [w_1, w_2, \ldots, w_n] \quad (8)$$ (8)

8. Improvement Analysis

Previously, the impact assessment step results in an environmental score being computed for the individual components according to various criteria and their associated weights.

In the improvement analysis phase of the study, the scores for the components are combined into a final environmental score representative of the overall environmental quality of the printer. This final figure would be useful in bench-marking the product against that of competitors', thus indicating if environmentally-related improvements are needed to put the printer on par with or even exceed the environmental quality of a competitor's product. In addition, this figure would be useful in assessing if environmental burdens have been reduced (i.e., environmental quality has been improved) as a result of changes to the product and its related process/activities.

The results of the assessment can be very much affected by the assumptions made during the study. Hence, sensitivity analysis should be performed on the results to assess the effects of making changes to the system.

8.1. Computation of Overall Environmental Quality

The procedure for combining the individual environmental scores for the components to compute an overall environmental quality of the product is explained next. For a product consisting of m components of which an ES has been determined for each component, the ES matrix is defined as equation (9).

$$ES = [ES_1, ES_2, \ldots, ES_m] \quad (9)$$

Let SWj be the sum total of the AHP weights associated with the criteria that have been used to determine ES_j for component j expressed as a fraction of the maximum possible total of AHP weights. Therefore, for m number of components, SW is defined as equation (10).

$$SW = [SW_1, SW_2, \ldots, SW_m] \quad (10)$$

SW is determined using equation (11), where W is given by equation (8), CA is given by equation (12), and MAX is the maximum sum total of AHP weights.

$$SW = 1/MAX(W \times CA) \quad (11)$$

For m number of components in a product, and n number of criteria, CA is defined as equation (12).

$$CA = ca_{11}\ ca_{12} \ldots ca_{1m}$$

. . . .

. . . .

. . . .

$$ca_{n1}\ ca_{n2} \ldots ca_{nm} \quad (12)$$

For $1 \leq i \leq n$ and $1 \leq j \leq m$,

$ca_{ij} = 1$ if criterion i has been used to evaluate component j

$ca_{ij} = 0$ if criterion i has not been used to evaluate component j

The final environmental score for a product consisting of m components is determined using equation (13).

$$\text{Final Environmental Score} = SW^{T} \times ES \qquad (13)$$

To illustrate the above methodology, it is assumed that there are five scoring criteria and four components are being considered. Table 7 below summarises the results of the IA phase. The 2nd column displays the weight assigned to each criterion as determined by the AHP method. Also, make-believe scores are shown in the last row for each component.

Criteria No.	Weight (assigned by AHP)	Part A	Part B	Part C	Part D
1.	0.250	*X*	*X*	-	*X*
2.	0.100	*X*	*X*	*X*	-
3.	0.300	*X*	-	*X*	*X*
4.	0.150	*X*	*X*	*X*	-
5.	0.200	*X*	*X*	-	-
Total	1.000	0.700	0.500	0.300	0.150

Table 7. Output of Impact Assessment Phase

Table 8 is used to compute the overall environmental score indicative of the environmental merit of the printer. *x* represents an environmental score computed for the component according to a particular criterion, and - represents that the part is not scored for this particular criterion.

Part	Sum Total of AHP Weights Associated With No. of Criteria Used	Ratio of Individual Part AHP Total to Max. Possible AHP Total	Environmental Score	Column 3 x

				Column 4
A	1.000	1.000/1.000	0.700	0.700
B	0.700	0.700/1.000	0.500	0.350
C	0.550	0.550/1.000	0.300	0.165
D	0.550	0.550/1.000	0.150	0.0825
				Σ = 1.298

Table 8. Improvement Analysis Phase – Computation of Overall Score

In Table 8, the 2nd column displays the sum total of AHP weights associated with the criteria used in scoring each component. As different components are scored according to different number of criteria, the sum total of the AHP weights is different. For example, as shown in Table 7 above, Part B is scored according to Criteria Nos. 1, 2, 4 and 5, and the sum total of the AHP weights associated with these four criteria is 0.700 (0.250 + 0.100 + 0.150 + 0.200). The 3rd column of Table 8 expresses the sum total of AHP weights for each component as a fraction of the maximum possible total of AHP weights (which according to the AHP method of assigning weights is 1.000). The 4th column in Table 8 displays the overall environmental score associated with each component, as derived from Table 7. Part D has the lowest overall score, followed by Parts C, Part B, and Part A.

From Table 8, the 3rd column represents the SW matrix and the 4th column represents the ES matrix. Therefore, using equation (13), the final ES of this product is 1.298. With respect to the 2nd column in Table 8, for a particular part in general, a low (high) sum total would indicate that the impact of the part on the environment is of relatively lesser (greater) importance. A low (high) sum total also indicates a less (more) objective environmental score as fewer (more) criteria are used to score that component.

In this formulation, the overall product environmental score takes into account the relative importance of the environmental impact associated with each component, as well as the level of objectivity involved in computing the part score. The computation of the final score is based on a weighted-average of the contribution of the individual part scores. The emphasis given to the individual part scores (ES_i) is represented by the sum total of the AHP weights for the respective parts expressed as a fraction of the maximum possible sum total of the AHP weights (W_i/Max).

Hence, the final environmental score is representative of the environmental merit of the printer. It takes into account the relative importance of each component in terms of its impact on the environment, the level of objectivity involved in the computation of the individual component scores, and also how environmentally "poor" or "good" each component is.

8.2. Sensitivity Analysis

A mixture of factual data and assumptions are applied in the course of the study. These assumptions permit an assessment of the system conditions when factual data is either unobtainable within the context of the study or does not exist. As the assumptions made can significantly affect the results, "what if" calculations or sensitivity analysis should be performed on the results in order to examine the effects of making changes to the system. Sensitivity analysis involves temporarily modifying one or more parameters and observing the changes in the results. Therefore, the analysis aids in determining the importance of the assumptions with respect to the results.

9. Case Study

This section presents a case study on PE bags and Kraft paper bags that has been tested with PLCAT. Data from a separate study prepared by the West German Federal Office of the Environment focusing only on alternatives for the manufacture of shopping bags (1988) were used in this case study /3/. Due to commercial confidentiality, the case study using the printer cannot be published.

9.1. Summary of Data and Results

The authors for the German study focused only on the alternatives for the manufacture of shopping bags - developing energy and environmental impact comparisons for low density polyethylene shopping bags, unbleached Kraft paper bags, and bags made of either polyamide fibres or jute fibres. The first two categories were assumed to be single-use bags, while the third category of bags made from polyamide or jute fibres were assumed reusable for 100 or 50 times, respectively. Table 9 presents the estimates of energy use and environmental releases from the production of 50 000 bags.

	Bag Material		
Energy/Pollution Parameter	**Low-density Polyethylene**[a]	**Unbleached Kraft Paper**[b]	**Paper Combinations**[c,d]
Energy (GJ)			
Production Processes	29	67	69
Contained in Material	38	29	29
Total Energy Consumed	67	96	98
Air Polluting Emissions (kg)			
Sulphur dioxide (SO_2)	9.9	19.4	28.1
Nitrogen oxides (NO_x)	6.8	10.2	10.8
Organic Materials	3.8	1.2	1.5
Carbon Monoxide	1	3	6.4
Dust	0.5	3.2	3.8
Waste Water Burden (kg)			
Chemical Oxygen Demand	0.5	16.4	107.8
Biological Oxygen Demand	0.02	9.2	43.1
Organic materials (except phenols)	0.003	NA	NA
Phenols	0.0001	NA	NA
Chloro-organic compounds	NA	NA	5

Table 9. Comparison of Environmental Impacts from Production of 50 000 Bags of Competing Materials

Notes on Table 9: (a) 0.4m^2 of PE film, 50 microns thick (18g); (b) 0.4m^2 of paper with surface weight 90g/m^2 (36g); (c) This material consists of 60% white Kraft paper, 25% brown Kraft paper, 15% white sulphite paper; (d) Energy consumption for the process includes 29GJ obtained from burning residual raw materials; this and the materials portion derive from the wood raw material; and (e) BOD within 5 days

9.2. Computation of Environmental Score and Preliminary Sensitivity Analysis

Several assumptions are made so that the data of the German study may be employed to test this project’s methodology. The data are scored according to a total of eight criteria. The results of applying these assumptions are tabulated in Table 10, together with the individual environmental scores corresponding to the various criteria. The assumptions are listed below.

i. The following Energy/Pollution Parameter categories and scoring criteria are considered equivalent: Energy of Production Processes and Process Energy, Energy Contained in Material and Energy of Material Resources, Air Polluting Emissions and Airborne Emissions, and Waste Water Burdens and Waterborne Emissions.
ii. Four IA criteria are applied to the test data, namely Waste to Energy Value, Waste Disposal Factor, Post-Consumer Recycle Percentage, and Global Warming Potential.

iii. The comparison is on a per bag per use basis. The first two categories of materials are for single-use bags, whereas bags made of the last category of material are assumed reusable for 50 times.
iv. The units of measurement are converted from kilograms to milligrams, where applicable.
v. The airborne emissions are assumed to be measured on a per cubic metre basis (i.e., the units for airborne emissions are mg/m^3).
vi. The waterborne emissions are assumed to be measured on a per litre basis (i.e., the units for waterborne emissions are mg/l).
vii. The reusable bag weighs the same as the single-use paper bag, and has the same waste-to-energy value.
viii. All computations of environmental scores for individual criterion are similar to that proposed in the study, except for the criterion Global Warming Potential. In this instance, for this criterion, the highest quantity of emissions is assigned a score of 1.0 and the ideal lower limit of zero emissions is assigned a score of 0. A linear scale is assumed, based upon which the other emission quantities are scored accordingly.

Input/Output	Criterion	LDPE (18g)	Kraft Paper (36g)	Combination (36g)
ENERGY (LCI)	Process Energy (MJ)	0.580	1.34	0.0276
AHP1		***0.433***	***1.000***	***0.021***
RAW	Energy of Material Resources	0.760	0.580	0.0116
MATERIALS (IA)	(MJ)	***1.0***	***0.763***	***0.015***
AHP2				
AIRBORNE	$S0_2$	198	388	11.24
EMISSIONS (LCI)	Limit 0.10g/m3	***1.98***	***3.88***	***0.112***
AHP3				
	NO_X	136	204	4.32
	Limit 1.0g/m3	***0.136***	***0.204***	***0.004***
	CO	20	60	2.56
	Limit 1.0g/m3	***0.020***	***0.060***	***0.003***
	Dust	10	64	1.52
	Limit 0.20g/m3	***0.050***	***0.320***	***0.008***
	*Organic Materials	76	24	0.6
AIRBORNE	Global Warming Factor	136	204	4.32
EMISSIONS (IA)	- NO_X	***0.667***	***1.000***	***0.021***

AHP4	(GWP = 290)			
WATERBORNE	COD	10	328	43.12
EMISSIONS	Limit 600mg/l	***0.017***	***0.547***	***0.072***
(LCI)				
AHP5	BOD	0.4	184	17.24
	Limit 400mg/l	***0.001***	***0.460***	***0.043***
	Phenols	0.002	NA	NA
	Limit 0.5mg/l	***0.004***	-	-
	*Organic Materials (except phenols)	0.06	NA	NA
	*Chloro-organic compounds	NA	NA	2
SOLID WASTE	Waste-to-energy value	20000 btu/lb	7590 btu/lb	7590 btu/lb
(IA)		***1.00***	***0.759***	***0.759***
AHP6				
SOLID WASTE	Waste Disposal Factor	Burn	Burn	Reuse/recycle
(IA)		***2/3***	***2/3***	***1/3***
AHP7				
SOLID WASTE	Post-Consumer Recycle %	0%	0%	100%
(IA)		***1.0***	***1.0***	***0***
AHP8				
FINAL SCORE		**F1**	**F2**	**F3**

Notes on Table 10: (a) All units in mg, unless otherwise stated; (b) Individual Environmental Score are in bold italic in Table 10; (c) * indicates data not considered (no regulatory limits); and (d) Final Score (after inclusion of AHP weight). The final score for each bag is computed by multiplying the individual environmental scores by their respective AHP weights, followed by summing the results of multiplication.

Preliminary sensitivity analysis is performed using various combinations of AHP weights so as to obtain different sets of final scores, as shown in Table 11 below.

Case	**Description**	**AHP Weights**	**Final Score**		
			F1	**F2**	**F3**
1.	Using equal AHP weights for all criterion	AHP1 to AHP8 = 1/8	0.87	1.33	0.17
2.	Global Warming Factor criterion assigned relative importance	AHP4 = ¼ AHP1 to AHP3,	0.84	1.28	0.15

	compared rest of criteria	AHP5 to AHP8 = 3/28			
3.	IA criteria assigned relative importance compared to LCI criteria	AHP1,AHP3,AHP5 = 1/18 AHP2,AHP4, AHP6 to AHP8 = 1/6	0.87	1.06	0.20
4.	LCI criteria assigned relatively importance compared to IA criteria	AHP1,AHP3,AHP5 = 4/17 AHP2,AHP4,AHP6,AHP7, AHP8 = 1/17	0.88	1.77	0.13
		Average	**0.87**	**1.36**	**0.16**

Table 11. Summary of Preliminary Sensitivity Analysis

9.3. Discussion

The results of applying this study's methodology to data from the German study show agreement with the following conclusions of the German study.

1. That there is no ecological basis for requiring a switch from single-use LDPE (final score = 0.87) to paper (final score = 1.36) bags.
2. That switching toward the LDPE bags would not produce a 'significantly lower burden' to the environment because of the significance of the solid waste burden created by either single-use bag (as both paper and plastic are found to degrade very slowly in landfills).
3. The results instead suggest that reusable bags (final score = 0.16) are the preferred alternative and will result in net energy and environmental benefits.

Thus, the criteria developed are able to assess the environmental impacts related to the test data, and the end result is applicable for improvement analysis. In addition, preliminary sensitivity analysis results indicate that varying the relative importance of the various criteria does not adversely affect the computed end-results, and hence the conclusions of the study.

10. Conclusions

The twofold objective of this study has been achieved. Firstly, in the course of this streamlined LCA, criteria have been developed to assess the environmental impacts associated with the resource consumption and environmental emissions at the various stages of the life-cycle of a product. Secondly, the end result of the study, an environmental score representing the overall environmental quality of the printer, has shown to be useful in analysing the need and opportunities for improvements to the product and its related processes and/or activities.

Hence, in line with the objectives of this study, the impact assessment and improvement analysis phases of an LCA have been examined in greater detail. A software tool has been developed to perform the computations necessary to produce the final result, which has both environmental and commercial importance.

The methodology that has been implemented was tested using test data from a separate study. The results show agreement with the conclusions of this separate study. In addition, preliminary sensitivity analysis results indicate that varying the relative importance of the various criteria does not adversely affect the computed end-results.

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