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Life Cycle Assessment as a Tool for Green Manufacturing Education

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Abstract

The design and production of engineering products that have a reduced impact on the environment and human health has increasingly become a strategic goal of corporations. Consequently, starting engineers will need to be educated in green design techniques. One method that is particularly attractive to engineers is Life Cycle Assessment (LCA). LCA is an objective approach to evaluating the environmental burden of a product, process or activity by identifying and quantifying material and energy usage and waste outputs at every life stage. LCA involves three steps: identification of scope of analysis, life cycle inventory, and impact analysis. Such an approach has two attractive features for engineers. First, it is a rational and quantitative process that is easily appreciated by engineers. Second, because it examines all stages of the life cycle, it allows engineers to easily identify what design or process improvements will lead to the greatest reduction in environmental impact.

The present paper will describe a laboratory experience used in a senior level materials and process selection design course developed by the author. The project involves conducting a LCA analysis on a telephone as part of a redesign of the phone to reduce its environmental impact. Students begin the project by dismantling the phone and taking inventory of the materials contained within the phone. This information is used to determine the energy consumed in production of the phone. Information is also provided regarding energy consumption in the distribution, use and disposal of the phone. Students are then asked to examine a variety of different design and process changes and determine the relative change in environmental impact resulting from these changes. The paper will discuss the LCA approach (including streamlined LCA), details of the laboratory project, student outcomes and suggestions for improving the project.

Introduction

With increased societal and industrial interest in reducing the environmental impact of human activity, the need for environmentally conscious design and manufacturing has become more pronounced. While there have been considerable national and international efforts in recent years, including ISO 14000[1], corporations are only now beginning to recognize the need to train product and manufacturing engineers in the tools and techniques of design for environment[2]. Engineers have tremendous influence on the environmental impact of products at all life stages including the materials used, energy consumed and pollution generated during manufacturing, distribution and use. In addition, they can have a definite impact on the ease with which a product can be reused, remanufactured or recycled prior to disposal.

The project described in this paper is intended to inform students of one particular tool for design for environment known as life cycle analysis (LCA). This technique examines each life cycle stage of a product from material extraction to product disposal to determine the greatest environmental impacts in the product's life cycle. With this information engineers can focus their efforts for environmental improvement. In recent years there have been a large number of examples of LCA being used for engineering design applications[3-8]. This is particularly true in the automotive industry, which is now responding to the European Union's End-of-Life Vehicle Directive[9,10].

For the project described here, students conduct a LCA of a telephone with the intent of providing practical recommendations for environmental improvement. A simplified form of this method is used so that the educational benefits are still achieved without overwhelming the students with detail. It is important to point out that the focus of the project is to acquaint students with the LCA approach rather than the details of the telephone life cycle. Consequently, many significant details of the telephone's life cycle are ignored and data is sometimes contrived to simplify the analysis for the students. In addition, the project uses software (Cambridge Engineering Selector by Granta Designs Ltd.[11]) to provide much of the data for the analysis. A copy of the most recent project description is provided at the end of this paper.

This paper begins with a brief explanation of life cycle analysis, including streamlined life cycle analysis approaches. The project is then described and student outcomes, as well as, suggestions for improving the project are provided. Both the instructor's and an independent evaluator's evaluation of assessment results suggest that the project has been very successful in introducing students to life cycle assessment and encouraging in them a sense that as an engineer they can have a significant role in protecting the environment.

Life Cycle Analysis

Life cycle analysis (LCA) is an objective approach to identify, examine and evaluate the relevant environmental impact of various societal activities including the production of goods and services by corporations. Primarily, LCA is used at the national and/or global level to identify environmental burdens resulting from the activities of a society, region or industrial sector. However, it is also capable of providing valuable insight to the engineer tasked with reducing the environmental impact of a specific product or process[12,13,14].

An important aspect of LCA is that it encompasses an investigation of environmental burden at each life stage of the product as shown in Figure 1. This includes material extraction, processing of raw materials, manufacturing, transportation and distribution, use/re-use/maintenance, recycling and disposal. The engineer has an important role in defining the relative impact of each of these life stages. For example, designers may specify a virgin material be used that consumes tremendous energy in the processing of the ore into raw material, such as aluminum. An alternative approach would be to use recycled aluminum. Engineers could also incorporate more efficient motors into products, reducing their energy consumption during use which in turn reduces the emission of green-house gases at coal and petroleum burning power plants. Finally, engineers can design products to be more easily disassembled so recyclable components are captured before final disposal of the remaining product.

LCA is concerned with identifying the environmental impact at each of these life stages. Full implementation of LCA allows the engineer to make a quantitative comparison of the stages of a product's life, determine where the greatest environmental benefit is to be gained, and ultimately monitor the long-term effect of changes in design and/or manufacturing. For example, in the production of clothing, the energy consumed in manufacturing an article of clothing makes up only 18% of the total energy consumed.[15] The majority of energy consumed during the products life is consumed during cleaning (79.5%) with the remaining energy being consumed in the manufacture of detergent. Furthermore, consumer use accounts for 66% of the solid residues generated during the product's life. From this simple analysis it is clear that the biggest impact is to be made at the consumer use life stage. Approaches that have been taken include developing fibers for clothing that can be cleaned in cooler water, reducing the energy needed to heat water; using fibers that dry faster; designing clothing to require lower concentrations of detergent; and labeling clothing to recommend the use of cold water and line drying. All of these activities involve engineering input and decision making.

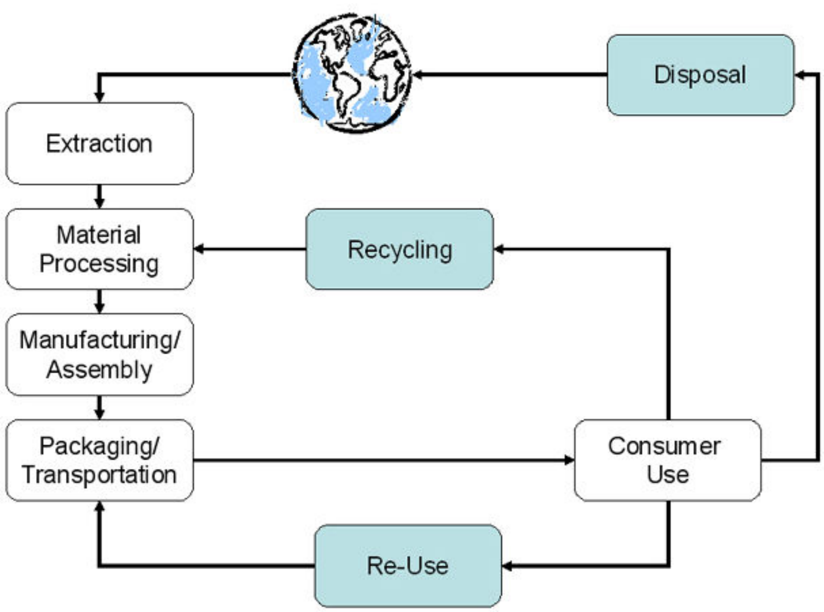

Figure 1: Relevant activities in the life cycle of an engineered product for Life Cycle Analysis

As shown in Figure 2 LCA involves four primary steps: (1) identification of the goal and scope of the project; (2) inventory analysis; (3) impact analysis and (4) improvement analysis. At each step an interpretation of the results can be conducted. During goal and scope definition, the engineer must consider what materials, products and processes are to be considered within the analysis, what the limitations of the study are and how broadly alternatives can be defined. This step in LCA is perhaps the most critical given the open-ended nature of the approach. A comprehensive LCA of even a simple product could involve thousands of man-hours and other financial resources. As a general rule, "the depth of analysis should be related to the degrees of freedom available to make meaningful choices among options and to the importance of environmental issues leading to evaluation."[16]

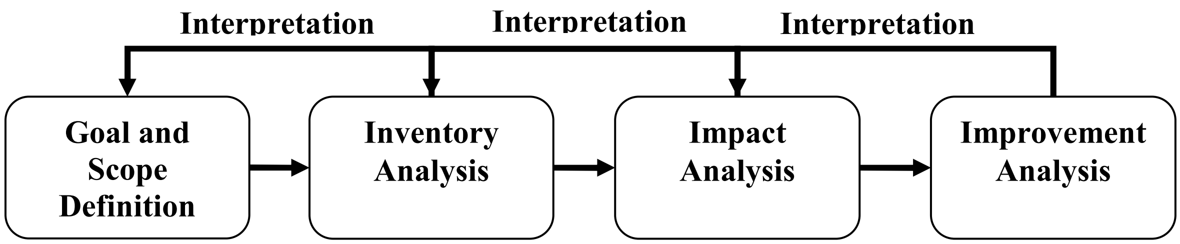

Figure 2: Life Cycle Assessment Framework

The second step in LCA is inventory analysis during which a quantitative measure of the material and energy inputs to the product or process is made. In addition a measure of the product and by-product outputs is measured, as well as environmental releases to the extent possible. Again this is ideally done over the entire life cycle, but practicality often limits it to those aspects of the life cycle over which the engineer or corporation has direct or indirect control. During impact analysis, the outputs of the system at each stage are related to direct impact on the external world. For example, the release of chlorofluorocarbons (CFCs) would be quantified and related to a specific impact on ozone reduction. The trouble with this stage is that data is controversial, incomplete or wholly unavailable. Furthermore, quantifying the release of substances, especially gaseous substances, and relating this to specific environmental impact within a local, rather than global, region can be difficult. Consequently, data for this step is often qualitative in nature.

The final step in the process involves using the findings from the three previous steps to draw conclusions and make recommendations for the environmental improvement of the product or process under consideration. Ideally this information provides direct input for proactive approaches such as design for the environment initiatives. At the very least it could advise decision making in pollution control efforts.

One of the criticisms of the LCA approach is that it consumes enormous resources of time and money to complete in a comprehensive way. A product or manufacturing engineer with other responsibilities will have little time for a comprehensive LCA. Consequently, several alternative approaches have been developed in recent years. These approaches are referred to as streamlined life cycle analysis (SLCA) methods. Given that SLCA methods are more practical, many companies, looking to introduce more sustainable practices, have adapted their own, often proprietary, SLCA tools including Monsanto, Herman-Miller, Dow, Battelle Corporation, Motorola and IBM[16]. Frequently, these tools take the form of matrices with qualitative rankings for material and energy inputs, as well as, environmental impact estimates. Because SLCA methods are cheaper, faster, easier for current employees to use, and usable at the conceptual design stage when quantitative data is not available, SLCAs are seen as a more acceptable option by many engineers and managers. Accordingly, they stand a much better chance of being adopted for a wide range of products and business activities.

Telephone LCA Project

For the past two years, Kettering University has offered a course in Materials and Process Selection (IME-302) taught by the author. The course focuses on team-oriented design projects that emphasize the proper selection of materials and processes for a wide range of products. In addition to customer and economic requirements, the students are encouraged to consider environmental design constraints. LCA is presented as an engineering tool available to assist in this effort. Approximately three hours are spent at the beginning of the term discussing the LCA approach and methodology. Concurrently, students spend four hours during the weekly laboratory period completing a life cycle assessment of a standard office telephone.

The educational objective of the telephone LCA project is to introduce students to the idea of LCA through a hands-on, team-based learning opportunity. The technical objective is to determine the best strategy for reducing the environmental impact of the phone. This may be accomplished by changing the production, materials, design, transportation, or end-of-life stages of the phone's life cycle. A copy of the most recent (at the time of publication) is provided at the end of this paper. The goal and scope of the project are predetermined given the complexity of the problem. In this case, the project is limited to examining only the energy inputs to the system at each life cycle stage. Material inputs are converted to an energy value based on the published energy content of the raw material. The impact of material usage on non-renewable resources is not considered in this analysis. Furthermore, solid, liquid and gaseous residues and their impacts on the environment are ignored. These steps were taken because of a lack of data to complete the analysis and because the complexity of the problem would have quickly overshadowed the educational benefit of introducing students to the technique.

The first step for the students is to complete an inventory analysis of the telephones in question. The class is usually divided into teams of 3-4 students, each of which is provided with a telephone being discarded by the university. Students are provided with tools to dismantle the phones and separate the components by material. Given the large number of components within a phone, the students are provided with assistance in estimating the material of each component. The cumulative mass of each material is then determined using a triple beam balance. Students then determine the energy content of each material. This is accomplished by using the Cambridge Engineering Selector (CES) software, described earlier, to find the production energy of each material within its database. From this information, students can determine the total energy content of the materials included within the telephone, thus completing the inventory analysis for the first stage, materials extraction and processing. Material extraction and processing typically accounts for 30% of the energy consumed in the life cycle of the telephones.

Students are next asked to consider the influence of production. Since we are considering the redesign of an existing product, it is reasonable to assume that the primary production process for making the phones (in this case injection molding of the housing and handset) is fairly well entrenched within the corporation making substantial changes difficult and costly. Students are asked to consider only the scrap rate of the injection molding process used to make the acrylonitrile butadiene styrene (ABS) housing of the phones. Again using CES, students are able to find data on the approximate scrap rate of injection molding processes (10-40% of material consumed) and compute the energy content of the material resulting from scrap. This life stage generally accounts for 3-6% of the telephones' life cycle energy consumption.

To determine the energy consumed during transportation and distribution of the telephones, students use an average distance traveled for a delivery truck (675 miles), the number of phones that can be carried by a truck (1920), the fuel economy of the truck (19 miles/gallon) and the energy content of the fuel (136 MJ/gallon for diesel). Based on this information the students can compute the energy consumed in transporting one telephone to an average distributor. Students usually find that the energy consumed in this stage is small (~1% of total).

During the use phase, telephones consume a small, but important amount of electrical energy. Students are told that the phones they are investigating have an average lifetime of 5 years, and consume approximately 1.5 J/s. This works out to a total energy consumption over the life of the telephone of approximately 237 MJ, which exceeds that of all other life stages by a considerable margin (60 - 70% of total energy consumed).

Finally, students are asked to consider potential end-of-life options for the telephones including disposal, recycling and incineration. During disposal, the energy content of the materials in the telephone is essentially lost resulting in a net change of zero. Energy consumed in transporting the phones to a landfill is ignored. Recycling presents an attractive option given the fact that the energy content of the recycled materials can be regained, resulting in a net reduction of the energy content of a telephone. Data on the recyclable fraction of the materials in the phone is provided in the CES software. Energy consumed during the recycling and reprocessing of the materials is also ignored. Incineration also presents some benefits given that the energy released during incineration can be converted to electrical power or heat for other uses. The energy that can be regained through incineration is based on the calorific values of the materials involved. For this project, the information was obtained from the Manchester Metropolitan University Design for Environment Research Group.[17]

At this point the inventory analysis is complete. Impact analysis is essentially skipped over in this project. In this case, only data regarding the energy consumed in the material extraction, manufacture, use and disposal of telephones is considered. For a complete impact analysis, information regarding the solid, liquid and gaseous outputs would be needed, as well as the impact of the material extraction process. An intermediate step would be to convert the net energy content consumed to an equivalent energy produced at a power plant and use pollution data for a typical power plant. Though this approach would introduce polluting emissions to the problem for the students' benefit, it overly simplifies the problem by ignoring environmental damage introduced by acquiring the materials in the first place and the potentially harmful impact of pollutants produced during manufacturing.

The final step of the project is to complete an improvement analysis. For this the students are provided with a series of questions to consider, each of which deals with a different candidate for reducing environmental impact. These questions include:

- If you were going to consider changing the materials in the telephone's design, which would you consider first? Why? Can you propose an alternative material based on data provided in the CES software? How would this change in material affect the manufacturing of the telephone and the overall environmental impact?
- If you could reduce the amount of any material used in the telephone, which would you choose? Why? What would be the net effect of changing the material mass by 10% for your choice?
- What would be the effect of reducing the ABS injection molding scrap rate by 50% on the energy content of the telephone?
- What would be the effect of using larger trucks to ship the telephones? Assume that these larger trucks have an increased delivery capacity of 2880 telephones per truck, but a fuel economy of only 17 miles/gallon.
- What would be the effect of increasing the service life of the telephone to 10 years through re-use? If you assume that only half the number of phones need to be manufactured each year, how much energy is saved in manufacturing?
- What would be the net effect of reducing the energy consumed by the telephone to 1 J/s?
- Which end-of-life process provides the best option for reducing energy content of the telephones.

The ultimate goal of this exercise is to arrive at a set of recommendations for the telephone manufacturer to follow that will have the greatest effect in reducing the environmental impact of the telephone. In addition, students are asked to consider if any life stages have been ignored during this analysis and whether we have provided a complete picture in our analysis of those life stages that are included. Students must also provide counter-arguments to potential criticisms of their recommendations that stem from economic and/or political considerations.

Student Outcomes

Assessment of student outcomes is based on evaluation of student presentations/reports for the telephone LCA project. Evaluation was conducted by the author and the independent evaluator for the National Science Foundation CCLI project to develop the Material and Process Selection course that includes this project. In addition, student comments were collected via written comments in design journals and through small group discussions facilitated by the Director of the University's Center for Excellence in Teaching and Learning.

Overall, the students do quite well on this project, and in the author's opinion develop a better appreciation for design for the environment and LCA. Depending on the term, students have presented their results in either a written report or an oral presentation. The average grade for these reports over the past two years has been 90.4%, primarily because students do an excellent job of conducting the analysis and organizing their reports/presentations. This is not surprising given that the students in the course are mostly seniors who have considerable practice at these skills. However, the primary weakness in their work seems to be in their ability to synthesize the data they collect and compute during the LCA, generate appropriate conclusions based on this synthesis and arrive at reasonable recommendations.

In terms of the analysis, students do a very good job of identifying consumer use as the most significant source of energy consumption. In addition, a few student teams have generated truly creative recommendations for the manufacturer, particularly design changes that would assist with recycling. For example one team recommended eliminating the use of mechanical fasteners to assist in disassembly for recycling. Another group suggested using fewer materials to make separation during recycling simpler and more efficient.

Students sometimes have difficulty identifying which material to replace in the telephone, basing their decision on the density of the materials (steel becomes an obvious choice), rather than the total energy content of the materials (ABS is now a better choice). They also tend to ignore other factors, most notably the cost of the materials involved. Students have also had some difficulty figuring out how exactly to incorporate scrap energy content into the analysis. Students also struggle in identifying missing life stages and/or inputs to life stages that are included in the analysis. This is not surprising, however, given their limited experience with LCA.

Perhaps the most encouraging outcome is the long-term effect it has on student attitudes. Students in the course are asked to comment on the value of the course in either their design journals or through an end-of-term Small Group Instructional Diagnostic (SGID) conducted by the University's Director of the Center for Excellence in Teaching in Learning. Through these qualitative assessment methods, it is the opinion of the author and the independent evaluator that students have developed an increased awareness of the engineer's role in industrial ecology. Indeed, several students in the course have specifically commented that it has made them more aware of the environmental impacts of their co-op sponsors' industrial activities. Students at Kettering University spend 6 months of each year working in a co-op engineering position in industry.

Suggestions for Improvement

The main improvement that could be made to this project would be the inclusion of an impact analysis stage. The author has chosen not to take this step thus far because of the complexity involved in doing so. An alternative approach would be to investigate and incorporate streamlined life cycle assessment approaches currently in use.

Other specific steps could be taken to broaden the scope of the LCA. This might include considering the effect of resource depletion and the production of pollution during the extraction of the materials included in the telephone. Including additional aspects of the production stage such as supplier processing, part delivery, storage and final assembly could make further improvements. The energy consumed and the pollution created from these activities could be incorporated.

It might also be wise to consider incorporating a measure of the pollution generated by power production. This could be an important environmental impact given that consumer use is the primary source of energy consumption during the life cycle of a telephone. Another consideration would be to include the energy consumed in the recycling stage and the pollution produced through incineration and land filling. As a general rule, the data included in the LCA can always be made more accurate.

The telephone represents a fairly complex system with literally hundreds of components. It may be worthwhile to investigate alternative systems for analysis, particularly those that include fewer materials, manufacturing processes and assembly steps. For this project the telephones are being disposed of, eliminating the need to purchase a product that will be completely and irreversibly disassembled. The author is presently considering approaching local industries to act as sponsors of the project by providing products for analysis.

Finally, the author has come to the realization that it is important to emphasize the synthesis of data and consideration of alternative inputs to the analysis such as cost, corporate inertia, etc. Students often ignore these important variables, focusing instead on the information provided within the project description. One approach that might increase student awareness of these issues is to use an SLCA tool developed by an actual company. Often these tools require designers to consider these non-technical issues.

Conclusions

Overall, the project has been a definite success within the context of the Materials and Process Selection course. Though it requires considerable use of class time to complete the project (typically 4 hours), the opportunity to work in a team setting on an open-ended project motivates the students to learn in more depth than they would from a lecture. Perhaps the most important outcome has been an improved appreciation of the role of the engineer in preserving our environment.

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References

1 *Environmental Management and ISO 14000: Manual 10*, International Organization for Standardization, Geneva, Switzerland: ISO, 2001.
2 Lawrence, P.R., "Design for the Environment (DFE) Process and Training at Ford Motor Company," 1998 Total Life Cycle Conference Proceedings, Warrendale, PA: Society for Automotive Engineers, n. 982204, pp.307-311, 1998.
3 Berkhout, F., "Life Cycle Assessment and Innovation in the Automotive Industry," 1998 Total Life Cycle Conference Proceedings, Warrendale, PA: Society for Automotive Engineers, n. 982178, pp.127-137, 1998.
4 Schoech, H., Florin, H., Kreissig, J., and Eyerer, P., "LCA Based Design for Environment in the Automotive Industry," *Proceedings of the 2000 Total Life Cycle Conference*, P-353, Warrendale, PA: Society for Automotive Engineers, n.2000-01-1517, pp.379-383, 2000.

5 Sullivan, J.L., Williams, R.L., Yester, S., Cobas-Flores, E., Chubbs, S.T., Hentges, S.G., Pomper, S.D., "Life Cycle Inventory of a Generic US Family Sedan: Overview of Results of USCAR AMP Project," 1998 Total Life Cycle Conference Proceedings, Warrendale, PA: Society for Automotive Engineers, n. 982160, pp.1-14, 1998.
6 Lave, L., MacLean, H., Lankey, R., Joshi, S., McMichael, F., Horvath, A., and Hendrickson, C., "Life Cycle Inventories of Conventional and Alternative Automobile Fuel/Propulsion Systems: Summary and Conclusions," *Proceedings of the 2000 Total Life Cycle Conference*, P-353, Warrendale, PA: Society for Automotive Engineers, n.2000-01-1504, pp.283-291, 2000.
7 Thiel, C. and Jenssen, G.B., "Comparative Life Cycle Assessment of Aluminum and Steel Bumper Carriers," *Proceedings of the 2000 Total Life Cycle Conference*, P-353, Warrendale, PA: Society for Automotive Engineers, n.2000-01-1495, pp.225-231, 2000.
8 Gibson, T.L., "Life Cycle Assessment of Advanced Materials for Automotive Applications," *Proceedings of the 2000 Total Life Cycle Conference*, P-353, Warrendale, PA: Society for Automotive Engineers, n.2000-01-1486, pp.161-171, 2000.
9 "Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles," *Official Journal of the European Communities*, pp. L 269/34 - 42, 2000.
10 Kirkpatrick, N., Dowdell, D. and Glazebrook, B., "A Life Cycle Assessment of the Implications of Implementing the Proposed End of Life Vehicles Directive in the United Kingdom," *Proceedings of the 2000 Total Life Cycle Conference*, P-353, Warrendale, PA: Society for Automotive Engineers, n.2000-01-1468, pp.35-41, 2000.
11 Cambridge Engineering Selector, Granta Design Ltd., www.grantadesign.com
12 Stephens, R.D., Williams, R.L., Keoleian, G.A., Spatari, S., and Beal, R., "Comparative Life Cycle Assessment of Plastic and Steel Vehicle Fuel Tanks," 1998 Total Life Cycle Conference Proceedings, Warrendale, PA: Society for Automotive Engineers, n. 982224, pp.483-496, 1998.
13 Binder, M., Kaniut, C., Cetiner, H., Schröter, H., Schmitt, K., "Life Cycle Assessment of a Truck Component - Air Deflection System," 1998 Total Life Cycle Conference Proceedings, Warrendale, PA: Society for Automotive Engineers, n. 982173, pp.97-100, 1998.
14 Coulson, G. and Stobart, R., "Life-cycle Analysis and the Fuel Cell Car," *Proceedings of the 2000 Total Life Cycle Conference*, P-353, Warrendale, PA: Society for Automotive Engineers, n.2000-01-1485, pp.157-160, 2000.
15 Graedel, T.E. and Allenby, B.R., *Design for Environment*, New Jersey: Prentice Hall, 1998.
16 Graedel, T.E., *Streamlined Life-Cycle Assessment*, New Jersey: Prentice Hall, 1998.
17 Young, J.M., "Life Cycle Energy Modelling of a Telephone", *DFE Report 22*, Manchester Metropolitan University Design for Environment Research Group, DDR/TR22, http://sun1.mpce.stu.mmu.ac.uk/pages/projects/dfe/pubs/dfe22/report22.htm, April 1995.

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