LIFE CYCLE ANALYSIS

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Summary

Environmental impact assessment is a major issue that faces every nation today. However, consistently and objectively measuring the environmental impact is difficult. During the past two decades, a process called life cycle assessment was developed that tried to make consistent and objective environmental assessments. The Society of Environmental Toxicology and Chemistry has now broadened the concept to not only include the inventory, as previously considered in life cycle analysis, but also the environmental impact and improvement phases. The Society of Environmental Toxicology and Chemistry defines life cycle assessment as "an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements."

Life cycle assessment has received both positive and negative feedback on its utility as a process to evaluate environmental impact. This paper provides a brief history and overview of life cycle assessment, illustrating how it has been used and misused, listing its benefits and limitations, and outlining its possible applications to the Wood Preservation industry. Life cycle assessment provides an opportunity to quantify some environmental impacts of various wood preservation techniques and treatments; however, the process must be appropriately applied to gain the full benefit.

1. Introduction

Public concern about the environmental consequences of producing and using various materials and products is increasing. The concerns range from the effects on old-growth forests and tropical forests to issues of air and water quality and landfill disposal sites. Governments are increasingly asked to incorporate these concerns into policy decisions, and corporations are increasingly held accountable. Consumers are aware that consumption of manufactured products have an effect on resources and the environments. These effects occur at every stage in a product's life cycle—from the extraction of the raw materials from the ground, through the processing, manufacturing, transportation phases, and ending with use and disposal or recycling. The effects can either be direct, such as air emissions produced from automobile usage, or indirect, such as the pollution and impact on waterways from the production of electricity used in the manufacturing process. One popular methodology in use today is life cycle assessment (LCA) that quantifies these direct and indirect effects of products and processes.

2. Historical Overview

The first life cycle analysis was conducted in 1969 on beverage containers (Hunt et al., 1992). The major objective of the analysis was to determine which type of container had the least effect on natural resources and the environment. The result was an accounting of the energy and materials flow without determining the environmental impact. Figure 1 illustrates the general energy and materials balance diagram for "cradle-to-grave" analysis of a product and its distribution system.

The oil shortages of the early 1970s refocused the discipline on developing an inventory of the energy supply and demand for both fossil and renewable alternative fuels. Interest in the methodology waned after the energy crisis, but was rekindled in the 1980s when governments faced mountains of trash accumulating in their cities and countrysides. With landfill space at a premium and questions about the health effect and cost of alternative disposal methods, reducing waste at the source became a paramount issue.

Corporations were held accountable by consumers who wanted "greener" products. Companies found themselves scrambling to prove to the public that their products were greener than their competitors,. Some of these companies, through industry trade associations, conducted LCA studies and advertised the results as a "mine is better than yours" statement. In the past several years, comparisons have been made on products such as high-density polyethylene milk jugs and paperboard cartons, recycled polyethylene bags and Kraft paper grocery bags, coffee cans and vacuum-packed wrappings with paper and plastic linings, and disposable versus cloth diapers. However, these LCA inventory studies did not delve into the impact or degree of environmental consequences.

Many initial studies did not apply similar methodologies, so efforts began to standardize the process. Although many groups have tried to bring consistency to the procedures, the most notable is the Society of Environmental Toxicology and Chemistry (SETAC) who issued a report on technical guidelines for appropriate use of LCA. One major finding of the SETAC was that complete LCAs should be composed of three separate but interrelated components:

- Life-Cycle Inventory: Process for quantifying the energy, water, and natural resources used to extract, produce, and distribute the product and the resulting air emissions, effluents, and solid waste.

- Life-Cycle Impact Analysis: Process to assess the ecological and human health effects of the environmental loadings identified in inventory.
- Life-Cycle Improvement Analysis: Process to reduce the environmental burden associated with energy and raw materials use and environmental releases throughout a product's entire life cycle (Fava et al., 1991).

The three-tiered approach of SETAC goes beyond the traditional focus of the inventory stage that is prevalent in most LCA studies. However, determining the environmental impacts is proving to be a difficult task and most LCAs still only involve the inventory aspects. Both the American Society of Testing and Materials and the International Standards Organization have activities underway to address consistent methods and procedures and to quantify environmental impacts. One of the best and most recent sources of the specific details of an LCA is by Vigon et al. (1994), who outlines the guidelines and principles for the LCA. However, there is still debate within the LCA practitioner community whether a scientific basis exists for applying impact assessment techniques to LCA quantitative inventory data.

3. Wood and Paper Product Assessment

Research by the Western Wood Products Association (1993) indicates that customers of wood products ask questions regarding the impact of wood use on the environment. Such concern has been highlighted by the increased use of LCA by competitive materials. In response, the wood products sector has responded with its data effort to examine the unique characteristics of the wood products industry. The first limited life cycle inventory was conducted by the National Research Council, Committee on Renewable Resources for Industrial Manufacturing (CORRIM) (National Research Council, National Academy of Sciences, 1976). The CORRIM report compared the energy requirements for wood and possible substitute materials. The CORRIM developed methods of systems analysis that would permit assessing the amount of energy required to produce different building construction materials. The CORRIM reported that, in the 1970s, it took nine times more energy to produce a steel stud than a wood stud, three times more energy for a concrete block wall than a wood stud wall, and 21 times more energy for a 102-mm concrete slab floor than a raised wood floor.

Peter Koch (1992) reported that with the expected decline in timber harvests in the Pacific Northwest and substitution with nonrenewable materials, consumption of fossil fuel would increase 2.7 x 10^6 m^3 annually, and about 6.8 x 10^9 kg of carbon dioxide would be added to the atmosphere for each billion board feet of annual harvest reduction. Many authors have cited statistics that examine the amount of energy and carbon dioxide emitted into the atmosphere to manufacture wood construction materials and compared them with substitute materials. They highlight data that indicate wood uses less energy in its manufacturing process with lower emissions than does steel or concrete (Honey and Buchanan, 1992, Arima 1991, 1992).

However, most previous studies were not a full-blown LCA and primarily compared inventory data for the manufacturing process. For wood products, a full LCA inventory would consist of all phases from the timber harvesting, debarking, through manufacturing and processing, use, and final disposal or recycling. Lubert et al. (1991) illustrate the following flow diagrams for the phases between harvesting and chipping (Figure 2) to final pulp production (Figure 3). The most significant aspect of this flow diagram is the complexity of the details and intensive data demand to construct the energy and material balances around each phase. In addition, this represents only the production process up to the pulping stage, and a full LCA inventory would involve many more processes for a paper product.

Richter and Sell (1992) and Richter (1993) conducted a comprehensive LCA from extraction to disposal or recycling of wood as a raw material and construction component. Using the LCA methodology, Richter and Sell collected data for energy use and air emissions for the production of softwood lumber, glued-laminated timber, particleboard, and fiberboard. The LCA was regional in scope, using logging and transportation costs from Switzerland. The two major end-uses examined were four types of wall construction using timber, plastered brick (two designs), and brick with exterior insulation. The timber frame and brick with exterior insulation had similar energy use and emission levels (Table 1).

In Richter and Sell's LCA of window-frames, the environmental impacts differed depending on the level of recycling assumptions used in the analysis. The stepwise procedure rated the windows (1) after completion in the plant, (2) after being used under two service-life periods and exposure conditions, and (3) with the assumption of different recycling and waste-disposal scenarios. The final disposal options significantly altered the results. Wood-based frames exhibited lower energy use and emission levels until recycling options for the aluminum, steel, and polyvinyl chloride windows were considered. With high-level recycling rates, the environmental effects of wood are equivalent to the other materials.

A current study by Forintek Canada Corp., is developing a systems model to assess the environmental consequences of using alternative materials for specific building designs. Their initial research is on vertical and horizontal structural assemblies using wood, steel, and concrete products in industrial and commercial buildings. This study focuses on comparing building assembly designs, rather than on comparing materials directly. Preliminary results compare a typical exterior infill wall assembly constructed using steel as the post and beam supporting structure. The exterior opening is then compared using the infill material of either 20-gage nonstructural steel studs or 2- by 4- wood studs. The steel wall is three times more energy intensive, has three times higher carbon dioxide emissions, and significantly more water demand. However, the solid waste generated during manufacturing and construction was greater for the wood wall assembly (Meil, 1993).

In the area of preservative-treated wood, two case studies were reported at the International Research Group of Wood Preservation. Smith et al. (1993) reported on an LCA of preservative-treated wood that was underway. The analysis was still in progress at the time of publication. Erlandsson et al. (1992) reported on an LCA conducted on utility poles. These authors concluded that poles made of concrete, steel, and aluminum lead mainly to emissions in the air, and treated wood poles lead mainly to leaching of preservatives. A comparison of the environmental burdens between these materials is extremely difficult.

In the wood and paper products sector, most LCAs have been on paper products. The number of analyses is too numerous to consider indepth. However, one of the most complete analysis to date compared the environmental burdens of disposal with cloth diapers. The results from this LCA will be discussed indepth to highlight some advantages and disadvantages of the LCA methodology.

4. Disposable Versus Cloth Diapers

The work was conducted for the American Paper Institute, Diaper Manufacturers Group, by Franklin Associates Ltd. (1992), a leading authority on life cycle inventory procedures. The purpose of the study was to determine the comparative energy consumption, water requirements, and environmental emissions associated with the three predominant types of children's' diaper systems: single-use diapers containing absorbent gels, commercial-laundered cloth diapers, and home-laundered cloth diapers. The basis of comparison was daily usage of each system with 9.7 cloth diapers/day and 5.4 single-use diapers/day. Total energy consumption, water requirements, and environmental emissions, including atmospheric, wastewater particulates, and solid waste, were determined. Figures 4 through 8 show the net energy requirements, water volume requirements, solid-waste burden, atmospheric emissions, and wastewater particulates, respectively. The results indicate that home laundering consumes the greatest amount of energy, with commercial laundering only slightly more than the single-use system. Commercial laundering consumes the largest volume of water, followed by home laundering. With respect to the environmental waste burden, single-use systems were the largest solid-waste burden; home laundering produced the most atmospheric emissions as a result of energy consumption in the home dryer; the wastewater particulates were about equal for both cloth systems and exceeded the single-use system by five times.

If the energy requirements are calculated using a closed thermodynamic energy balance, which includes internal or embodied energy, the energy results are altered slightly. In the current procedures, the internal energy content of the fossil fuels is already included; however, a closed thermodynamic balance then requires assigning an energy value to raw cotton and trees and including these in total energy requirements. The energy requirements using the thermodynamic energy balance is given in Figure 9, indicating no significant difference in the energy requirements between the three diapering systems.

Thus, the primary difference between the three comparative diapering systems is the environmental waste burden. Again, the question is, How do you compare one type of environmental burden with another type of environmental burden?

5. Problems and Limitations

Data

From the previous examples, it is apparent that LCA is a data-intensive methodology. In many cases, two similar analysis will not arrive at the same level of environmental burdens. In many reports, limitations were described, such as out-of-date information, omissions of certain phases, omission of packaging forming, and filling and transportation stages. All such limitations do not inspire confidence in the robustness of the data. In addition, the SETAC guidelines stress reliance on primary data, which are obtained directly from the plant operator. However, most LCA studies require a large range of material products. It is impossible to collect primary data for every single input, otherwise the time needed to produce a report would be excessive. Most LCA studies conducted by experts in the field rely on accumulated data analyses that are not published and therefore not available for peer review. This presents major problems in credibility and reliability of the information. In addition, because LCA represents a static analysis, databases must be updated routinely to reflect current advances in manufacturing and processing technologies. Given the complexity of some analysis, data management is an enormous task and needs to be unified and systematically assembled. All interested users should be able to access these databases.

Boundary Conditions

Setting boundary conditions in an LCA is problematic at best. Because the primary difference between ordinary analysis and LCA is defining indirect impacts on the environment, the critical issue in setting boundary conditions has to do with the information a researcher can use to establish rational expectations regarding the potential influence on the results of adding details and expanding the scope. The SETAC guidelines of excluding components comprising less than 5% of the inputs assumes that the components excluded do not have an associated significant environmental burden. For example, the amount of electricity used in a particular activity might be a small input. However, if the electricity is produced from a high sulfur coal plant, it is entirely possible that the environmental burden might far outweigh the proportion of that activity's contribution to the product. Thus, the assumption that environmental burdens do not occur outside the boundary condition can be a major source of concern. Such an assumption routinely leads an opposing material or product representative to widen the boundary conditions and add details.

> "Several recent reports assessing the relative life cycle environmental impacts of cloth and disposable diapers devote considerable effort to tracing the indirect impacts of each alternative in greater depth than previous studies, although they arrive at mixed and different conclusions. Moreover, the study prepared for the National Association of Diapers Services, which concludes that the overall environmental impact of cloth diapers is less than disposables, devotes nearly six pages (out of a total of 40 pages in the summary report) to describing why its results are superior to previous—because its boundaries are more expansive than earlier assessments." (Arnold, 1993)

Environmental Burdens/Impact Analysis

Most LCAs target consumer and producer decisions that are connected to a wide variety of activities that potentially cause environmental burdens. The public is generally paying the costs of these environmental burdens because the true economic cost cannot be determined. These environmental burdens include use of energy, emissions to air and water, use of natural resources, and production of wastes. The measure of environmental burden is not direct and needs to take into consideration geographical and local sensibilities. For example, with the single-use and cloth diaper study using the closed thermodynamic energy balance, the environmental burden involved use of water or generation of solid waste. For consumers to choose between these two environmental burdens, they must choose one of the two "evils" and trade off environmental burdens. The use of single-use disposable diaper systems rather than commercial or home laundering in the Southwest during times of drought would probably be the preferable choice to a consumer, while in New Jersey, plagued with landfill problems, the cloth diaper system would likely be the most preferable. The relevant question is not, Which diapering choice is better for the nation? but, Which diapering choice is environmentally better for a particular set of circumstances? Thus, making policy decisions solely on the basis of a particular LCA study is not advised.

6. Advantages and Applications

Despite difficulties in dealing with certain aspects of the LCA procedures, this does not imply that LCA is not a valuable tool. There is a need to establish comprehensive baselines of information on a system's overall resource requirements, energy requirements, energy consumption, and emission loadings and to identify points within a single product's life cycle where the greatest reduction in environmental burdens can be achieved. There is a critical need to study product manufacturing processes and identify and minimize direct pollution and other environmental harms. The LCA inventory procedure is the best method to examine a particular process or activity. Seeking to minimize direct environmental consequences is socially beneficial, analytically coherent, and reasonable in practice. Thus, LCA is a valuable engineering tool in studying the direct pollution caused by economic activities. However, current attempts to use LCAs as the sole means of evaluating environmental impact is currently unproductive. In the United States, conflicting claims of "more environmentally friendly" by competing products is leading to a lack of confidence in LCA studies, primarily because of the lack of robustness. In this situation, the misuse of LCA methodology has become primarily a tool of marketing executives and just another marketing ploy.

The major problem is translating the quantitative measures into sometimes subjective measures of environmental burden. Life cycle assessment is still an unproven concept and is not a household term, and the ordinary consumer may not fully understand the difference between carbon dioxide and chlorofluoro carbon emissions. However, the consumer does understand Green labeling or ecolabeling.

7. Future Direction

Ecolabeling

Ecolabeling is a designation awarded to products that are judged to be environmentally preferred compared with alternative products. Germany, Canada, Japan, Nordic countries, and the European Community either have government-funded ecolabeling programs or will have them in the near future. The United States has no National program, although two private efforts are underway. A concern of private efforts is that ecolabels may be based on different appraisal methods that could lead to confusion about which products are actually better for the environment. Of the two private efforts in the United States, both claim to use LCA procedures to provide decision information but primarily rely on public involvement to set environmental impact criteria specific to a product. A National designate ". . . to develop standards for the certification of private ecolabeling in the United States might increase the consumer confidence that products that are carrying certified ecolabels are in fact better for the environment." (Congress of the U.S., Office of Technology Assessment, 1993). The use of ecolabeling schemes, with LCA of products at the heart, appears to be the most logical approach to encourage consumer confidence and activity in selecting products with the minimum environmental impact. At the global level, the International Standards Organization (ISO) Technical Committee 207 on Environmental Management has a subcommittee (SC3) on Green labeling.

Environmental Technology Assessment

The process of examining utility and application of LCA has lead the USDA Forest Service, Forest Products Laboratory (FPL), to initiate a line of research that will incorporate economic modeling and technology forecasting along with fundamental principles of LCA. At FPL, we conduct research that provides assessment of new technologies, aimed at improving the use of wood or wood fiber. Until recently, FPL research has focused mainly on physical performance of wood and paper products (e.g., strength or durability of wood products or strength, brightness, and recyclability of paper products). We have occasionally assessed the economic performance and potential of new technologies and production processes (e.g., comparative costs, profitability, and likely rates of commercial adoption). We have generally recognized that some new technologies offer both environmental and economic advantages, in comparison with conventional technologies. However, we have lacked a comprehensive methodology to analyze and account for the environmental benefits or burdens of new technologies. Therefore, we have initiated research that will extend our existing economic modeling methodology to encompass forecasting of environmental burdens of new technology, as well as providing economic and technology forecasting. We have termed this approach environmental technology assessment.

The FPL developed a North American pulp and paper sector model (NAPAP Model), which projects future technological changes, regional production and capacity change by process and product grade, product demand, imports, exports, and related market equilibria for the United States and Canada. The model combines regional information on supply and demand, transportation costs, and manufacturing costs to compute future market equilibria and production trends year to year. The model determines annual changes in production capacity among different competing production processes and regions as a function of relative profitability and market conditions. It projects evolution of manufacturing processes based on economic optimization procedures and provides fairly accurate simulations of the evolution of production and markets, based on a comparison of historical trends.

Because the NAPAP Model incorporates all the principal manufacturing processes and product grades of the pulp and paper sector, it provides the framework for a comprehensive economic assessment of technology throughout the entire pulp and paper sector. In addition, the model is designed so that new production processes can be incorporated into the model to project relative impacts and rates of commercial adoption, vis a vis the conventional technology and trends of the entire industry. Thus, the model provides a framework in which the industry-wide environmental impacts of new technology can be assessed, along with economic benefits and costs.

For example, in the manufacture of paper products, a conventional chemical pulping technology known as sulphate or kraft pulping is the predominant pulping technology used in the United States today. However, it is projected that recycling technology and mechanical pulping technology will eventually assume a larger share of total production as a result of economic advantages. Kraft pulping has substantially higher capital investment requirements than mechanical pulping or processes based on recycled fiber. The processes also have substantially different environmental impacts. Kraft pulping has higher emissions of sulfur dioxide, but mechanical pulping and recycling in some cases can require higher electrical energy inputs (as purchased electricity generated in coal or nuclear power plants). Although the NAPAP Model currently projects the trends in production for all primary manufacturing processes among all primary product grades produced by the U.S. pulp and paper industry (including processes-based kraft pulping, mechanical pulping, and recycling), the NAPAP Model does not yet incorporate data on the environmental impacts or provide an LCA inventory of such impacts for the various processes. However, such data can be readily programmed into the model, providing a capability to assess both the economic and environmental impacts of evolution in production technology.

The FPL has initiated research on improving the NAPAP Model along the lines I have just outlined, and the work will take a couple of years before FPL can demonstrate the comprehensive methodology. However, FPL anticipates that the methods will be useful to comprehensively define the benefits and costs of technology development, including both commercial and environmental benefits and costs. It is also anticipated that FPL will apply the same general methodology to assessment of technology in the solid-wood sector (lumber, plywood, particleboard, housing), including chemical treatments.

8. Concluding Remarks

Life cycle assessment procedures alone are not leading consumers to make environmental choices between similar products. In fact, the proliferation of conflicting LCA on the same products are causing consumer confusion and a lack of confidence in the LCA methodology. The problem is with the complexities in using LCA, the data intensity of the method, and the level of detail chosen in selecting the appropriate boundary conditions. There are still questions on whether LCA as part of a national ecolabeling scheme can alleviate some confusion and concern regarding the proliferation of this tool as a marketing strategy. The most appropriate use of LCA is to evaluate direct environmental burdens for particular processes, identify areas of improvement, and implement these changes to reduce energy, resource, consumption, and environmental emissions from "cradle-to-grave."

9. Literature

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Table 1—Values for exterior wall type (Richter and Sell, 1993)

Wall type	Width (m)	Mass (kg/m^3)	U-value (W/m^{2}K)	Energy (MJ/m^2)	Critical air volume (×10^{3}m^3/m^2)	Disposal
Timber frame	0.23	79	0.32	840	1,333	Recyclable
Brick, plastered	0.51	609	0.39	1,675	2,473	Road construction
Isomodul, plastered	0.39	407	0.40	1,430	2,770	Road construction
Brick, with exterior insulation	0.31	264	0.39	806	1,027	Road construction

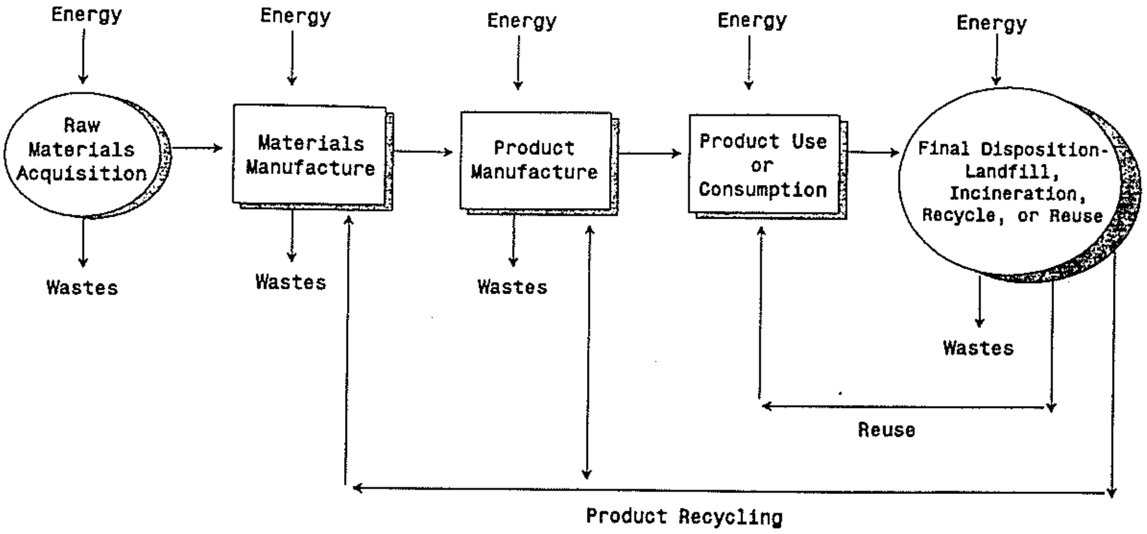

Figure 1—General materials flow for "cradle-tograve" analysis of a product distribution system (Hunt et al., 1992).

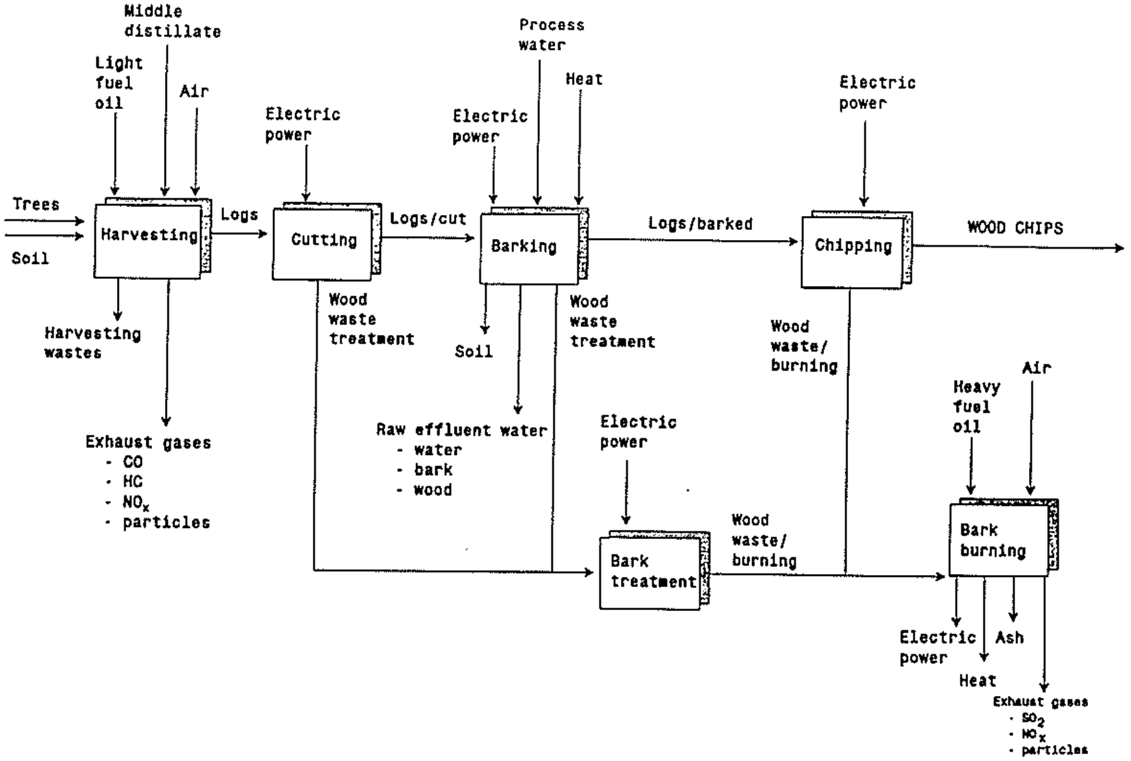

Figure 2—Wood harvesting process flow (Lubbert et al., 1991).

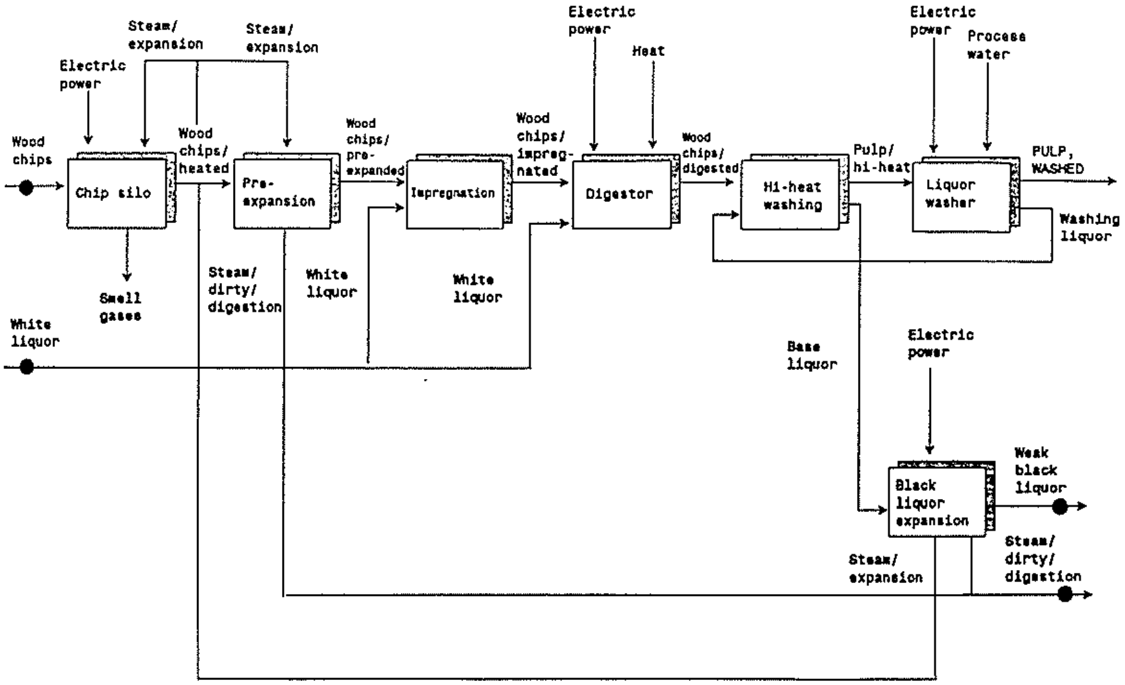

Figure 3—Pulp reduction process flow diagram (Lubbert et al., 1991).

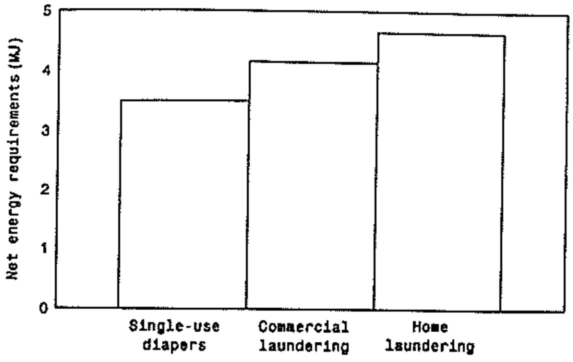

Figure 4—Net energy requirements of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

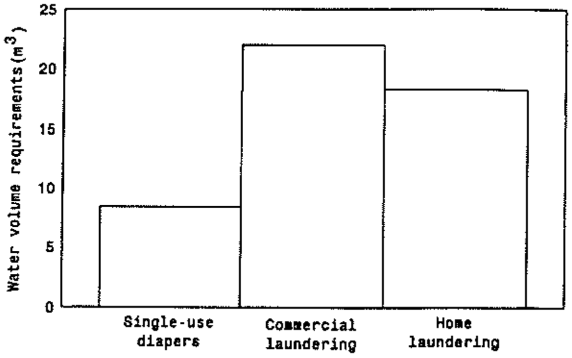

Figure 5—Cumulative water requirements of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

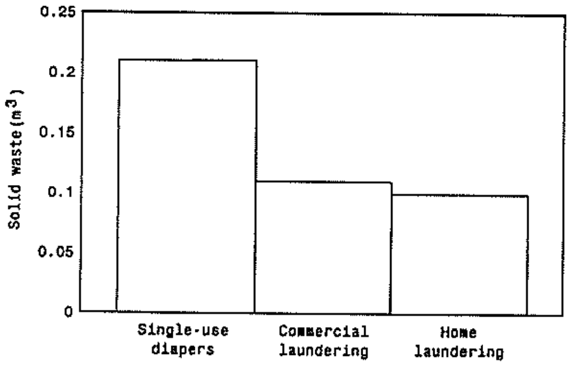

Figure 6—Cumulative solid-waste volume of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

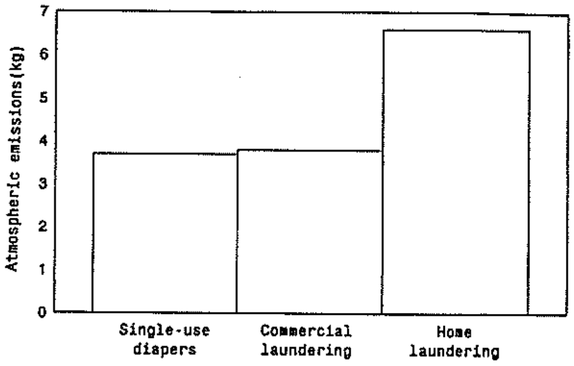

Figure 7—Cumulative atmospheric emissions of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

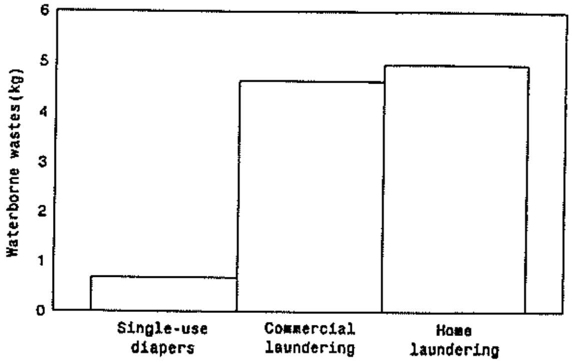

Figure 8—Cumulative wastewater particulates of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

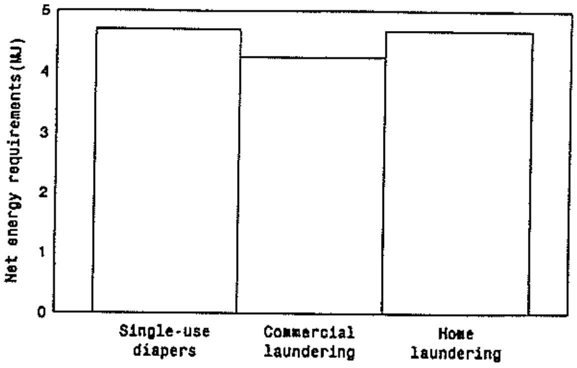

Figure 9—Net energy requirement using a closed thermodynamic balance of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

Figure Captions

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Figure 6—Cumulative solid-waste volume of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

Figure 7—Cumulative atmospheric emissions of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

Figure 8—Cumulative wastewater particulates of three diapering systems using life cycle assessment methodology (Franklin Associates, Ltd., 1992).

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