LIFE CYCLE ASSESSMENT CASE STUDY OF NORTH AMERICAN RESIDENTIAL WINDOWS

by

JAMES SALAZAR

B.Sc., The Georgia Institute of Technology, 2003

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA

December 2007

ABSTRACT

This thesis is a life cycle assessment (LCA) on three window types commonly available to the North American residential consumer: PVC, fiberglass, and wood covered with an aluminum cladding. The LCA was a case study based on the production of the three windows by a single representative manufacturer of each type. Average transportation distances, commodity systems, maintenance, and service life estimations were used to complete the life cycle inventory model. These inventories were grouped into impact categories and scaled based on IMPACT 2002+ v2.1 characterization and damage factors.

The damage modeling results indicated that the life cycle impacts are dominated by the combustion of nonrenewable energy resources. Burning fuels cause increased emissions of respiratory inorganics, terrestrial acidification/nutrification impacts, and global warming. The PVC window's life cycle used the most nonrenewable energy and caused the most damage due to that window's shorter service life, 18 years vs. 25 years for fiberglass and aluminum clad wood. This is despite the fact that PVC requires less energy to produce than the fiberglass. The impacts of the steel reinforcement required to strengthen the PVC window outweigh the benefits of the PVC over the fiberglass. The wood window was negatively affected by the addition of aluminum cladding, which required greater energy to manufacture than the wood component. The sensitivity analysis revealed that replacing the virgin material in aluminum cladding with recycled content improved the life cycle impacts of the wooden window. Using fiberglass or PVC to clad the wood window also improved the environmental performance by reducing

energy consumption. The use of cladding materials other than aluminum also prevented the disposal of aluminum into municipal landfills which reduced the aquatic ecotoxicity of the wood window's life cycle. Other potential improvements to the impacts of the three windows' life cycles include improving energy efficiency, particularly during secondary manufacturing.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

Allocation: The assignment of input or output flows of a process with multiple coproducts to the functional unit of interest.

ATHENA SMI: The ATHENA Sustainable Materials Institute is a North American nonprofit organization that conducts and directs LCA research of building materials.

Caulking: Elastic sealant applied to joints in the building envelope.

Characterization: The second step of life cycle impact assessment, characterizes the magnitude of the potential impacts of each inventory flow to its corresponding environmental impact.

Characterization Factor: Factor derived from a characterization model that is applied to convert the assigned LCI results to the common unit of the category indicator.

Classification: The first step of a life cycle impact assessment, the process of assigning inventory outputs into specific environmental impact categories.

Commodity: Product that serves as an input to secondary manufacturing processes.

Cradle to Gate: Processes that include resource extraction, primary and secondary manufacturing.

Cradle to Grave: All processes in the life cycle of a product, includes resource extraction, manufacturing, use, maintenance, replacement, and disposal.

Composite Data: Data from multiple facilities performing the same operation that have been combined or averaged in some manner.

Co-Product: A product produced together with another product.

ecoinvent: A European database of process inventories for common materials, processes, waste disposal, and recycling practices.

End of Life: Point in the life cycle in which materials have no further utility to the user and are either disposed of or recycled.

Franklin 98: A North American database of process inventories for common materials, processes.

Functional Unit: The unit of comparison that assures that the products being compared provide an equivalent level of function or service.

Heating Degree Day: Unit of common climate indicator that is based on the intensity and duration of temperature differential between outdoor and indoor air.

Impact Categories: Classifications of human health and environmental effects caused by a product throughout its life cycle.

Interpretation: The evaluation of the results of the inventory analysis and impact assessment to reduce environmental releases and resource use with a clear understanding of the uncertainty and the assumptions used to generate the results.

Life Cycle Assessment / Life Cycle Analysis: A cradle-to-grave approach for assessing industrial systems that evaluates all stages of a product's life, provides a comprehensive view of the environmental aspects of the product or process.

Life Cycle Impact Assessment: The assessment of the environmental consequences of energy and natural resource consumption and waste releases associated with an actual or proposed action.

Life Cycle Inventory Analysis: The identification and quantification of energy, resource usage, and environmental emissions for a particular product, process, or activity.

Municipal Solid Waste: End of life process in which used materials are either burned or landfilled.

Normalization: A technique for changing impact indicator values with differing units into a common, unitless format by dividing the value(s) by a selected reference quantity. Normalization increases the comparability of data among various impact categories.

Process Flow Diagram: A depiction of the inputs and outputs of a system and how they are connected.

Product Life Cycle: The life cycle of a product system begins with the acquisition of raw materials and includes bulk material processing, engineered materials production, manufacture and assembly, use, retirement, and disposal of residuals produced in each stage.

Product System: Representation of the processes considered within the LCA boundary.

Sash: Frame component used in the movable panel of an operable window.

Sealed Unit: Window subassembly that contains two or more glass panes that are separated by a spacer bar, sealed, and filled with argon gas.

Secondary Manufacturing: Processes that commodity materials undergo to achieve the utility defined in the functional unit definition.

Sensitivity Analysis: A systematic evaluation process to assess the effect of variations of inputs on the outputs of a system.

Spacer Bar: Bar used to separate glass panes in double and triple glazed sealed units.

Specific Data: Data that are characteristic of a particular subsystem, or process.

System Process: Process representation that aggregates the inputs and outputs of multiple processes to report values as cumulative to the system represented.

Transportation Load: Unit of measuring material transport, a product of distance and weight.

Unit Process: Process representation that defines a particular process by the inputs and outputs required to produce one functional unit.

Weatherstripping: Rubber gaskets applied to the sash and frame that mate to create a weatherproof seal.

Weighting: The act of assigning subjective, value-based weighting factors to the different impact categories based on their perceived importance or relevance.

ACKNOWLEDGEMENTS

I would like to thank Natural Resources Canada for funding this research. I would also like to thank Ian Smallwood at Loewen, Albert Goertzen at Euroline, George Casselman at Inline, Wayne Trusty and Jamie Meil at ATHENA, Jennifer O'Connor at Forintek, as well as Phil Evans and Paul McFarlane at UBC for their access and guidance. Finally I would like to thank my advisor, Taraneh Sowlati, for her support, patience, and expertise, without which this research would have been impossible.

DEDICATION

I would like to dedicate this thesis to my father, Mike Salazar. His healthy skepticism and unceasing encouragement temper me.

CHAPTER 1: INTRODUCTION

1.1 Background

The modern environmental movement has grown in participation and influence in the last half century. While the breadth and depth of anthropogenic effects on the biosphere have risen in the public consciousness, numerous organizations have emerged as avenues for protection of environmental values. Legislatures have established protection policies; NGO's have lobbied and raised awareness; businesses have adopted certification schemes and eco-labels; researchers have characterized and quantified socio-ecological relationships; and consumers have performed both rationally and irrationally in economies of varying information and fairness.

Advocates of sustainable development have focused on the building sector due to the recognition that building construction, use, and demolition contribute significantly to the resource use and waste caused in North America. Annually, building operations in the United States consume 39% of all primary energy (USDOE 2006), and 71% of electricity (USDOE 2006). Construction and demolition uses 40% of all raw materials globally (Lenssen and Roodman 1995) while causing 65% of American municipal waste (USEPA 1997).

The concept of green building has emerged as a synthesis of efforts to improve the environmental performance in all aspects of buildings. As buildings are complex in their composition of numerous materials and subassemblies, tools have been developed that attempt to better inform environmentally preferable decisions. The dominant theme in the development of these tools has been the balance of communicability and ease of use with completeness and transparency (Scheuer and Keolian 2002).

Certification schemes and eco-labeling are examples of solutions that weigh pragmatism heavily and have grown in acceptance. This is illustrated by the now dominant status of the US Green Building Council's LEED certification in North American green building discourse. The scientific community, however, has rallied behind life cycle assessment (LCA) as a structured analytical method for recognizing impacts caused by complex systems like buildings. It has been successfully argued that a responsible green building scheme should consider the results of LCA research and incorporate their findings (Trusty and Horst 2002), and the US Green Building Council (USGBC) has taken steps towards integrating LCA research into the LEED standard. Tom Hicks, vice-president of the USGBC, recently stated that there is "a responsibility to ensure that LEED's evolution addresses LCA in a meaningful and relevant manner." (USGBC 2007)

Life Cycle Assessment (LCA) is a methodology to account for all significant material and energy usage and subsequent environmental impact that result from a product's life cycle. Considering a building as a product, the life cycle includes the extraction of raw materials from the biosphere, their conversion into standardized building products, on-site construction, occupancy, and disposal at the end of life. While specialized simulation tools have been used to consider the significant energy and water use that is required for a home, life cycle assessment has addressed the resource use and waste generated by construction and demolition. The focus of these LCAs has been the calculation of life cycle inventory values for each of a home's numerous interchangeable components.

1.2 Life Cycle Assessment of Windows

Windows account for 10-25% of a building's exposed surface (Recio et al. 2005) or roughly 27 square meters in an average newly built American home (NAHB 2007). The life cycle of a modern window is complex as they are composed of numerous engineered materials. Several LCAs (Entec 2000 and Asif et al. 2002) of windows have sought to determine the most environmentally preferable frame material (wood, PVC, or aluminum), however, none of these considered fiberglass frames or product life cycles specific to North American practice.

This research is a life cycle assessment of three window types commonly available to the North American residential consumer: PVC, fiberglass, and aluminum clad wood. Aluminum frames were excluded from this analysis due to their incomparability as an insulation medium that would outweigh any potential benefit over the rest of the life cycle[1]. The LCA was based on the production of the three windows by a single representative manufacturer of each type. Average transportation distances, commodity systems, maintenance, and service life estimations were used to complete the life cycle inventory model.

[1] Previous LCAs on aluminum frames found them to be the most energy intensive during manufacturing (Citherlet et al., 2000) (Asif et al., 2002) and use (Recio et al., 2005). The thermal performance of aluminum windows was improved with the advent of breaks between internal and external surfaces, but was still found to be considerably worse than PVC or wood (Recio et al., 2005).

1.3 Objectives

Several objectives were established for this work.

- Evaluate and compare the impacts caused by the production of each window type and by the entire life cycles.
- Recognize the significant contributors to impacts throughout the life cycle to direct the focus of improvement and abatement efforts.
- Present the findings so that the product system model and its sensitivity to uncertainty are transparent.

1.4 Organization

This document is an account of the research that was completed by the degree candidate over the past two years. As such, a review of LCA practice and preceding LCAs on window materials are included as a supplement to the analysis that was performed.

Chapter 2 is a background on LCA practice and standardization. The state of LCA as a tool for environmental management is first discussed, followed by the history and standardization of the LCA methodology. The four major components of LCA, Goal and Scope Definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation are covered.

Chapter 3 is a literature review on life cycle assessments relating to windows. The life cycles and impacts of common frame materials (wood, PVC, and aluminum) are described as well as the LCAs that directly compare their use in window frames. Also included are those LCAs in which the use phase was considered to determine energy paybacks during use.

In Chapter 4, the goal and scope definition are presented. The communication requirements and intended audiences are first recognized. Next, the functional units of comparison are formally defined. The scope and focus of the assessment are then determined based on the constraints and requirements of the LCA. Finally the use of Sima Pro software is explained as a data source and computational tool.

Chapter 5 explains the life cycle inventory that was considered in modelling the lives of the three windows. First, the manufacturing process inventory is shown. These findings are then used to trace materials upstream to their related commodity manufacturing for which published inventory data was adopted. Chapter 6 contains the life cycle impact assessment. First, the selection of impact categories and characterization factors are explained. Next, the significance of accounting for the various impacts is recognized. Finally, the cradle to gate and cradle to grave impacts are shown. The impacts are traced to individual processes and life stages to focus abatement efforts and to recognize differences between the three products.

Chapter 7 presents the findings of the sensitivity analysis. Modeling the three life cycles required numerous assumptions as to data representativeness, the averages assumed in the default case, as well as the source and material used to clad the wood window. The sensitivity of the results to alternative datasets, specific material source and installation locations, and alternative cladding materials was explored.

Chapter 8 contains the conclusions that may be drawn based on the impact assessment and sensitivity analysis. Limitations are identified based on the sensitivity of the results and inherent methodological constraints. The thesis concludes by recognizing potential continuations of this research.

CHAPTER 2: LIFE CYCLE ASSESSMENT

Life cycle assessment is a quantitative technique for evaluating the resource use and associated environmental burdens of a product from "cradle to grave". It considers all life stages of a product from resource extraction and commodity manufacturing, to secondary manufacturing, use, maintenance and end of life. Figure 2.1 illustrates a generic product life cycle and shows its related product system, which includes the product and all flows of material and energy for each life stage. The linear arrows in Figure 2.1 represent transportation of materials between each life stage and are necessarily included in the life cycle and product system definitions.

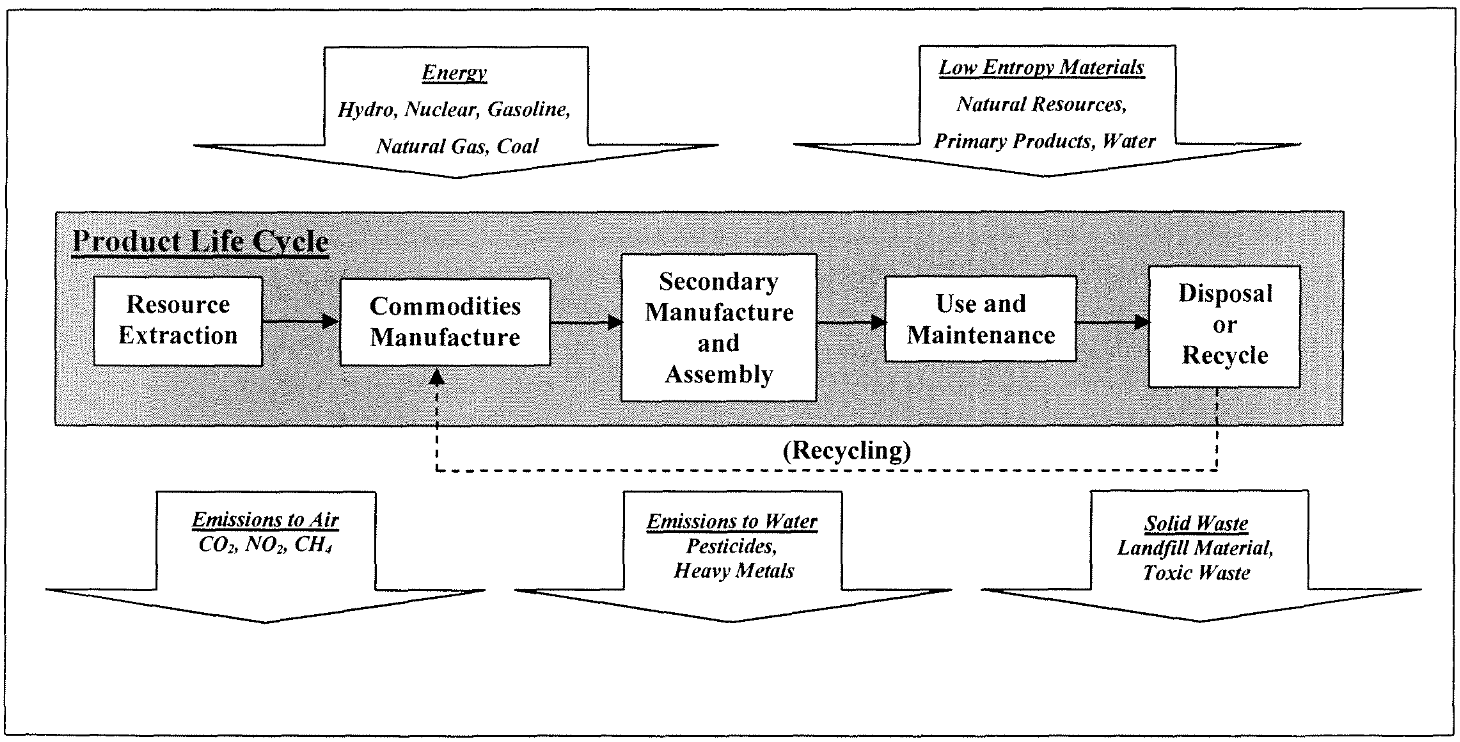

Figure 2.1: Generic Product System Process Flow Representation

The flows of resource use and emissions in the product system are calculated for each process included in the product system definition. This is called the life cycle inventory (LCI). The impacts on the environment are then calculated based on the LCI for the entire product system and factors relating their flows to indices of environmental degradation, called characterization factors (Pennington et al. 2004). This aspect of LCA is called life cycle impact assessment (LCIA) and includes the grouping of impacts into categories for which a single metric is calculated. This is achieved by scaling inventory values by their relative influence and reporting in common terms, greenhouse gas emissions as CO_2 equivalents for example. These emission equivalence categories are referred to as midpoint impact categories, while further modeling may be completed to calculate their effects on human health, ecological quality, and resource use damage categories. Life cycle impacts may then be either reported directly, normalized to show the relative scale, or weighted based on estimates of valuation functions used by generic or particular interest groups.

2.1 LCA Practice and Standardization

The first LCA was performed in 1969 by Coca Cola on plastic and glass beverage containers. The results of this study highlighted the usefulness of LCA by unexpectedly indicating the preferability of plastic when life cycle resource use and energy consumption were considered for the first time. The oil crisis in the 1970's and the issue of landfill overcrowding in the 1980's drove LCA research in its early development (LeVan 1996). LeVan (1996) noted that LCAs of this era were not conducive to replication as various methodologies were used to calculate the material and energy flows, and conversion to subsequent environmental impacts was often excluded.

Questions on the validity of LCAs performed under marketing pressures and the manipulation of results by practices such as inconsistent product system boundary definition further undermined acceptance of LCA and its adoption (Klopffer 2005). Based on experience and a desire within the scientific community for replicability, some standards were established and a methodological framework emerged. The Society of Environmental Toxicology and Chemistry (SETAC) made a major step toward standardization when it published the "Code of Practice" (Consoli et al. 1993), which separated life cycle assessment into three distinct methodological components. These are the goal and scope definition, life cycle inventory, and life cycle impact assessment.

In 1997 the International Standards Organization, ISO, published the 14040 standard, "Principles and Framework", which adopted the three components of the SETAC code and added Interpretation as a fourth. Figure 2.2 appeared in ISO 14040 and shows the logical relationship of the four LCA components. The bi-directional arrows indicate the continuous need to modify the assessment, and backtracking to previous stages, based on the interpretation of the findings at each stage.

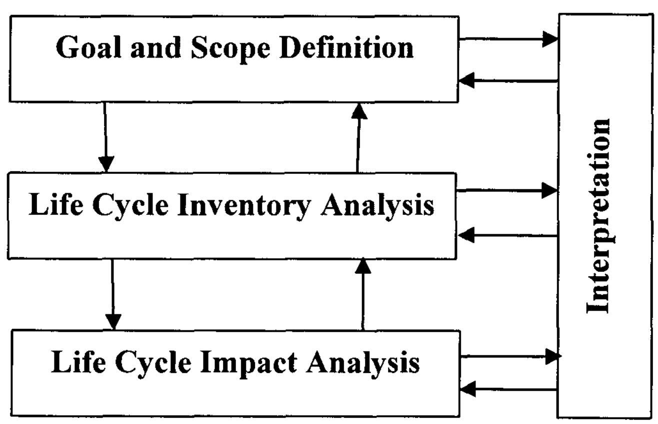

Figure 2.2: Life Cycle Assessment Framework (ISO 14040, 1997)

In the 3 years following the publication of 14040, ISO published three other standards, ISO 14041,14042, and 14043. These served the role of further defining LCA practice while balancing pragmatic flexibility with the need for standardized practice. In 2006, ISO published an update to the standard, ISO 14040:2006 and ISO 14044:2006, which are now the consensus methodology for life cycle assessment.

2.2 Goal and scope definition

Goal and scope definition was first identified as a distinct component of life cycle assessment in Heijungs et al. (1992) as it was recognized that differing reasons for conducting the LCA would lead to different system models (Rebitzer et al. 2004). The following describes the numerous uses for LCA results as recognized in LCA101 (2007).

- **Support broad environmental assessments:** LCA results of individual products may be combined with those performed on complimentary products and in addition to data from other methodologies to determine environmentally preferable activity.
- **Establish baseline information for a process:** Determining the impacts of the status quo life cycle so that efforts may be judged for improvements.
- **Rank the relative contribution of individual steps or processes:** Process contribution analysis reveals the individual processes in the life cycle that are primary contributors to impacts and should thus be the focus of improvement efforts.
- **Identify data gaps:** In completing the life cycle inventory, it may be recognized that representational data is unavailable for the product system model and must be gathered before proceeding. This data may be used in other similar LCAs.

- **Support public policy:** LCA may guide or test the relevance of administered improvement efforts.
- **Support product certification**: LCA results may be used to facilitate certification processes by recognizing holistic tradeoffs between materials or processes that are impossible to capture otherwise.
- **Guide product and process development:** – When incorporated into the design process, the impacts may be recognized at a stage in the product life cycle that allow improvements to be made through material sourcing and recognizing potentials for improvement during use and disposal.

All LCAs undergo a degree of streamlining to balance the needs for specificity with resource limitations. This streamlining is achieved by recognizing processes that require specific first hand data and those that are either comparable or less significant and can either be ignored or represented with less specific data. Data quality is determined by several factors that represent the similarity between the model that was assumed in calculating the inventory values and the processes in the product system that are to be represented. These include country and regionally specific commodity, transportation, and energy production systems, age of the data, similarity in boundaries and allocations.

The functional unit is determined in this stage and serves as the starting point for investigation into the product system. This is achieved by formally stating the service provided by the product, so that all flows necessary to provide this utility can be determined. This is necessary as utility is typically derived from the use of multiple complimentary products that perform different functions.

2.3 Life cycle inventory

The life cycle inventory step of LCA requires the collection of data for all of the material and energy flows of processes determined in the scope definition. This step is typically the most time consuming and resource intensive aspect of conducting a life cycle assessment (Rebitzer et al. 2004). Public and fee-based data sources are available for processes that are common to many products, particularly the production of commodities. The goal and scope definition may require reconsideration during the LCI as the data desired may not be available or the processes may be different than was previously assumed (ISO 14040 2006).

By relating the inputs and outputs of each process in the product system, both energy and material, to the production of one functional unit, data for each process can be scaled to find the unit process flows, which are required to produce the unit of service (ISO 14041 1998). The life cycle inventory is the sum of all unit process flows in the product system. Finding the unit process flows is often difficult because many production processes are not only used for the functional unit under consideration, but are used for the production of multiple products of different utilities. ISO 14041 (1998) provides three methods to deal with multiple output processes in order of preference. The first is to expand the definition of the functional unit to include the other functional units produced by that process. If the original functional unit is critical for a comparison or the relevance of the results, then the LCA practitioner should attempt to calculate the unit process flows by modeling the process based on the physical reality of the system. If this is not possible, then the flows should be assigned by another utility of the process that serves as a surrogate for the functional unit, such as the net revenue gained by the production of each product (ISO 14041 1998).

2.4 Life cycle impact assessment

The life cycle impact assessment is the evaluation of potential human health and environmental impacts associated with the resources used and emissions identified in the life cycle inventory. ISO 14042 (2000) specifies that all resource use, health consequences, and ecological consequences be grouped into impact categories to which an impact indicator, or metric, is calculated. The impact indicator value is found by multiplying the LCI values by characterization factors that relate the flows in the LCI to anticipated impacts (Pennington et al. 2004). These parameters are based on characterization modeling which are scientifically justifiable environmental impact studies as specified by ISO 14042 (Pennington et al. 2004).

Pennington et al. (2004) highlighted three issues that define the current state of LCIA debate and complicate the determination of meaningful and accurate characterization factors.

- **Assumed Nature of Impact:** The impacts are either assumed to occur at the margin, incrementally based on one extra unit of production, or are averaged over the total impacts of all functional units.
- **Depth and Breadth of Cause-Effect Chain:** Chemical emissions are often the beginning of complex cause-effect chains and the proximity to the emission or eventual impact chosen for the indicator must balance the goal of finding impacts with the uncertainty inherent in cause-effect prediction. Impact categories such as global warming potential can adequately be reported as a "midpoint" effect, as

CO_2 equivalents for example, instead of the harm caused by that warming. However, for impact categories defined as effects, such as human health detriment, local impacts, and global environmental damage, modeling these linkages is necessary for meaningful results (Bare et al. 2000).

- **Site/Temporal Variability:** Resources and emissions come from and go to a variety of landscapes over varying periods of time which limits applicability of impact estimation to multiple contexts.

Despite these sources of uncertainty, indicators have been developed for the impact categories of climate change, stratospheric ozone depletion, acidification, aquatic eutrophication, terrestrial eutrophication, human toxicological effects, ecotoxilogical effects, photooxidant formation, biotic and abiotic resource use (Pennington et al. 2004). The impact indicators are then either grouped further into broader impact categories and scaled based on relative impact, normalized into a single impact score by weighting the perceived significance of each impact, or are reported directly, allowing the results user to apply their own weighting and grouping (ISO 14042 2000). ISO 14042 (2000) rejected the aggregation of impacts into weighted indices for comparative marketing, but recognized the practicality of grouping impact categories into summary values.

ISO also recognizes several optional practices in life cycle impact assessment that further elucidate the findings. These include Normalization, Weighting, and Grouping.

- **Normalization:** Normalizing introduces the magnitude of the effects described by the characterization. The results are scaled based on the magnitude of the impact relative to those caused by the entire economy. The characterization value is multiplied by a ratio that relates the impact to the per capita causation of the impact by an average person in that economy in a given year, specifically Europe in all the provided methods.

- **Weighting:** The normalized or non-normalized impact indicators may then be weighted based on a perceived understanding of their relative significance. The weights are typically the opinions of experts and may include valuation schemes specific to different types of results users.

2.5 Interpretation

Interpretation is a phase of an LCA in which the results are analyzed and their implications communicated. In this step, data, assumptions, LCI results and LCIA results are examined in detail (ISO 14043 2000). The results are checked to insure completeness and to test the sensitivity of assumptions made in the LCA. The boundaries and data quality are also checked to ensure consistency amongst materials with different life histories. Finally, the results of the LCA study are described and reported in a manner that is meaningful to the proposed audience. This step should be given adequate attention as LCA results may influence decisions in the design of products and subsequently affect environmental impacts (ISO 14043 2000).

A fundamental concern of LCA interpretation is addressing uncertainty that is present in the results. This uncertainty results from inherited uncertainty in the datasets, incorrectly representing the product system, and the exclusion of processes outside the system boundary.

Dealing with uncertainties from externally produced data is a statistical exercise in which a confidence interval is assigned to the result as a function of the process data distributions. Calculating result uncertainty from these is complicated, however, as life cycle inventory values are typically reported as an average or most likely scenario with no distribution given.

Often, multiple datasets and alternative assumptions are available to the LCA practitioner that may reasonably be assumed as representative of the product system in question. One way to test the reaction of the results to switching data or assumptions is to perform sensitivity analysis in which the results are recalculated based on substitutions in the model. Insignificant changes to the results in sensitivity analysis indicate the ability to exclude those decisions as potentially detrimental to justifying assertions. Sensitivity analysis may also lead to the conclusion that every result is circumstantial, and relies wholly on the assumptions that were made.

Prior to the sensitivity analysis, it may be useful to first isolate the processes that have the potential to significantly influence results when the assumptions are changed. In process contribution analysis the individual processes and life stages are considered individually to recognize the most significant impact contributors in the product life cycle. This analysis allows the recognition of the modeling decisions that are critical to the results and makes it possible to focus on those found to be the most significant.

CHAPTER 3: LITERATURE REVIEW

3.1 Background

Windows perform multiple functions in built structures, most notably as the light transmissive interface between the interior and exterior environments. Research in holistic housing has also raised new considerations as to the functionality of windows to include air circulation and quality, and other measures of occupant health and comfort (Menzies and Wherrett 2005). The translucent components, typically glass, are either openings in a building envelope, in which case a fixed or operable frame is included, or comprise the entire façade.

Life cycle assessments of windows vary significantly in the decisions they seek to inform and hence the scope and design of such analyses are also heterogeneous (Chevalier et al. 2003). Life cycle inventory values have been developed for the production of different frame materials, glazing spacing, gas infill, and glass treatments by modeling the processes used to manufacture windows. Resource use and emissions have been determined for the extraction and processing of commodity materials that are used to manufacture window components and the specific processing that they undergo. The required maintenance and end of life processes have also been considered in some cases.

As the significance of use-phase performance is well established, simulation programs have also been used to calculate use-phase thermal and optical flux as life cycle inventory values for inclusion in life cycle assessment accounting. The varying scopes, data sources, functional units, assumptions, and findings of the windows LCA literature will be discussed to understand previous efforts and the wisdom gained from these analyses, and also to provide precedent and direction for this research.

Several LCAs have been completed on building products specific to the North American marketplace. The focus of these has been the comparison of wood assemblies to those made of other materials. The National Research Council's Committee on Renewable Resources for Industrial Manufacturing, CORRIM, completed the first LCA of forest products in 1976 in response to mischaracterizations of the environmental friendliness of wood from marketing-driven LCAs by advocates of competing materials (LeVan 1996). The results of this study were that wood products require considerably less energy than competing materials (1/9 the energy of steel studs, and 1/4 the energy of concrete walls) (LeVan 1996). Twenty years later Trusty and Meil (1999) demonstrated ATHENA's Environmental Impact Estimator software, comparing wooden frame walls compared with steel and drew similar conclusions.

3.2 Life Cycle of Windows

3.2.1 Anatomy of a Modern Window

Modern windows are composed of numerous parts of different materials. These parts are shown in Figure 3.1 and a description of each follows.

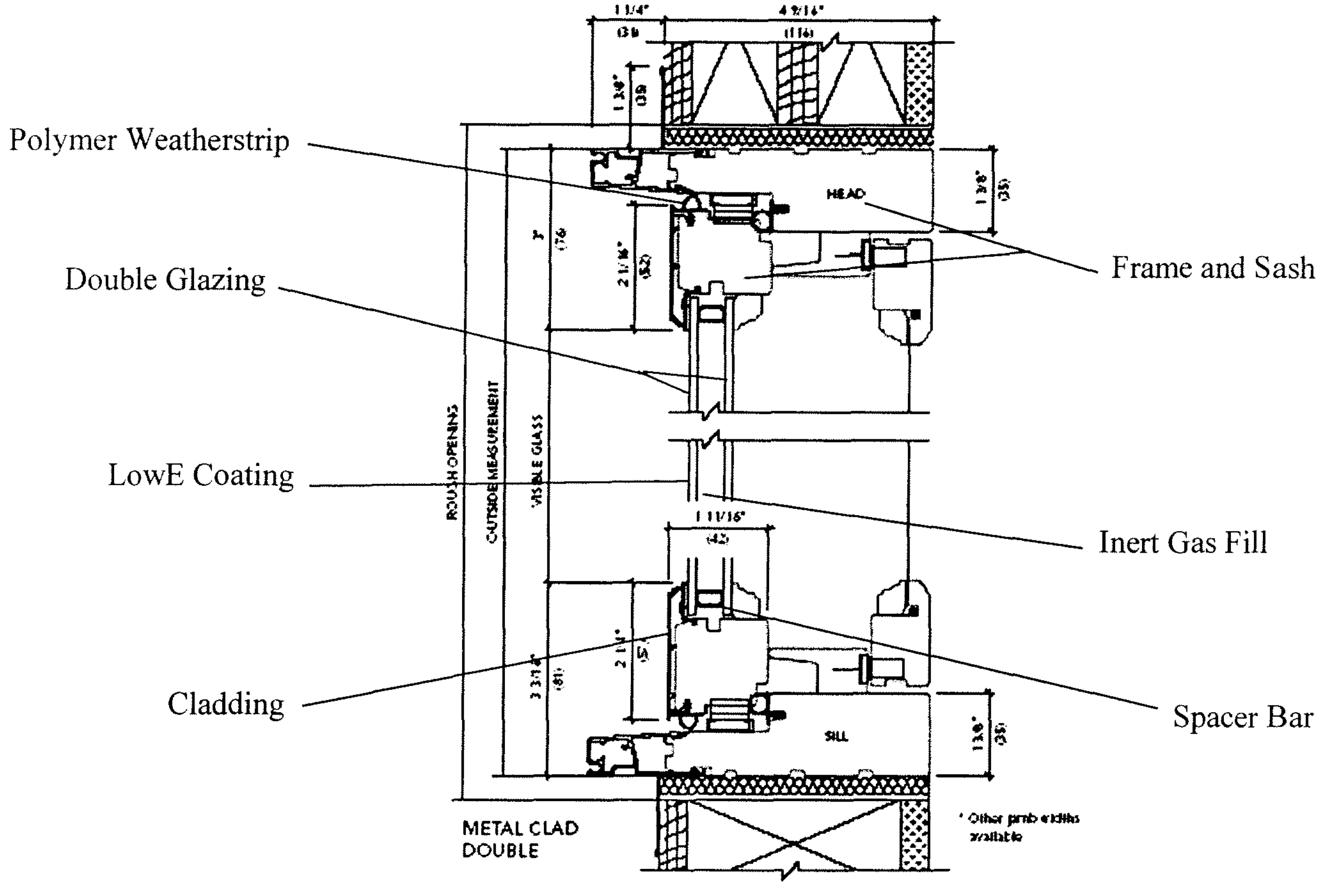

Figure 3.1: Typical Anatomy of a Modern Window

Polymer Weatherstrip: Rigid and flexible polymers are used to create a weatherproof seal between the fixed frame and operable sash.

Double Glazing: Two and sometimes three glass panes are used to create a gap between surfaces exposed to external temperatures and those contacting climate controlled environments.

LowE Coating: Glass surfaces are available with LowE coatings that allow high frequency sunlight to permeate, but trap lower frequency radiant heat.

Cladding: Aluminum, PVC, and fiberglass cladding is applied to protect traditional wooden frames from decay and lower maintenance costs.

Inert Gas Fill: Argon gas, as well as other inert gasses like xenon and krypton, is injected between panes to further improve the insulation of sealed glazing components.

Spacer Bar: Aluminum and foam spacer bars are used to separate multiple glazings. Foam is better than aluminum because it provides a superior thermal break between surfaces.

Frame and Sash: Wood, aluminum, PVC, and fiberglass are commonly used to construct the frame and sash.

3.2.2 Modeling the Window Life Cycle

The life cycle of a window reflects the materials that it is made of and also the recognition that the functionality is reliant on its placement in an enclosed building envelope. The life cycle of any window begins with the extraction of raw materials from the natural environment. Resource extraction causes impacts to local ecosystems, depletes stocks of non-renewable resources, requires energy, and causes waste. After extraction, the raw materials are then shipped to large-scale commodity manufacturing facilities at which they are converted to standardized inputs for use in the window-specific secondary manufacturing. Wood, PVC, glass, fiberglass, and aluminum are the most commonly used window materials. After manufacture, the window is shipped to the installation site where it is placed in the structure and undergoes maintenance and replacement until the building is demolished. Figure 3.2 shows the life cycle of a window and its related product system.

Calculating the life cycle inventory values for each life stage requires data from different sources. For commodity manufacturing and extraction, published data is used

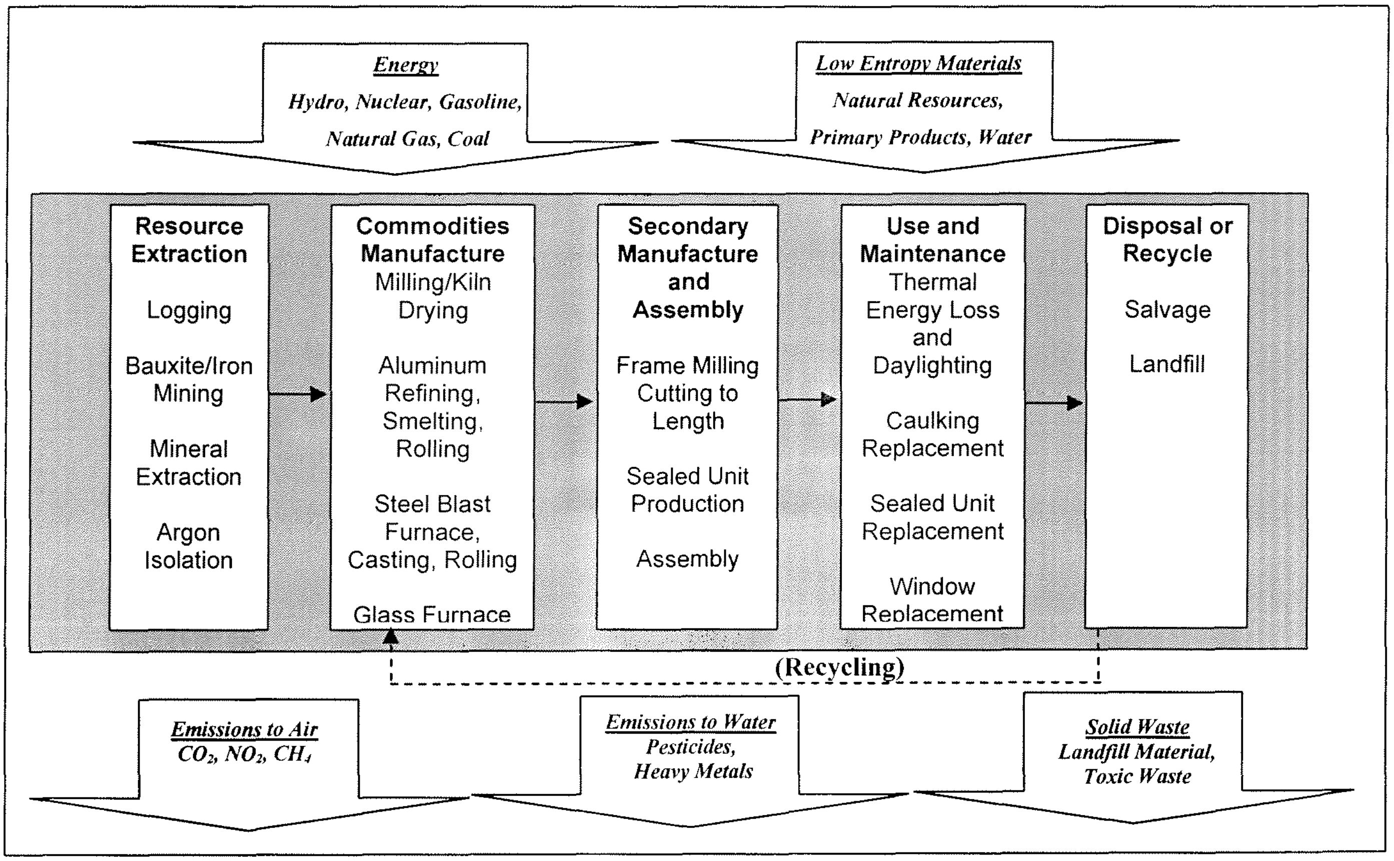

Figure 3.2: Generic Window Product System Process Flow Representation

while first hand data may be required when none is available. Secondary manufacturing processes are those specific to windows and require first hand data collection or assumptions as to waste generation and resource use when specificity is not required. The maintenance and replacement effects are determined through estimations by building product experts and surveys while simulation software may be used to generate use-phase energy flows.

Life cycle assessments of windows have generally been used for two purposes.

1. Compare window frame materials and determine their relative contribution to impacts.

2. Justify greater resource use during manufacturing for improved use-phase characteristics of new technology.

The design of LCAs conducted on windows reflects the difference in the nature of these two goals. The first, comparing frame materials, directs the focus to the processes in the life cycle that are directly related to the frame material. These processes include cradle to gate production emissions and resource use, differences in secondary manufacturing processes, maintenance and service life differences, as well as options for recycling at the end of life. The second, calculating energy payback during use, typically streamline the life cycle inventory to consider carbon emissions or energy use only and compare this to the expected energy savings or generation during use. Several LCAs consider both issues concurrently by recognizing differences over the entire life cycles of window frame materials including their thermal differences.

Table 3.1 lists the window LCAs that have been published. The goals of each, comparing frame materials or justifying the energy payback, are shown along with the functional units that were considered, and the processes that were deemed within the product system boundaries. One study, Weir and Muneer (1998), only considered the manufacturing of a finished window and made no comparisons between frame materials.

Section 3.3 examines the implications of window frame material selection by considering the current state of the North American residential window market and the recent prevalence of PVC. Next, the cradle to gate processes and emissions of each of the most popular frame materials, wood, pvc, aluminum, and fiberglass, are discussed. Finally, the results of comparative LCAs performed on window frames are presented.

Section 3.4 presents the results of LCAs that consider use phase energy to justify energy payback for window technologies. These technologies are innovations in glazing technology that include tints, inert gas filled sealed units, shading systems, and electrochromic devices.

Table 3.1: LCAs of Window Materials Published in the last 10 years

STUDY	GOAL	FUNCTIONAL UNIT	LIFE STAGE CONSIDERED IN STUDY: RESOURCE EXTRACTION AND COMMODOTIES MANUFACTURE	SECONDARY MANUFACTURING	USE, MAINTENANCE AND REPLACEMENT	END OF LIFE
Weir and Muneer 1998	Consider Relative Impacts	Double Glazed Wood Window	Argon, Krypton, and Xenon	Sealed Unit	–	–
			Wood	Wood Frame	–	–
			Aluminum	Aluminum Flashing, Spacer and Hardware	–	–
			Glass	Manufacturing Overhead	–	–
Citherlet et al. 2000	Compare Frame Materials & Justify Energy Payback	Numerous Window Systems	Float Glass, Fiberglass, Argon, Aluminum, Thermoplast, Wood, Plywood, PVC,	Wood, PVC, and Aluminum Frame, Sealed Unit, Blinds, and Finished Window System	Replacement	–
					Thermal Performance	–
Entec 2000	Compare Frame Materials	Wood and PVC Window Frames	Wood, Paint, PVC, Steel, Aluminum, TBTO Preservative	Wood Frame, PVC Frame	Thermal Performance	Landfilling
Asif et al. 2002	Compare Frame Materials	Aluminum, PVC, Wood, and Clad Frames	Aluminum PVC Wood	Aluminum Clad Frame, Aluminum Frame, PVC Frame, Wood Frame	Maintenance and Replacement	–
Kiani et al. 2004	Justify Energy Payback	Fully Glazed Commercial Building Envelope	Glass	Tinted and Reflective Sealed Unit	Thermal and Lighting Performance	Recycling
			Argon and Krypton		Replacement	
Recio et al. 2005	Compare Frame Materials & Justify Energy Payback	Five Window Types	PVC Steel Glass Aluminum Wood	Aluminum, Wood, PVC Frame	Thermal and Permeation	Landfilling
Syrrakou et al. 2005	Justify Energy Payback	Electrochromic Device	K-glass Tungsten Oxide PMMA PC Lithium Perchlorate Silicone	Electrochromic Device	Thermal Performance	–

3.3 LCAs of Window Frame Materials

Of the 70.5 million windows sold in the United States in 2005, 58% contained a frame made of polyvinyl chloride (PVC), 27% wood, 13% aluminum, and less than 3% fiberglass (USDOE 2006). This is in contrast to the dominance that wood enjoyed in 1990, with 48% market share to 27% for aluminum and 24% PVC (USDOE 2006). Fiberglass frames were not significantly used in 1990. Figure 3.3 shows this trend.

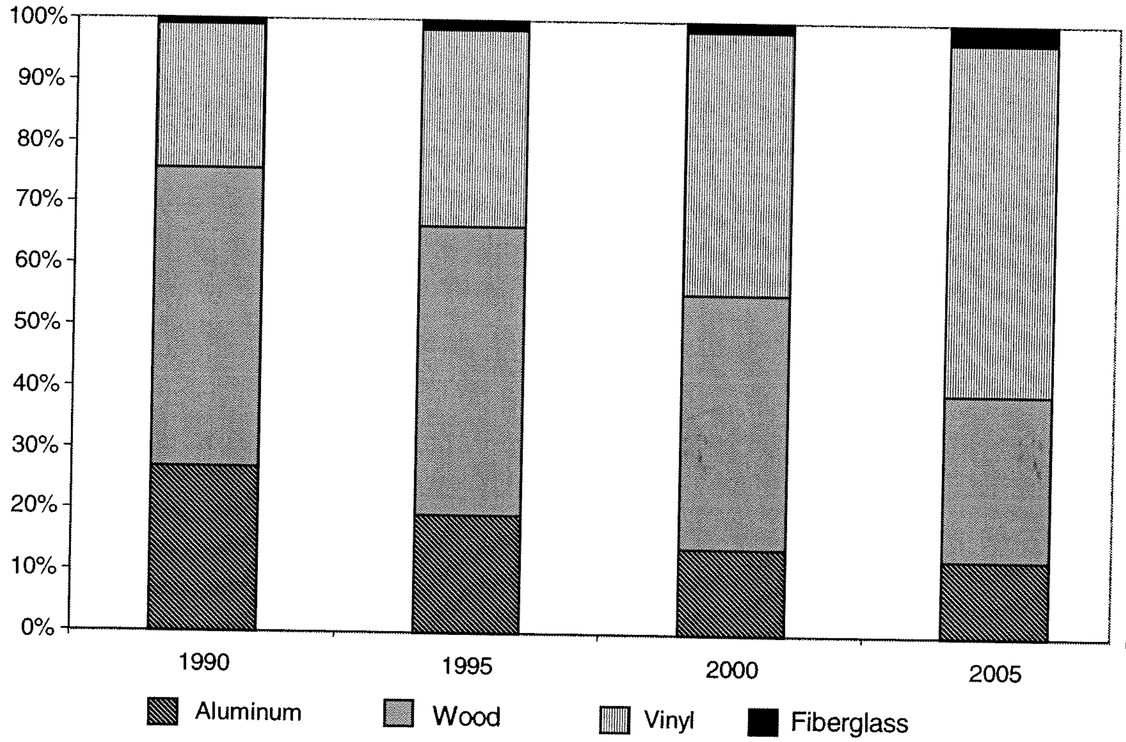

Figure 3.3: US residential window market share by window type (USDOE 2006)

The question arises whether the changes in frame selection, with PVC gaining greater acceptance at the expense of wood and aluminum, while fiberglass has gained slow acceptance, is in accordance with the movements towards more sustainable buildings. To date no LCA has been completed on a fiberglass frame window. Several have considered wood, PVC, and aluminum window frames. As these materials are products of their respective commodity systems, an LCA must consider the cradle to gate life cycle inventories of each of these materials. The cradle to gate processes for wood and PVC will be discussed in more detail in Sections 3.3.1 and 3.3.2 as much has been written regarding the environmental performance of these materials.

3.3.1 Cradle to Gate Wood Production

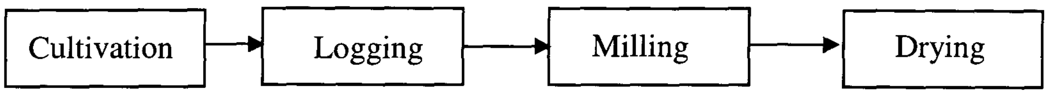

Figure 3.4: Cradle to Gate processes of kiln-dried lumber

The first phase in the life cycle is either the logging of timber or the cultivation that is undertaken in managed forests. Thinning practice, fertilization, and other cultivation activities may either be deemed within or beyond the scope of the LCA.

The environmental impacts of forest harvesting are ones that are open to wide discussion as forests are typically of high ecological and cultural value. It is difficult to measure the direct impacts of forest harvesting due to the necessity of end-point consideration, and there is predictable lack of agreement as to the proper way to account for these impacts, let alone the impacts that actually occur. While agricultural production can typically consider resource in one growing season or several, the considerable time (up to hundreds of years) required to cultivate harvestable timber further complicates modeling of forestry activities (Perez-Garcia et al. 2005). Seven criteria for sustainable forest management have been recognized for which hundreds of indicators, performance metrics, have been developed that communicate the health of forests in quantifiable terms (McHugh et al. 2005). These include impacts on biological diversity, the reduction of nutrients in the soil, aesthetic loss, degradation of cultural and recreational value, and the occupation of the limited resource land area (Ekvall 1999). Direct impacts of forestry to the surrounding ecosystem are typically deemed beyond the scope of LCA on wood products.

In 1995, the European Forest Institute organized the workshop "LCA – A Challenge for Forestry and Forest Products Industry" at which Richter (1995) effectively summarized the following key findings of forest products LCAs up to that point.

- Wood is a renewable resource, which, if considered, improves performance in the impact categories related to resource use.
- The embodied energy of wood products is considerably lower than those of alternative building materials.
- Wood waste can be burned and thus causes minimal solid waste volume.
- Wood subjected to weathering requires greater maintenance and use of protection systems including preservatives, sealants, and coverings.
- Local impact studies completed with more scrutiny are less favorable to wood's green perception.

By 1996, life cycle assessments had been applied to a wide range of forest products, including paperboard milk cartons, paper grocery bags, recycled and virgin newsprint, and disposable diapers (LeVan 1996). In that year CORRIM initiated a comprehensive investigation into the life cycle environmental impacts of wood use in residential construction. Their results include inventory values for the entire life cycle of wood building products, from forestry operations to disposal.

One issue critical to life cycle modeling of forest products is the assumptions made as to the carbon stored in non-decaying products. Lucier (1996) argues that carbon storage in forests increases with stand age and that this may lead to policy requiring longer harvest cycles. CORRIM contradicts this argument by noting that while active management and short cycles decrease the amount of carbon in the forest, there is a net solid carbon gain when the amount stored in wood products is considered (Perez-Garcia et al. 2005). This is because mature forests have no net carbon exchange while growing forests act as a carbon sink, meaning they extract CO_2 from the atmosphere and sequester it until the tree eventually decays and the carbon is recycled (Perez-Garcia et al. 2005). The difficulty of either claim is the uncertainty of decisions made after harvesting, including the application of preservatives, how long the product is used for, and what waste management the material is subjected to.

3.3.2 Cradle to Gate PVC Production

The life cycle of PVC products begins with the extraction of natural gas, salt, and oil from their respective natural systems. The associated risks and degradation from these extraction practices is, as is the case with forestry, the subject of research typically deemed beyond the scope of LCA.

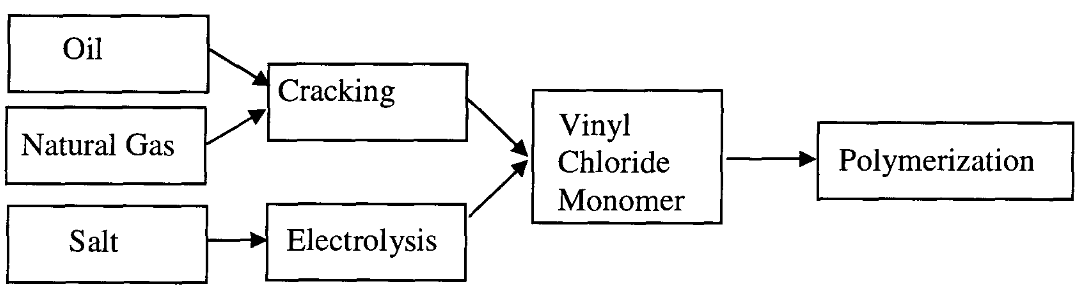

Figure 3.5: Cradle to Gate processes of PVC

The cracking and electrolysis processes are the major contributors to the cradle to gate impacts. These processes consume the most energy, which is the primary source of impacts in the life cycle. The compounding and processing require relatively little energy and thus cause less impact (PE Europe 2004).

The cradle to gate manufacturing processes require and introduce several known toxic substances. These are not necessarily released during manufacturing but introduce an inherent risk to these processes. Known emissions include mercury, chlorine, and EDC (1,2-dichloroethane) (Totsch and Gaensslen 1992). Significant variation exists in published data sources for the inventory values for these substances (Peereboom et al.1998). Peereboom et al. (1998) found that amongst six different data sources, the values for mercury varied by 1000%, 3000% for chlorine, and 1500% for chlorinated hydrocarbons.

One major criticism of the PVC life cycle is the creation of PCDDs, polychlorinated dibenzo-p-dioxin, (commonly referred to as dioxin) as a byproduct. The emissions of dioxin are extremely small, but require careful consideration because dioxin is a potent carcinogen (PE Europe 2004). Ayers and Ayers (1999) recognize the uncertainty in assigning the blame of dioxin production to PVC, however, as it has been shown that waste incineration as a whole, not just of PVC products, is a significant contributor to dioxin release. They also recognize that slash and burn agriculture may be a significant cause of dioxin.

One way to reduce the emissions of the cradle to gate processes is to use recycled material. PVC is not recycled in significant amounts however (PE Europe 2004).

3.3.3 Comparative LCAs of Window Frame Materials

Entec, (2000) published a comparative LCA on wooden and PVC window frames which considered the primary production of wood and PVC from raw materials, frame fabrication, installation, thermal effects during use, as well as landfilling at the end of use. The LCI showed that the PVC window consumed more than 3 times as much coal and oil as the wood window through the production of raw materials as well as producing 7 times as much CO_2 in that phase. The wooden window also acted as a carbon sink and it was assumed that 32.3 kg of CO_2 were consumed in tree growth and 7.5 kg were released at the end of its life netting a carbon sink of 25 kg.

Asif et al. (2002) also considered window frame material in their LCA of aluminum, wood, PVC, and aluminum-clad wooden window frames. The embodied energy was found for the four frame types with an accelerated aging test and industry survey used to gain an understanding of use-phase service life and maintenance expectations. Aluminum production was the most energy intensive (225 MJ/kg) with the use of recycled material only requiring 7% of this. PVC production was also energy intensive (70 MJ/kg) and caused emissions of hydrocarbons, dioxins, vinyl chloride, phthalates, and heavy metals. Wood frames had the lowest embodied energy (5.2 MJ/kg) and the best thermal characteristics, but require greater maintenance and preservative use. Cladding eliminated maintenance requirements by protecting the wood. The embodied energy of aluminum, PVC, aluminum clad timber, and timber were 6,000 MJ, 2,980 MJ, 1,460 MJ, and 995 MJ, respectively.

Asif et al. (2002) also recognized the critical nature of window longevity and performed accelerated aging simulations to test some of the weaknesses inherent in each design. These tests included immersion, dry-wet cyclic, salt spray, humidity & temperature, and UV exposure. Powder coated aluminum frames were unaffected by all tests. PVC suffered discoloration when exposed to extreme temperatures, humidity, and ultraviolet light. Wooden frames showed warping and cracking under extreme humidity and temperature, but remained unaffected when clad in aluminum. A survey was also distributed to "authorities" in which it was found that aluminum-clad wood windows provided the longest service, 46.7 years, with aluminum second, 43.6 years, wood third, 39.6 years, and PVC providing the shortest service, 24.1 years.

3.4 Justification of Energy Payback

Weir and Muneer (1998) published the first LCA of double-glazed windows in 1998 in which they focused on the stages up to and including the manufacturing of a 1200mm by 1200mm tilt and turn window. The inventory analysis considered the inert fill gas, timber sash and frame, aluminum, sealed unit, and manufacturing overhead. The following processes were considered for each classification and they also considered energy expenditure and subsequent greenhouse gas emissions:

- Inert fill gas: Argon, Krypton, and Xenon isolation
- Timber sash and frame: Scandinavian forestry, primary milling, frame milling
- Aluminum: Cradle to Gate virgin and recycled material systems, cutting
- Sealed Unit: Pane manufacture, assembly, filling, and sealing
- Manufacturing: Heat and lighting

The results showed that the window required 137.1 MJ of energy, 33.2 MJ from the sash and frame, 6.0 MJ from the sealed unit, 0.2MJ from aluminum production, and 97.7 MJ from lighting and factory energy requirements. The three inert fills that were tested yielded 94.7 kg of CO_2 for argon, 207.6 kg for Krypton, and 1,094.7 kg for Xenon. The use-phase energy simulation revealed that the lower inventory values for clear float glass was outweighed by the use of LowE coating and the best performing sealed unit constructed of a "transparent insulation material" for the glazed surface.

Citherlet et al. (2000) completed an LCA of advanced glazing systems in which they focused on several different options for materials and designs. The variables in window design and material included the number and types of panes to be used, the gas used between panes, spacers between panes, and frame material. The impacts of non-renewable energy requirements, global warming potential, acidification potential, and photochemical ozone creation were considered in the manufacture and disposal of materials. The manufacturing LCI data and assumptions were adopted from the EMPA's (1996) findings energy simulation software used to calculate the use-phase energy. The windows were analyzed for potential energy savings in their use through the simulated office, classroom, and residential applications in the climates of Glasgow, Lausanne, and Rome. Citherlet et al. (2000) considered energy loss through the window unit throughout its lifetime and concluded that improved thermal insulation outweighed increased production requirements and that windows caused the least environmental impacts when they are made of insulative materials such as wood and multiple panes used with inert gas. One seemingly counterintuitive assumption was made in this study, which was to equate the service life of the window to the longevity of the longest lasting component. This implies that the window is still usable until the last part has failed. The information in this report was illustrated graphically with no exact figures provided.

Kiani et al. (2004) considered the manufacture of fully glazed curtain walls and the use-phase energy effects of tinted and reflective glass. The embodied energy was established for glass manufacturing, with published figures considered ranging from 12 to 31 GJ/ton with sealed unit assembly data adopted from Weir and Muneer (1998). The cradle to grave life cycle inventory indicated that 21.1% of total energy was used to manufacture, assemble and ship the units with the remainder attributable to energy loss in a 25 year simulated service life in London. Low E glass and insulated glazed units reduced the operational energy requirements of the structure by 53%, which far outweighed the increased manufacturing energy, a savings of 9,826 GJ against an increase of 1,536 GJ.

Recio et al. (2005) performed a recent LCA of several window systems common to Spain. Life cycle inventory values, embodied energy, and CO_2 emissions, were found for the production of the following windows:

- PVC With Double Glazing
- Aluminum with Double Glazing (without break)
- Aluminum with Double Glazing (with break)
- Wooden with Double Glazing
- Wooden with Single Glazing

The embodied energy of the wood window was found to be 74.5 kWh, 253.6 for PVC with no recycling, and 1,981.1 for virgin aluminum. Although the wooden framed window was shown to have the lowest embodied energy of the three materials considered, the analysis assumed greater conductivity of the wood frame than the PVC that outweighed the benefits in the manufacturing stages. Aluminum was found to have the highest manufacturing energy requirements and the highest conductivity (and subsequent energy use) during the use phase. The total energy requirements over the life cycles for the three window types were 1,780 kWh for PVC with no recycling, 2,633 kWh for wood, and 3,819-4,413 kWh for non-recycled aluminum, depending on whether a thermal break was used.

Syrrakou et al. (2005) established life cycle inventory values for the manufacture of an electrochromic device, a technology that uses a low-voltage switch to tint the glazing unit and thus vary light transmission characteristics. The authors demonstrated that the increase in manufacturing energy required to produce an electrochromic sealed unit, 49 MJ against 42 MJ, was far surpassed by the potential energy savings of the device. In fact, it was estimated that the energy pay-back period was less than two years and that the unit saved 52% of total energy requirements, or more than 33 times the energy required for its manufacture (Syrrakou et al. 2005).

3.5 Summary

In all LCAs that considered frame materials, wood had lower embodied energy than the market alternatives, PVC and aluminum (Asif et al. 2002, Menzies and Muneer 2003, Citherlet et al. 2000, Recio et al. 2005). Moreover, PVC suffers from the fact that numerous toxic chemicals are required in its manufacturing and may be released at the end of its life (Asif et al. 2002). The uncertainty of these releases and their effects has caused controversy over any claim that PVC is either a superior or inferior material through LCA.

The inclusion of use-phase energy amounts has been used to show the relative insignificance of frame production (Entec 2000) and to justify increased resource use in manufacturing with improved energy performance during occupancy (Kiani et al. 2004), (Syrrakou et al. 2006, Asif et al. 2002, Citherlet et al. 2000). The inclusion of use-phase energy in the LCA uses many specifications such as the placement of windows in a structure and its geographical location, and may be completed as various cases in conjunction with a material-based LCA performed at the economy scale.

Of the LCAs described thus far, none considered designs specific to the North American market place or ones made of fiberglass frames.

CHAPTER 4: GOAL AND SCOPE

The primary goal of the life cycle assessment performed in this thesis was to evaluate and compare the environmental impacts of windows made from aluminium clad wood, PVC and fiberglass for the North American residential market. In all previous LCAs that considered frame materials, wood was identified as having lower embodied energy than its market alternatives, PVC and aluminum (Asif et al. 2002, Menzies and Muneer 2003, Citherlet et al. 2000, Recio et al. 2005). However, no LCA has yet been published that considered designs and manufacturing practice specific to North America, nor has an LCA been completed on windows made of fiberglass frames.

It is recognized that despite the inherent limitations of conducting an LCA based on a case study, the results will serve as a benchmark for North American window production. Thus, the design of the study and the communication of results are critical so that the information requirements may be met while the methodology used to arrive at those results and their sensitivity to uncertain modeling decisions is clear.

4.1 Functional Unit

The investigation into a product system requires first identifying a unit of economic service that can be defined in quantitative terms, and in the case of comparative assessment, the same as that of another product. This necessitates the recognition of all processes and materials that are required to provide a service of comparable value. For instance, a window with a more frequent replacement is not directly comparable with one with a longer service life. This results from the recognition that the service of a window is reliant on its installation in a sealed structure.

The most common window produced in North America is the awning/casement variety. This fact was validated through consultations with the three subject manufacturers. It was also determined that a window, 600mm wide by 1200mm high, was a suitable representative size. The other standard options included: double glazed sealed unit with Low E glass, standard frame depth, and operable hardware.

The functional unit required a unit of time to further define the service in a building. CORRIM, the Consortium for Research on Renewable Industrial Materials, recently conducted studies of housing stocks to determine the average house life in North America. They concluded that the average service life of a house was at least 75 years and used this for their analysis (Winistorfer et al. 2005). This research will also adopt this assumption for the service life of a building.

The formal declaration of the functional unit is:

- **Size:** 600 mm x 1200 mm
- **Style:** Casement
- **Glazing:** Double glazed sealed unit with Low E glass
- **Frame Profile:** Standard frame profile for North American market
- **Operable:** Operable
- **Length of Service:** 75 years
- **Maintenance:** Sealed Unit Replacements and Recaulking

4.2 Scope, Focus, and System Boundaries

The LCA study included all life stages from raw material extraction and commodity manufacturing to product manufacturing, installation, maintenance and disposal at the end of life Figures 4.1, 4.2 and 4.3 show the process diagrams of aluminum clad wood, PVC and fiberglass windows, respectively. Transportation was considered for all materials up to the point of installation. Trucking the used windows to the municipal waste treatment site was ignored as this distance and subsequent burden is a small component of the total transportation in the life cycle and is the same for all window types.

The focus of the data collection in this LCA is on the manufacture of the three windows. This provides not only a bill of materials, emissions, and resource use for the production of a window, but also provides a point of investigation to the upstream effects of commodity manufacture. Direct assessment of the inventory values for the manufacturing phase is required in this case and was achieved through direct measurement and multiple-output allocations of the flows occurring at a representative manufacturer of each window type. While specific inventory values were gathered for manufacturing, published data were used for the completion of the life cycle inventory. These datasets represent the current manufacturing processes used to supply the three manufacturers. Unfortunately, many of the published inventory values are specific to Europe or include different processes than the particular material that is under consideration here. As the data for the frame materials themselves are the most critical to the stated goals of the project, these were adopted most carefully to the modeled case while those common to all windows may be imperfect in their representation while still

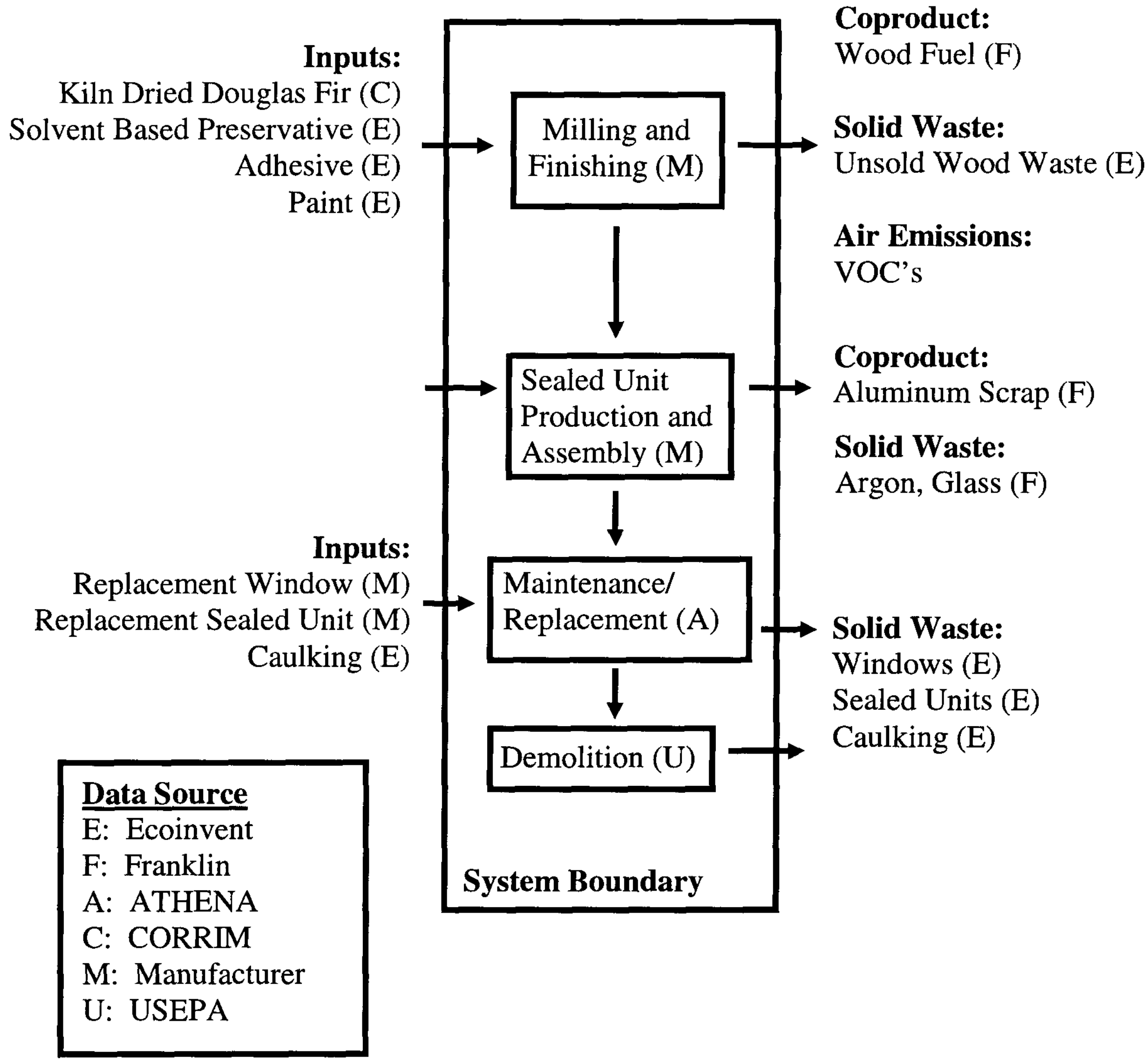

Figure 4.1: Aluminum clad wood window product system

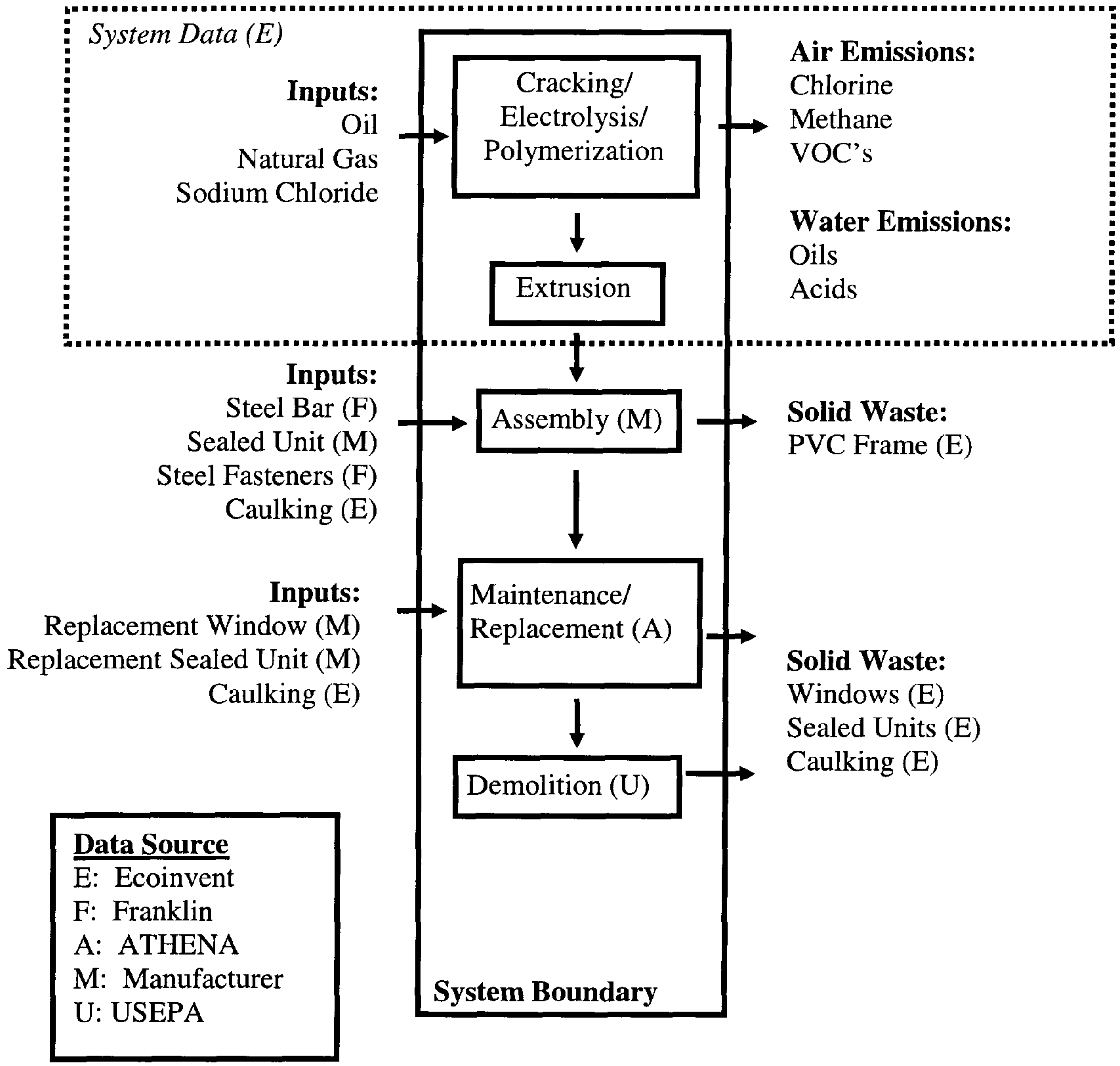

Figure 4.2: PVC window product system

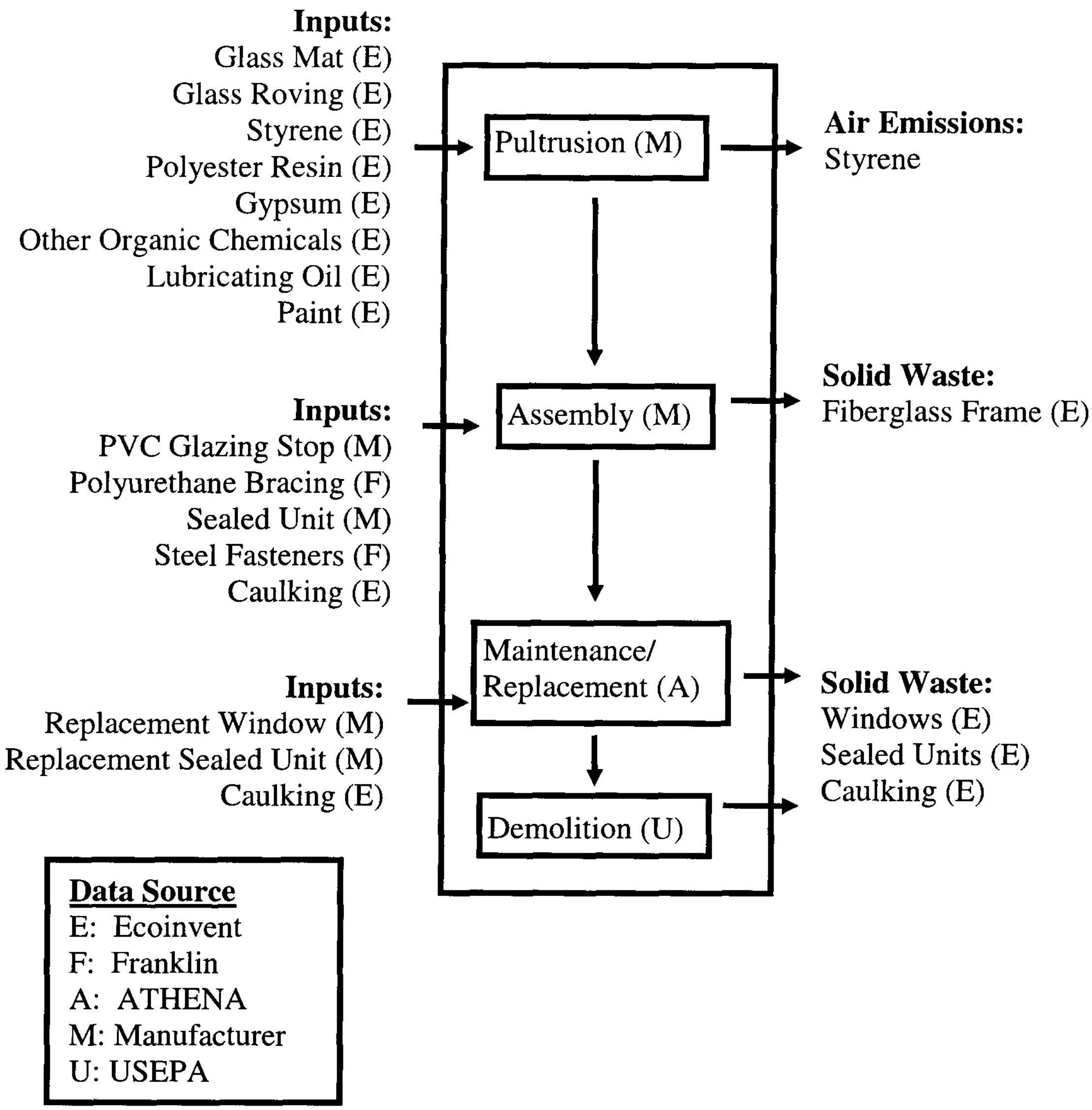

Figure 4.3: Fiberglass window product system

showing relative significance of the various components. The adaptation of foreign data sets to the North American model is described in Chapter 5.

The model that will be developed only represents some of the processes affected by the decision of selecting one type of window. This is clear when one considers that all of the machines that lead to window manufacture also undergo complex life cycles and production emissions. Ignoring these "third order" processes, like infrastructure manufacture, is required in this LCA so efforts may be focused on the processes most critical in determining impacts.

In establishing the LCI, it is also necessary to determine the boundary of the product system to the natural environment, the point at which the flows are considered external to the product system. The boundaries with nature in this case are the point at which the material is extracted from its natural state and the end state after waste management has commenced. This is a straightforward assumption for non-agricultural products, but raises questions as to the definition of a forest as a manufacturing system. To resolve this issue, the carbon sequestered by the growing forest and flux to this system caused by the logging in the wood window product system will be included in the sensitivity analysis and reported alongside the results.

4.3 Sima Pro

Conducting an LCA on a complex product requires a software tool to assist in the calculation of the LCI and LCIA. This is necessary for calculating the process flows that represent the window product system and the impacts caused by the numerous inventory values that are established. Sima Pro was selected to complete this LCA as it serves both purposes.

Sima Pro was developed by Product Ecology Consultants[2], PRe, and automates much of the calculation process. To build a cradle to gate product system in Sima Pro, the practitioner relates the production of a material assembly to the processes that its constituent materials must undergo to arrive at that state. This involves the selection of process trees, nonlinear product chains, which represent the product system.

Sima Pro comes packaged with numerous data sets and accepts the addition of alternative data published in a standard format, Spold and EcoSpold, or the generation of new processes based on entered values. Sima Pro is also sold with several sets of life cycle impact characterization factors. These automatically recognize materials from the life cycle inventory and group into categories of similar impact. The results are reported in the units of the characterization. Sima Pro allows investigation as to the influence of individual processes and data sets by automating calculations and exporting results in tabular form.

---

[2] www.pre.nl

CHAPTER 5: LIFE CYCLE INVENTORY

The Life Cycle Inventory was established through the use of numerous data sources that were selected in accordance with the focus stated in the goal and scope definition. Specific manufacturing inventory values were gathered at the three window manufacturers, with the bill of materials used to trace resources upstream to their origins in the natural system. It was determined that generic data was acceptable for modeling energy generation, transportation, and commodity manufacturing processes. The ATHENA Sustainable Materials Institute was consulted for assumptions regarding maintenance and replacement.

5.1 Secondary Manufacturing Material Inventory

The three manufacturers that were visited not only utilized different materials, but also employed varying degrees of vertical integration in their practices. The wooden window producer purchases sheet glass and spacers to make sealed units while neither of the other two manufacturers produce sealed units in their facilities. For this reason, the sealed unit manufacturing inventory from the wood window manufacturer was used to provide data for those companies that outsourced this component.

Each manufacturer generated solid waste. Unless otherwise specified, all solid waste is assumed to enter the municipal waste stream. The fate of these materials is described in Section 5.6.

5.1.1 Aluminum Clad Wood Window Manufacturer

The selected wood window manufacturer produces a high volume of aluminum clad wood windows, 198,000 in 2004, from unplaned kiln dried Douglas fir. Wood was one of several materials that were used to produce a wooden lineal, an uncut frame or sash profile. Preservatives, adhesives, paint, fasteners, and hardware were also used. Table 5.1 shows the amounts of each material that are required to produce one aluminum clad wood frame.

Table 5.1: Material Inputs in the Production of one 600mm x 1200mm Aluminum Clad Wood Window Frame

INPUTS	UNIT	AMOUNT
Kiln-Dried Douglas Fir	m^3 (kg)	0.07 (28.25)
Spirit-Based Preservative	l (kg)	0.37 (0.29)
Formaldehyde Adhesive	kg	0.15
Paint	l (kg)	0.24 (0.30)
Aluminum	kg	2.729
Polypropelene	cm^3 (g)	111.63 (118.33)
Thermoplastic Elastomer	cm^3 (g)	95.45 (92.11)
Steel (Operator)	Kg	1.79
Steel (Fasteners)	Kg	0.16

Several air emissions and solid wastes were generated through the use of these materials. Wood waste was produced from shaping a frame out of rough lumber and was collected in a bagging system. A small portion of this, 10g, was emitted as sawdust. The remaining wood waste was either burned during winter months for heat, or bagged and sent to a municipal landfill.

Aluminum waste was also generated by cutting the cladding pieces to length. A portion of this waste was recycled with the majority going to the municipal landfill. The amounts that were sent to recyclers were modeled by giving a credit to that emission in the amount of the difference between the virgin system and recycled system. This expands the boundary to include the recycled material as an economically valuable co-product. It was learned through discussions with APEL, an aluminum extruder, that recycled aluminum was suitable for construction cladding and thus the recycling assumes no material degradation.

Emissions were also caused by the use of preservatives and adhesives that contain volatile organic compounds released during drying. The emissions to air are shown in Table 5.2 while the solid wastes are shown in Table 5.3.

Table 5.2: Air Emissions Caused by the Production of One 600mm x 1200mm Aluminum Clad Wood Window Frame

AIR EMISSIONS	UNIT	AMOUNT
Phenol	g	1.43
Formaldehyde	g	1.43
Other Hydrocarbons	g	0.27
2-Heptanone	g	11.47
Carbamic acid	g	1.43
Paraffins	g	257.6
Saw dust	g	10

Table 5.3: Solid Waste Caused by the Production of One 600mm x 1200mm Aluminum Clad Wood Window Frame

SOLID WASTE	UNIT	AMOUNT
Wood waste	kg	4.96
Wood fuel	kg	15.09
Aluminum recycled	kg	0.737

The production of sealed units at this facility makes use of specialized machinery that holds the glass sheets in separation with an aluminum spacer bar, injects the unit with argon gas, and seals the gas inside with polysulphide and polyisobutyl sealants. Waste is generated from the cutting of glass sheets to size, bending and cutting aluminum spacer bars, and argon that escapes when the cavity is flushed prior to being sealed. A small amount of desiccant is also mixed with the spacer bar scrap. The glass scrap is sent back to the producer for use in reflective street paint and was not considered in this model. The remaining wastes enter the municipal waste stream. The amounts of each material used to produce a finished sealed unit are provided in Table 5.4 with all solid waste that is generated shown in Table 5.5.

Table 5.4: Material Input in the Production of one 0.48 m^2 Double Glazed Sealed Unit for use in a 600mm x 1200mm Casement Window

INPUTS	UNIT	AMOUNT
Glass	m^2	1.04
Argon	m^3 (kg)	0.106 (0.189)
Polysulphide	L (kg)	0.18 (0.317)
PIB	g	3.9
Aluminum	g	124.9
Desiccant	g	168

Table 5.5: Solid Waste Caused by the Production of one 0.48 m^2 Double Glazed Sealed Unit for use in a 600mm x 1200mm Casement Window

SOLID WASTE	UNIT	AMOUNT
Glass	m^2	0.08
Argon	m^3 (kg)	0.100 (0.179)
Aluminum	g	12.7
Desiccant	g	1.1

5.1.2 PVC Window Manufacturing

The PVC window manufacturer that participated in this assessment produced much lower volumes than the wood producer, 16,276 windows in 2004, and outsourced production of sealed units and PVC lineals. The operations at this facility were the cutting to length of the PVC lineals and steel reinforcement bars, and assembly with sealed units, steel hardware and fasteners, and weatherstrip. The only waste was generated from the steel and PVC cutting and was sent to municipal landfill. Table 5.6 and Table 5.7 show the material inputs and solid waste that was generated by the PVC window producer.

Table 5.6: Material Input in the Production of one 600mm x 1200mm PVC Casement Window

MATERIAL INPUT	UNIT	AMOUNT
PVC	kg	7.09
Steel (Reinforcement)	kg	6.26
Steel (Fasteners)	g	80
Steel (Operator)	kg	1.83
Weatherstrip	g	183.26
Finished Sealed Unit	m^2	0.48

Table 5.7: Solid Waste Caused by the Production of one 600mm x 1200mm PVC Casement Window

SOLID WASTE	UNIT	AMOUNT
PVC	kg	0.44
Steel (Reinforcement)	kg	0.16

5.1.3 Fiberglass Window Manufacturing

The fiberglass manufacturer that participated in this research produced fiberglass pultrusions and pultrusion machinery in house, while supporting these businesses with small scale window assembly. Their total production of windows in 2004 was similar to that of the PVC manufacturer, roughly 20,000. The fiberglass pultrusion lineals were assembled with purchased sealed units.

Fiberglass lineals are composed of glass roving and mat, polystyrene resins, and fillers and are heat cured. This process liberates 5.5% of the used styrene which is emitted to the air. The finished lineal contains roughly 60% glass (40% roving/20% mat), 10% gypsum filler, and 30% polystyrene. The exact inputs of these materials are a trade secret held by the manufacturer and are not disclosed in this document. The glass mat contains 100% recycled A-glass from light bulbs.

A finished fiberglass frame consists of fiberglass lineals, polyester bracing in the corners, and a PVC glazing stop. Waste is generated from the cutting of lineals and the glazing stops to length. Table 5.8 shows the material inputs for the pultrusion and assembly processes while the air emissions and solid waste are shown in Tables 5.9 and 5.10, respectively.

Table 5.8: Material Input in the Production of one 600mm x 1200mm Fiberglass Casement Window; approximate values for pultrusion materials are provided in this document while the precise amounts were used to create the LCI model.

MATERIAL INPUT	UNIT	AMOUNT
Textile Glass (Roving)	kg	~ 2.8
Textile Glass (Mat)	kg	~ 1.4
Polystyrene Resin	kg	~ 2.1
Calcium Carbonate	kg	~ 0.7
PVC	g	497
Polyester	g	370
Finished Sealed Unit	m^2	0.48
Steel (Operator)	kg	1.88
Steel (Fasteners)	g	88

Table 5.9: Air Emission Caused by the Production of one 600mm x 1200mm Fiberglass Casement Window

AIR EMISSION	UNIT	AMOUNT
Styrene	g	112

Table 5.10: Solid Waste Caused by the Production of one 600mm x 1200mm Fiberglass Casement Window

SOLID WASTE	UNIT	AMOUNT
Fiberglass Pultrusion	g	486
PVC	g	8

5.2 Secondary Manufacturing Energy Use

The energy amounts for the manufacturers were reported as cumulative values to the entire facility. These required allocation based on the perceived causation of that energy use by the production of a single window. The following is a description of energy allocations and adaptations of surrogate data when allocation was impossible.

5.2.1 Wood Window Manufacturing Energy

The wood window manufacturer uses three forms of energy at their facility; wood waste is burned for heat in the winter months; natural gas is used to supplement the wood heat; and electricity is used for lighting and powering machinery. The manufacturing plant consists of several departments that occupy different portions of the floor space. These are:

- Wood Milling, Shaping, and Lineal Production: 33%
- Assembly: 25%
- Offices, Shipping, and Receiving: 17%
- Sealed Unit Production: 25%

No data were available that considered the amount of energy used in each part of the facility. This does not affect the determination of heating by department as this was simply based on the relative floor space and corresponding air volume. An assumption was made that the electricity was also used evenly across the facility. This introduces uncertainty in that the machinery used varies in consumption and would skew this result. However, the lighting is assumed to be a large contributor to electricity use and would act to smooth out differences caused by machinery consumption. A typical North American manufacturing facility annually requires 64.5 MJ light for every 1 m^2 space (USDOE

2006), which accounts for 35,501 GJ of the total 48,781 GJ electricity that is consumed (73%). The breakdown of total energy values for the three departments is found in Table 5.11.

Table 5.11: Energy Use for Each Department at the Wood Window Manufacturer – Cumulative Values

DEPARTMENT	WOOD (GJ)	NATURAL GAS (GJ)	ELECTRICITY (GJ)
Lineal Production	21804	2091	16260
Assembly	16353	1568	12195
Overhead	10902	1046	8130
Sealed Unit	16353	1568	12195
Total	65412	6273	48781

The contribution to total energy use by a single window varies in each of the departments and the allocation used for each is based on this. The allocation for the wood lineal production was based on the amount of wood used to make a window, 28.25 kg, compared to the total wood use in 2004, 11,700 tons (allocation factor: 2.41×10^{-6}). Assembly processes include cutting lineals to length, installing hardware, and placing the sealed unit in the frame. These processes are the same for windows of any size and thus the allocation was based on the quantity of windows produced (allocation factor: 5.04×10^{-6}). To allocate the overhead energy use, the sales value of one single window, $ 500 CAD, was considered against total sales in 2004, $ 139 million CAD (allocation factor: 3.59×10^{-6}). The main processes in the sealed unit department are the cutting of glass to size and sealing of the unit after being injected with argon gas. The allocation was based on the perimeter of a 0.48 m^2 sealed unit, 3030 mm, against the total perimeter of all sealed units produced in 2004, 896.3 km (allocation factor: $3.38 \times 10\ 10^{-6}$). The result of these allocations for a single window is shown in Table 5.12.

Table 5.12: Energy Use for the Production of one 600mm x 1200mm Aluminum Clad Wood Casement Window – Allocation by Department Based on Processing Assumptions Described in Main Text.

DEAPARTMENT	ALLOCATION BASIS	WOOD (MJ)	NATURAL GAS (MJ)	ELECTRICITY (MJ)
Lineal Production	Wood Use	39.3	5.1	39.3
Assembly	Quantity	82.5	7.9	61.5
Overhead	Economic	39.2	3.8	29.2
Sealed Unit	S.U. Perimeter	55.3	5.3	41.2
Total		229.6	22.0	171.2

As the material inventory flows were adapted for the sealed unit production in the model of the PVC and fiberglass window life cycles, the energy required to produce a sealed unit was adapted as well. To adapt this data, a portion of the overhead energy use, 25%, was attributed to the production of a sealed unit. Also, since a typical sealed unit manufacturer does not burn wood waste, the energy from this fuel was assigned to natural gas. Table 5.13 shows the energy use required to make a sealed unit that was used to complete the manufacturing inventory of the other two window types.

Table 5.13: Energy Used for the Production of one 0.48 m^2 Double Glazed Sealed Unit for use in a 600mm x 1200mm Casement Window

PROCESS	NATURAL GAS (MJ)	ELECTRICITY (MJ)
Sealed Unit	60.6	41.2
Sealed Unit Overhead	10.7	7.3
Total	71.3	48.5

5.2.2 PVC Window Manufacturing Energy

The PVC manufacturer purchases natural gas to heat the facility and electricity to operate the machinery and lights. In 2004, this producer used 2059 GJ of natural gas heat and 1758 GJ of electricity. The energy allocation for the PVC manufacturer was less complex because fewer operations occured there. The only two departments at this facility are the assembly area and a small showroom and offices. Sales data was not available for this manufacturer and thus prohibited the use of an economic allocation to calculate energy allocation for the offices. Instead, the energy was allocated by quantity in a similar fashion to the assembly processes at the wood manufacturer. The allocation was based on the quantity of windows produced (allocation ratio: 6.14×10^{-5}).

Table 5.14 shows the energy required to produce a single window at the facility. This table also includes the sealed unit manufacturing energy that was adapted from the wood manufacturer. The energy required to produce PVC lineals was captured in the process inventory data that was used in the model and is not shown in the table.

Table 5.14: Energy Use for the Production of one 600mm x 1200mm PVC Casement Window

PROCESS	NATURAL GAS (MJ)	ELECTRICITY (MJ)
Allocated Energy Use	126.5	108.0
Sealed Unit	71.3	48.5
Total	197.8	156.5

5.2.3 Fiberglass Window Manufacturing Energy

The fiberglass window manufacturer also heats their facility with natural gas while purchasing electricity to power lighting and machinery. In 2004, they purchased 4,500 GJ of natural gas and 4,129 GJ electricity. The facility consists of the following four departments:

- Pultrusion: 25%
- Assembly: 40%
- Offices, Shipping, and Receiving: 15%
- Machine Shop: 25%

The total number of windows produced at this facility in a given year was unavailable. The variation of business practice by this producer also made impossible the allocation based on sales data. Energy values for assembling the window were adopted from the PVC manufacturer while the pultrusion energy was calculated based on a physical allocation.

To calculate the energy allocation for the pultrusion, it was estimated that half of the overhead energy is attributable to the production of lineals. This raises the total to 33% of the total energy used by the facility. This manufacturer produced 1670 km of pultrusions in 2004, of which 7.7 meters were required for the 1200 x 600 window (allocation factor: 4.61×10^{-6}). The result of this allocation is shown in Table 5.15.

As mentioned above, adopting the energy values from the PVC manufacturer was required due to lack of relevant data. The assembly of a fiberglass window is nearly identical to the assembly of one made of PVC, with the exception that the PVC window requires cutting steel reinforcement bars to length. Also, the scale of operations at the fiberglass manufacturer was similar to that of the PVC producer which indicates that variation due to economies of scale is minimal. While the electricity could be adopted directly, the heating fuel value was scaled based on the climates of the two locations. A unit of measure called heating degree days was used to create a ratio of heat requirements in the two locations. The metric is based on the intensity and duration of temperature drops during an average winter. Every time the temperature drops below a threshold temperature, typically 18° C, fuel must be burned to accommodate for the lost heat. The number of heating degree days is the antiderivative of the following function with the integrands assumed as a period of time, typically reported as a monthly and annual weather statistic.

$$\int_{0}^{T} y = (18 - temp) * Time$$

The fiberglass facility required 1.39 times the number of heating degree days as the PVC facility and thus the natural gas values were scaled accordingly. The adoption of this data from the PVC supplier is shown in Table 5.15.

Table 5.15: Energy Use for the Production of one 600mm x 1200mm Fiberglass Casement Window

PROCESS	NATURAL GAS (MJ)	ELECTRICITY (MJ)
Pultrusion	20.8	24.2
Adapted Assembly and Overhead	175.9	108.0
Sealed Unit	71.3	48.5
Total	268	188.4

5.3 Commodity Manufacture and Background Processes Inventory

The manufacturing inventory was used to recognize materials and processes that occurred upstream and required modeling. As was stated in the scope definition, this LCA adopted published life cycle inventory values for the production of commodity materials and background processes like transportation and energy production. Sima Pro comes packaged with two accompanying databases that were used to model the cradle to gate processes; these are Franklin 98 and ecoinvent. Descriptions of these databases, along with the CORRIM data on softwood lumber production that was used for the wood data, follows:

Franklin 98 (Norris et al. 2003): *Steel, Aluminum, Styrene, Butadiene Rubber, Heat from Natural Gas, Electricity, and Transportation*

The Franklin US LCI database was published by the Franklin Associates consulting firm and is based upon a variety of sources. The data are primarily from companies and other private sources, with public data used for commodity materials that frequently are not purchased from a specific source. The data are based on USA averages and USA electricity grids, pollution controls and solid waste practices. Both virgin and recycling systems are specified for each material, or recycling is included at average USA levels.

ecoinvent (Frischknecht et al. 2005): *PVC, Float Glass, Paint, Wood Preservative, Adhesive, and Desiccant*

The ecoinvent LCI database was published by the Swiss Center for life cycle inventories and was based on the market (and consumption) situation in Switzerland in the year 2000. As Switzerland's economy is closely related to those in the region, much data also pertains to Europe in general. Natural resources obtained from outside Europe are also included. In most cases, the data represents production using average technology.

CORRIM (Puettmann and Wilson 2005): *Wood*

In 2004, CORRIM, the Consortium for Research on Renewable Industrial Materials, published life cycle inventory values for the cultivation (including fertilization and preliminary thinning), harvesting, transportation, milling, and kiln drying of softwood lumber. This data included modules specific to the Pacific Northwest and the Southeast regions. The cradle to gate LCI of Pacific Northwest production was chosen as this reflects the materials purchased by the wood window manufacturer. The pre-logging forestry inventory values were removed from the values used in this LCA as the system boundaries for the other data sets exclude processes occurring prior to resource extraction.

While the processes that were deemed not as critical to the goals of the LCA were adopted outright, those specific to frame materials were altered to best match the North American window product system. The following describes the adaptations that were made to these data:

Wood: CORRIM reported values for planed kiln-dried lumber. The wood manufacturer purchases lumber that is rough cut. The process inventory values for the planing were subtracted out of the inventory. Also, the carbon sequestration assumed in CORRIM life cycle assessments was not introduced as an inventory value in the cradle to gate manufacturing.

Glass Fibers: These data was based on the Integrated Pollution Prevention and Control, IPPC, (2001) reference document on best available techniques in the glass manufacturing industry. This data included inputs from the European energy grid that were replaced with values specific to North American production. Also, the dataset reported elevated values for releases of cadmium, arsenic, and antimony, that were based on emissions limits in the Netherlands at the time the ecoinvent data was published. These values were replaced by those found in IPPC (2001) under the assumption that the fiberglass producers utilize either an electrostatic precipitator or bagging system, common practices in the industry for mitigating such releases.

PVC: The PVC data that was published by ecoinvent is based on the Association of Plastic Manufacturers in Europe, APME, reports released in the mid-1990's. ATHENA adopted this same dataset for use in the Environmental Impact Estimator as this is the only published data that is specific to suspension polymerization, the type used to make construction-grade cladding and window profiles. The ecoinvent data is specific to calendaring, the process used to finish pipes. Similar to ATHENA, the data that was used, subtracted values for calendaring and added values for extrusion, while substituting North American energy values for the European ones in the dataset.

5.4 Transportation

Transportation and energy use was included in the datasets for all processes up to the point of manufacture. This introduces uncertainty to the results as several materials were represented by European values that may vary from North American practice. Transportation of commodity materials to the window manufacturers was modeled based on average commodity transportation distances published by Statistics Canada (Statcan 2000, Statcan 2002, Statcan 2003). This data is shown in Table 5.16 and the distances assumed for each window component in Table 5.18. The sensitivity of these assumptions was tested by considering the transportation distances from the suppliers specific to the sampled manufacturers. Table 5.18 also contains the calculated load for trucking the window from the manufacturer to the installation site. The transportation load is a function of weight and distance with the reference unit tkm standing for one ton kilometer, or the load for moving one ton of material one kilometer. The total inventory values for transportation are provided in Table 5.17 for each of the three windows.

Table 5.16: Average Trucking Distances for Commodities to Secondary Manufacturer

MATERIAL	AVERAGE DISTANCE (km)
Glass[3]	563.2
Steel bar[4]	516.8
Lumber[3]	518.9
Crushed stone[5]	106.6
Other chemical products and preparations[3]	376.4
Inorganic chemical[3]	372.3
Pipes, tubes, and fittings of base metal[3]	404.8
Rubber articles[3]	330.3
Man made fibers and plastic basic shapes[3]	715.9

Table 5.17: Transportation Loads for Materials to the Manufacturer and Installation Site

TRANSPORTATION INPUTS	LOAD (tkm)
Aluminum Clad Wood	
Raw Materials to Manufacturer	76.9
Finished Window to Installation Location	11.5
Total Window Load	88.4
PVC	
Raw Materials to Manufacturer	24.9
Finished Window to Installation Location	12.7
Total Window Load	37.6
Fiberglass	
Raw Materials to Manufacturer	18.8
Finished Window to Installation Location	9.7
Total Window Load	28.5

[3] StatCan 2003
[4] StatCan 2002
[5] StatCan 2000

Table 5.18: Transportation Distances and System Loads from the Commodity Manufacture to the Window Producer and from the Manufacturer to the Installation Site – Individual Components and Finished Window

MATERIAL	AMOUNT (kg)	DISTANCE (km)	LOAD (tkm)
PVC Frame			
Steel Bar	6.3	517	3.2
PVC	7.5	716	5.4
Fiberglass Frame			
Glass Fiber	~4.3	716	~3.1
Polystyrene Resin	~2.1	372	~0.8
Other Organic Chemicals	~0.3	376	~0.1
Gypsum Filler	~ 0.7	107	~0.07
Clad Wood Frame			
Wood (Clad)	28.25	519	14.66
Aluminum Cladding	2.73	405	1.105
Common Frame			
Steel Hardware	1.8	405	0.729
Steel Fasteners (PVC & Fiberglass)	0.08	405	0.032
Steel Fasteners (Wood)	0.16	405	0.065
Caulking	1.37	376	0.514
Sealed Unit			
Glass	7.76	563	4.368
Aluminum Spacer	0.125	405	0.051
Argon	0.19	372	0.070
PIB Sealant	0.35	330	0.114
Weatherstrip	0.28	330	0.091
Sealed Unit	7.8	563	4.391
Finished Window			
Clad Wood Window	20.44	563	11.51
PVC Window	22.48	563	12.66
Fiberglass Window	17.23	563	9.70

5.5 Use Phase and Service Life Inventory

The use phase length is the predicted service life of the complete structure. This value was adopted from CORRIM's recently published LCI research on the average service life of North American residential buildings, 75 years (Winistorfer et al. 2005). The assumptions regarding use phase sealed unit failure, caulking replacement, and service life were taken directly from the document "Maintenance, repair, and replacement effects for building envelope materials", published by the ATHENA Sustainable Materials Institute and prepared by Morrison Hershfield Consulting Firm. The data produced by Morrison Hershfield made use of their numerous branches across North America that allowed the inclusion of region specificity. As no installation location was assumed in this LCA, the average value was assumed in each case with the variation due to specific regions included in the sensitivity analysis.

The expected service life is one fundamental assumption in this model. ATHENA's data includes estimates for PVC, wood and aluminum windows, but did not consider aluminum clad wood or fiberglass. The expected service life of an aluminum window was assumed to be the same as fiberglass and aluminum clad windows, 25 years. Asif et al. (2002) similarly concluded that aluminum clad wood windows closely followed the service life of aluminum windows. Fiberglass windows are suitable for commercial installation and offer lengthy warranties which indicate that the 25 year estimate is accurate for these as well. The service life for PVC windows was shorter than the other two, 18 years. The PVC windows installed in North America are typically the lowest cost option and are most commonly replaced for poor performance such as binding and allowing air and water infiltration. The resulting number of installed windows in the default case is 3 for aluminum clad wood and fiberglass, and 4.17 for PVC.

The caulking in an installed window requires periodic replacement. The caulking is replaced once every 10 years and is not affected by the choice of window frame material. As new windows are installed with fresh caulking, it follows that the more frequent replacement of PVC windows reduces the intermediate caulking that is required; the PVC life cycle requires caulking replacement 4 times compared to 4.7 for fiberglass and wood. It should be noted that the caulking replacement also incurs a transportation that is the same as for installing a new window.

Sealed units also fail independent of the type of frame that is used. It was estimated that sealed units fail on average 3% per year, which averages to once every 33 years of the life cycle. The sealed unit failure is independent of the age of the unit and was thus not affected by the replacement frequency as was the caulking. All three life cycles require 2.25 sealed unit replacements.

A summary of all cradle to gate assumptions is shown in Table 5.19. The use phase life cycle inventory was calculated based on these assumptions. Inventory values included the transportation, material inputs, and solid waste. These are shown in Table 5.20 for materials and transportation and Table 5.21 for solid waste. The solid waste include the disposal of each window that is in the life cycle as well as the replacement caulk and sealed units. The assumptions regarding the treatment of window waste are described in the next section.

Table 5.19: Maintenance and Service Life Assumptions

WINDOW TYPE	SERVICE LIFE (yrs)	CAULKING REPLACEMENT (yrs)	GLAZING REPLACEMENT (%/yr)
Al Clad Wood	25	10	3
PVC	18	10	3
Fiberglass	25	10	3

Table 5.20: Use Phase Transportation and Material Inventory

INPUTS	LOAD (tkm)
Aluminum Clad Wood	
Sealed Units (2.25)	9.9
Caulking (4.7)	2.4
Total Use Phase	13.3
PVC	
Sealed Units (2.25)	9.9
Caulking (4)	2
Total Use Phase Load	11.9
Fiberglass	
Sealed Units (2.25)	9.9
Caulking (4.7)	2.4
Total Use Phase Load	13.3

Table 5.21: Solid Wastes Sent to the Waste Stream in End of Life Phase

SOLID WASTE	MASS (kg)
Aluminum Clad Wood	
Sealed Units (2.25)	17.6
Caulking (4.7)	6.4
Windows	61.3
Total	85.3
PVC	
Sealed Units (2.25)	17.6
Caulking (4)	5.5
Windows	93.7
Total	116.8
Fiberglass	
Sealed Units (2.25)	17.6
Caulking (4.7)	5.5
Windows	51.7
Total	74.8

5.6 Waste Treatment Assumptions

The materials consumed during the manufacturing, use, and disposal of the window all enter the waste stream at the end of their useful life with exception of the aforementioned recycled aluminum and burned wood waste. It was assumed that all materials entered the municipal waste stream. The delivery of window waste to the waste treatment facility was ignored because this value is insignificant compared to the transportation in previous life stages.

5.6.1 Recycling Potential

It was determined that none of the materials used in North American residential windows were likely recovered for recycling. Recycling of windows is hindered by the realization that "health and safety considerations and pressures on speed of site clearance have transformed the demolition industry into a low labor, very high machine usage mode of operation that militates against the separation of low value materials" (SCI 2003). For this reason, recycling is more likely during the disposal of used windows during use phase replacement. The particular issues associated with recycling each of the primary materials in windows is provided below.

Wood: Wood waste from the disposal of durable goods, like buildings, is recycled at a rate of less than 0.05 percent (USEPA 2006a) in the United States. Wood is also considerably more likely to be recycled at the construction phase rather than the demolition phase as the separation is not as costly (USEPA 1997). Widespread disassembly of windows to recover the relatively small amount of wood in a window frame is unlikely.

Aluminum: Aluminum waste in durable goods is also recycled at a rate of less than 0.05 percent in the United States (USEPA 2006a). This is despite the fact that recycled aluminum may be used to produce high quality products such as construction grade cladding. The challenge and unlikelihood of disassembly led to the assumption that aluminum was not recycled although the sensitivity of this assumption was tested.

PVC: PVC waste is not typically recycled. No specific data are available on PVC recycling rates in North America, although plastics as a group only have a recovery rate of 4.2% (USEPA 2006a) while in Europe, where PVC recycling is tracked, only 3% is recycled (PE Europe 2004). In the EU, "post-consumer PVC recycling consists mostly of cable and packaging waste. Cable recycling and a considerable part of packaging recycling is mixed plastic recycling, hence, only recyclates of low commercial value are produced." (PE Europe 2004) The low rate of recycling and quality of material after recovery led to the assumption that no PVC was recycled.

Fiberglass: No specific data are available for the recycling rate of fiberglass reinforced plastic. It is assumed that it is not recycled in significant amounts considering the lack of recycling plastics as an average and the fact that polystyrene is a thermosetting plastic and can not be melted into usable resins. While some producers of the material have purchased granulating equipment to reduce the plastic into usable filler material, the manufacturer in this case did not, and it is assumed to be even less likely that a window would be disassembled to reclaim a small amount of filler.

Glass: Glass contained in durable goods is recycled in negligible amounts, less than 0.05 percent (USEPA 2006a). This is due in large part to the fact that this type of glass is considered a contaminate to glass container production and must be sent to a specialized recycler.

A collaboration between two British construction trade associations, The Steel Construction Institute (SCI) and the Centre for Window and Cladding Technology (CWCT), have sought to increase the number of float glass recyclers by making the practice more economically feasible with a regular material supply. They proposed automating the window disassembly process to do this, which if successful, would possibly improve the prospects for recycling all the low value materials in windows (SCI 2003).

5.6.2 Municipal Waste in the United States

Of the 246 million tons of materials that entered the municipal waste stream in 2005, 65%, or 160 million tons is caused by construction and demolition (USEPA 2006a). The majority of construction and demolition waste, 60%, is treated in the same manner as other municipal solid waste, while 40% is sent to landfills established especially for this type of waste. These construction and demolition (C&D) landfills offer lower fees, called tipping, as building waste is typically inert and does not require the same protection against leaching (USEPA 2006b). No data specific to these landfills are available for this LCA, and all landfilled material were modeled as being taken to a generic municipal waste facility.

The USEPAb estimates that 80% of material that is not recycled is sent to a landfill, while 20% is burned in an incinerator, most commonly a mass burn incinerator. Emissions data for the incinerator and decomposition and leaching data for the landfill are based on average releases for the entire waste management system. This introduces uncertainty as some of the materials that are sent to these processes contain heavy metals and known carcinogens that may be different than the average waste stream.

CHAPTER 6: LIFE CYCLE IMPACT ASSESSMENT

6.1 IMPACT 2002+ Impact Method

The environmental impacts of all resources used and wastes and emissions generated over the life cycle of windows identified in the life cycle inventory stage were assessed using IMPACT 2002+ v. 2.1 (Jolliet et al. 2003) midpoint and damage characterization factors. Fourteen impact categories were considered that can generally be classified as either affecting human health, ecosystem quality, resource use, and global warming. Hereafter global warming and resource use are grouped together under the heading carrying capacity as affects in these categories directly affect the earth's ability to support human populations. The following lists the impact categories and their general grouping into what has been coined "areas of protection." (Udo de Hayes et al. 1999)

- **Human health consequences:** Carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics
- **Ecological consequences:** Aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication
- **Carrying capacity:** Global warming, non-renewable energy, mineral extraction.

The midpoint category results are represented in terms of equivalence to a reference substance commonly associated with that impact. Reporting midpoint values is preferential as less uncertainty is present in modeling the cause-effect chain closer to the emission or resource use (Pennington et al. 2004). However, the midpoint values give little insight as to the effects of the product system beyond the relative intracategory impacts towards the three areas of protection. By multiplying the midpoint results by a second group of characterization factors that relate the midpoint category to a damage effect, the relative significance of each towards total effects on human health, ecological quality, and the earth's carrying capacity may be understood. The following describes the units that were used to calculate damage effects across midpoint categories:

- Human Health (DALY): Disability Adjusted Life Years or DALY is the decrease in life expectancy and healthy years due to disability.
- Ecosystem Quality (PDF*m^2*yr): Potentially Disappeared Fraction (of species) over a given area and a length of time relates ecosystem damage directly to the degradation of species' populations.
- Carrying Capacity – Resource Use (MJ): The energy value relates to the expected future increase in energy requirements to recover that resource due to depleted stocks.
- Carrying Capacity – Global Warming (kg CO_2): The global warming potential has been left in terms of the midpoint equivalence as endpoint modeling of their affects introduces unacceptable uncertainty.

A more thorough explanation of the midpoint and damage characterization factors as well as their units may be found in Jolliet et al. (2003). Table 6.1 is also provided to describe the midpoint categories, the emittants that are commonly characterized as influential to them, and their relationship to the given area of protection.

Table 6.1: Life Cycle Impact Assessment Category Description

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Carcinogens	*kg C_2H_3Cl*	*Human Health*

"The probability that a resident of the United States will develop cancer at some point in his or her lifetime is 1 in 2 for men and 1 in 3 for women[6]. Most scientists involved in cancer research believe that the environment in which we live and work may be a major contributor to the development of cancer[7]". The Carcinogens impact characterization considers all substances classified as carcinogens by the International Agency for Research on Cancer (IARC) and is based on epidemiological evidence as to their carcinogenic effects.

Source: National Toxicology Program. Retrieved on November 3, 2007 from http://ntp.niehs.nih.gov/index.cfm?objectid=32BA9724-F1F6-975E-7FCE50709CB4C932)

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Non-carcinogens	*kg C_2H_3Cl*	*Human Health*

All chemicals that are known to cause an adverse change to human health other than cancer are grouped into the non-carcinogenic category. "Calculations (of the characterized impact values) are performed using multimedia chemical fate models, human exposure correlations for organic chemicals, and toxicological methodologies designed for chemical risk screening in a regulatory context"

Source: Pennington et al. 2004.

---

[6] ACS. 2004. Cancer Facts and Figures 2004: Basic Cancer Facts. American Cancer Society. http://cancer.org/statistics/cff99/basicfacts.html#risk.

[7] Lichtenstein P., Holm N.V., Verkasalo P.K., Iliadou A., Kaprio J., Koskenvuo M., et al 2000.Environmental and heritable factors in the causation of cancer: analyses of cohorts of twins from Sweden, Denmark and Finland. N Engl J Med. 13, pp. 78–85.

Continued: Table 6.1: Life Cycle Impact Assessment Category Description

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Respiratory Inorganics	*kg PM2.5*	*Human Health*

"In winter the air can become loaded with the products of incomplete combustion such as particulate matter (PM), volatile organic compounds (VOCs), carbon monoxide (CO) and nitrogen oxides (NOx)".

Source: Environment Canada. Retrieved on November 10, 2007 from http://www.ec.gc.ca/cleanair-airpur/Winter_Smog-WSAFF4D58F-1_En.htm.

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Ozone Layer	*kg CFC-11*	*Human Health*

"Most of the ozone in the atmosphere is found in a layer between 15 and 35 km above the earth surface in a region of the atmosphere known as the stratosphere. The ozone layer is beneficial to life on earth as it absorbs the harmful ultra violet (UV) radiation from the sun. In recent years, a large "hole" in the ozone layer has opened over the Antarctic each spring, and a similar, but smaller depletion has been observed over the Arctic. A thinning of the ozone layer over mid-latitudes has also been recorded". Key contributors to ozone depletion are the release of fluorinated hydrocarbons (CFCs) and halons. Since the introduction of the Montreal Protocol, these substances are now being phased out and the stratospheric ozone layer is expected to recover by about 2050.

Source: Environment Canada. Retrieved on October 30, 2007 from http://www.msc-smc.ec.gc.ca/cd/brochures/understandozonelayer_e.cfm#4

Continued: Table 6.1: Life Cycle Impact Assessment Category Description

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Radiation	*Bq C-14*	*Human Health*

"In the nuclear fuel cycle, in phosphate rock extraction, in coal power plants but also in oil and gas extraction, air and waterborne radionuclides are released to the environment. Up to now, such emissions have rarely been considered in LCA due to a lack of appropriate impact assessment models." IMPACT 2002+ models the effects of human health effects caused by radiation release and exposure.

Source: The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report. Retrieved on November 2, 2007 from: http://www.pre.nl/eco-indicator99/ei99-reports.htm.

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Respiratory Organics	*kg Ethylene*	*Human Health*

"Ground-level ozone is formed by a combination of sun, nitrogen dioxide (NO2) and volatile organic compound (VOC). Humans in urban areas often release large quantities of organic compounds and at the same time, large amounts of nitrogen oxides (NOX) from combustion, to create electricity and to power cars. In warm temperatures and in sunlight (hence, the name summer smog), these processes generate additional quantities of ozone at ground level. At ground level (not in the stratosphere), this increase in low levels of natural ozone can harm some plants and may irritate the lining of our lungs. This chemical reaction process of VOCs, NOX, and sunlight is highly complex. The particular chemistry of a VOC, the local concentrations, how high the temperature may be, the wind conditions and other factors are all involved".

Source: P&G. Retrieved October 17, 2007 from http://www.scienceinthebox.com/en_UK/sustainability/summersmog_en.html.

Continued: Table 6.1: Life Cycle Impact Assessment Category Description

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Aquatic Ecotoxicity	*kg TEG water*	*Ecosystem Quality*
Terrestrial Ecotoxicity	*kg TEG soil*	*Ecosystem Quality*

The ecotoxicological effects are modeled based on species-specific fate models that consider the potentially disappeared fraction (PDF) and potentially affected fraction (PAF) of species to particular chemical exposures. "The main exposure route is assumed to be water for aquatic ecosystems and pore water for terrestrial ecosystems."

Source: The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report. Retrieved from Internet on November 2, 2007 from: http://www.pre.nl/eco-indicator99/ei99-reports.htm.

Continued: Table 6.1: Life Cycle Impact Assessment Category Description

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Terrestrial Acidification/Nutrification	*kg SO_2*	*Ecosystem Quality*

"For almost all plant species there is a clearly defined optimum combination of nutrient level and acidity. Any deviation from this optimum is detrimental for that specific species. As a result, changes in nutrient levels will mainly cause shifts in the species populations. Sometimes these shifts result in an increased number of species, sometimes there is a decrease." The model considers the degradation of certain "target species" that are considered representative and desirable for the health of specific ecosystems.

Source: The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report. Retrieved November 2, 2007 from: http://www.pre.nl/eco-indicator99/ei99-reports.htm.

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Land Occupation	*m^2org.arable*	*Ecosystem Quality*

The impacts of land-cover changes include both the species that are displaced directly by the conversion, and also the species in surrounding natural habitats. Habitat-species relationships are complex and require site-specific knowledge of the species diversity, species richness, and species accumulation factor.

Source: The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report. Retrieved November 2, 2007 from: http://www.pre.nl/eco-indicator99/ei99-reports.htm.

Continued: Table 6.1: Life Cycle Impact Assessment Category Description

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Aquatic Acidification	*kg SO_2*	*Ecosystem Quality – No Damage Factor*

Direct transfer of hydrogen ions to aqueous environments is considered separate from those to terrestrial environments as the fate modelling is very different for the two types. Similarly, slight changes to the pH in bodies of water effect specific species that are adapted to particular environments. The damage modelling for aquatic acidification has not been completed and is not considered in this assessment.

Source: The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report. Retrieved from Internet on November 2, 2007 from: http://www.pre.nl/eco-indicator99/ei99-reports.htm.

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Aquatic Eutrophication	*kg PO_4 P-lim*	*Ecosystem Quality – No Damage Factor*

"Aquatic eutrophication is the result of nutrient enrichment in aquatic environments. Under natural conditions, the supply of nutrients to water is in balance with the growth of biomass. Anthropogenic nutrient inputs can disturb this balance, leading to increases in algal growth that make the water turbid and decrease the level of oxygen content. This then leads, for example, to increases in fish mortality and ultimately the disappearance of bottom fauna" The damage modelling for aquatic eutrophication has not been completed and it is not considered in this assessment.

Sources: The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report. Retrieved from Internet on November 2, 2007 from: http://www.pre.nl/eco-indicator99/ei99-reports.htm.

Kristensen, P. and Hansen, H.O., 1994. European rivers and lakes. Assessment of their environmental state. *Environmental monographs* vol. 1, European Environmental Agency, Copenhagen, Denmark.

Continued: Table 6.1: Life Cycle Impact Assessment Category Description

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Mineral Extraction	*MJ primary*	*Resource Use – Carrying Capacity*
Non-renewable Energy	*MJ surplus*	*Resource Use – Carrying Capacity*

"The energy requirements needed to extract, grind, and purify an ore goes down with efficiency increases and technological developments" and this outweighs increases in energy expenditure caused by reductions in the grade of ores over time". The converse is true for non-renewable energy sources, which will increase significant increases in extraction and refinement energy as higher grade oil and natural gas are used up and are replaced by coal, shale, and tar sands.

Source: The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report. Retrieved November 2, 2007 from: http://www.pre.nl/eco-indicator99/ei99-reports.htm.

NAME	INDICATOR UNIT	DAMAGE CATEGORY
Global Warming	*kg CO2*	*Global Warming – Carrying Capacity*

Gases that trap heat in the atmosphere are often called greenhouse gases. Some greenhouse gases such as carbon dioxide occur naturally and are emitted to the atmosphere through natural processes and human activities. Other greenhouse gases (e.g., fluorinated gases) are created and emitted solely through human activities. The principal greenhouse gases that enter the atmosphere because of human activities are carbon dioxide, methane, nitrous oxide, and flourinated gases.

Source: EPA. Retrieved November 5, 2007 from: http://www.epa.gov/climatechange/emissions/index.html.

6.2 Midpoint Results

The midpoint effects are provided as these are not affected to a large extent by the uncertainty of cause-effect modeling. Table 6.2 provides the midpoint results associated with each life cycle while Figure 6.1 provides a graphical representation.

The midpoint impacts indicate relative similarity, with no difference within a category differing beyond a factor of 2 for all categories other than carcinogens and aquatic ecotoxicity. Little else can be distinguished from these values beyond the relative rankings of the three window types in each category as the contribution to damage effects is not included.

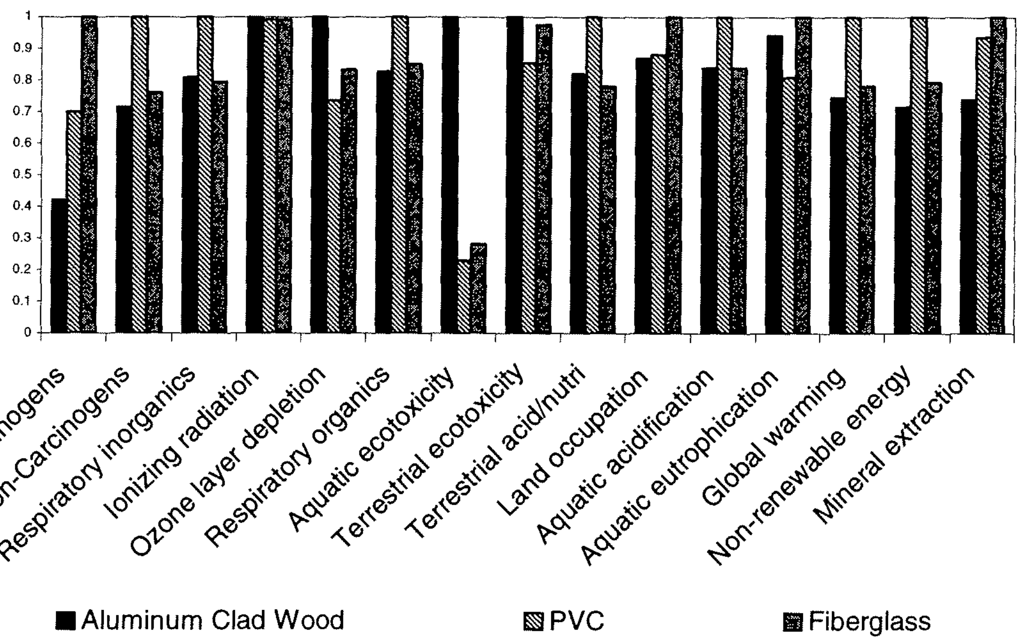

Figure 6.1: Cradle to Grave Midpoint Impact Totals for Aluminum Clad Wood, PVC, and Fiberglass Windows

Table 6.2: Cradle to grave midpoint impacts for aluminum clad wood, PVC, and fiberglass windows

HUMAN HEALTH		*Al Clad Wood*	*PVC*	*Fiberglass*
Carcinogens	kg C_2H_3Cl	1.48	2.45	3.50
Non-Carcinogens	kg C_2H_3Cl	4.95	6.93	5.25
Respiratory inorganics	kg PM2.5	0.50	0.62	0.49
Ionizing radiation	Bq C-14	1310	1300	1300
Ozone layer depletion	kg CFC-11	4.77E-05	3.51E-05	3.97E-05
Respiratory organics	kg ethylene	0.35	0.43	0.37
ECOSYSTEM QUALITY				
Aquatic ecotoxicity	kg TEG water	32300	7430	9140
Terrestrial ecotoxicity	kg TEG soil	1580	1350	1550
Terrestrial acid/nutri	kg SO_2	11.70	14.40	11.20
Land occupation	m^2org.arable	0.856	0.87	0.99
Aquatic acidification	kg SO_2	4.03	4.80	4.03
Aquatic eutrophication	kg PO_4 P-lim	1.59E-02	1.36E-02	1.69E-02
CARRYING CAPACITY				
Global warming	kg CO_2	341.00	456.00	357.00
Non-renewable energy	MJ primary	6110	8560	6800
Mineral extraction	MJ surplus	5.03	6.36	6.80

6.3 Damage Results

The life cycle impacts were disaggregated into the different stages in the lives of the three window types. The major life stages include the resource extraction and commodity manufacture, manufacture of the finished product, use and maintenance, and end of life treatment. Classifying processes into life stages in this way introduces ambiguity in that the manufacturing of caulking and sealed units are considered in the use/maintenance stage when they are required by maintenance processes, but are considered as resource extraction/commodity manufacture when installed with a complete window. Similarly, the replacement windows are considered as resource use/commodity manufacture and finished product manufacturing despite their requirement during the use phase. Specifically, the life cycle of windows was broken down into the following phases:

- **Resource Extraction and Commodity Manufacture:** Resource extraction, commodity manufacture, and transportation to the manufacturer
- **Secondary Manufacturing:** Energy use at the window manufacturer including overhead
- **Material Transportation:** Includes the transportation of raw materials to the manufacturer and of complete windows to the installation site
- **Maintenance During Use:** Manufacture, transportation, and disposal of replaced materials
- **End of Life Treatment:** Disposal of windows through municipal waste stream

The damage impacts of the three window types are shown in Figures 6.2, 6.3, 6.4, and 6.5. In these graphs, the relative contribution to the damage indicators are shown to illustrate the differences in the magnitude of these results. For this reason, the results in several categories do not appear in the scale of the graphs as they are insignificant compared to the more influential midpoint categories to that damage. The relative rankings for these are shown in the previous midpoint graph, Figure 6.1.

In Figure 6.2 it is evident that the emissions of respiratory inorganics contribute most significantly to the human health effects of each product system.

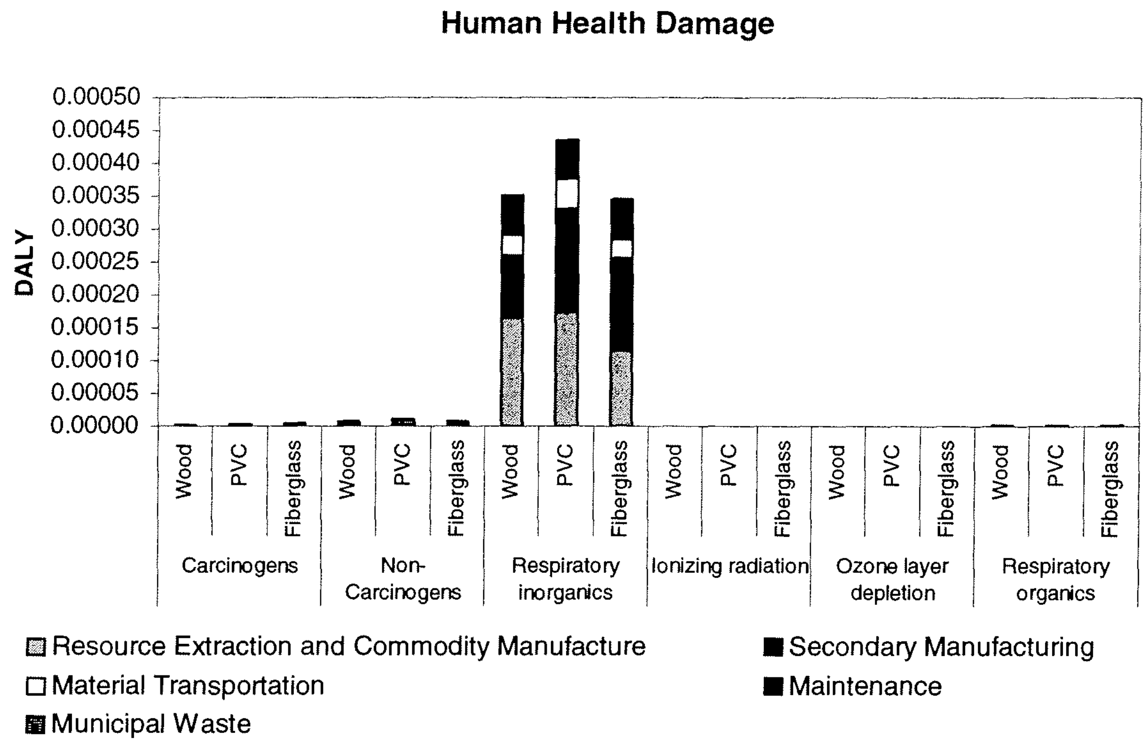

Figure 6.2: Human health damage resulted from different life stages of aluminum clad wood, PVC and fiberglass windows shown as mid-point damage categories

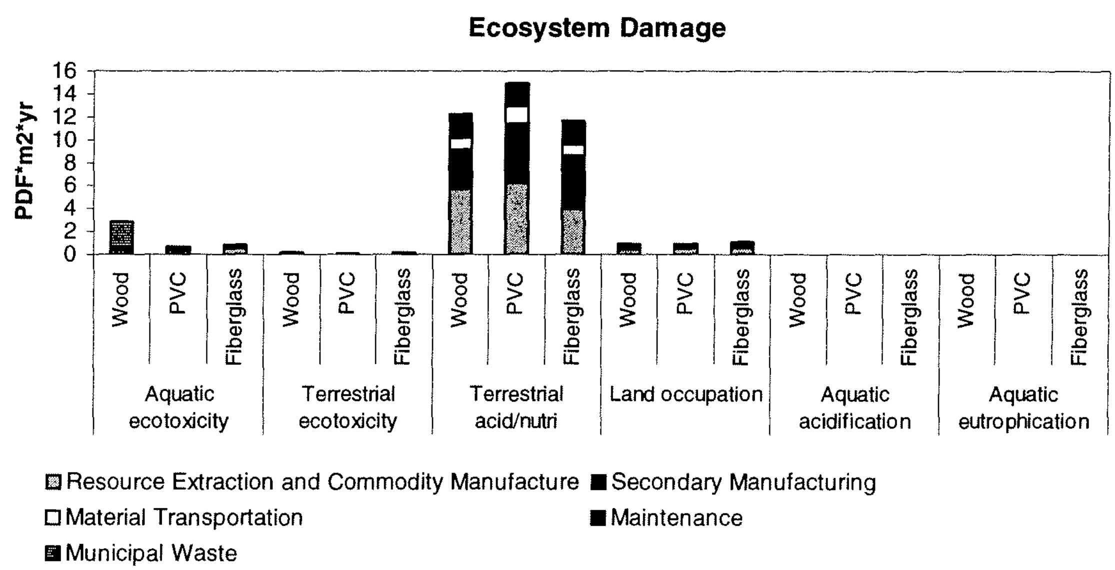

Figure 6.3: Ecosystem damage resulted from different life stages of aluminum clad wood, PVC and fiberglass windows shown as mid-point damage categories

Figure 6.3 similarly shows dominance of a single midpoint impact category, terrestrial acidification/nitrification, to the total ecosystem damage caused by each life cycle. Aquatic ecotoxicity is also shown to contribute to ecosystem damage to a much smaller degree. IMPACT 2002+ (Jolliet et al. 2003) recognizes the significant uncertainty in damage modelling and specifies that all damage impacts greater than 1% of the total be considered. This research complies with this by considering not only the 4 dominant midpoint categories, but also aquatic ecotoxicity, which although not nearly significant as the other results was also found to be greater than the 1% threshold.

Figure 6.4 shows that nonrenewable energy use is a much more significant cause of resource depletion than mineral extraction. Figure 6.6 also shows the global warming associated with each window type. There is a strong correlation between non-renewable energy use and global warming contribution in regards to the life stages that these effects occur. It is also noteworthy that this correlation may be extended to respiratory inorganics and terrestrial acidification/nitrification which suggests that the burning of fossil fuels may also significantly impact the results in these categories.

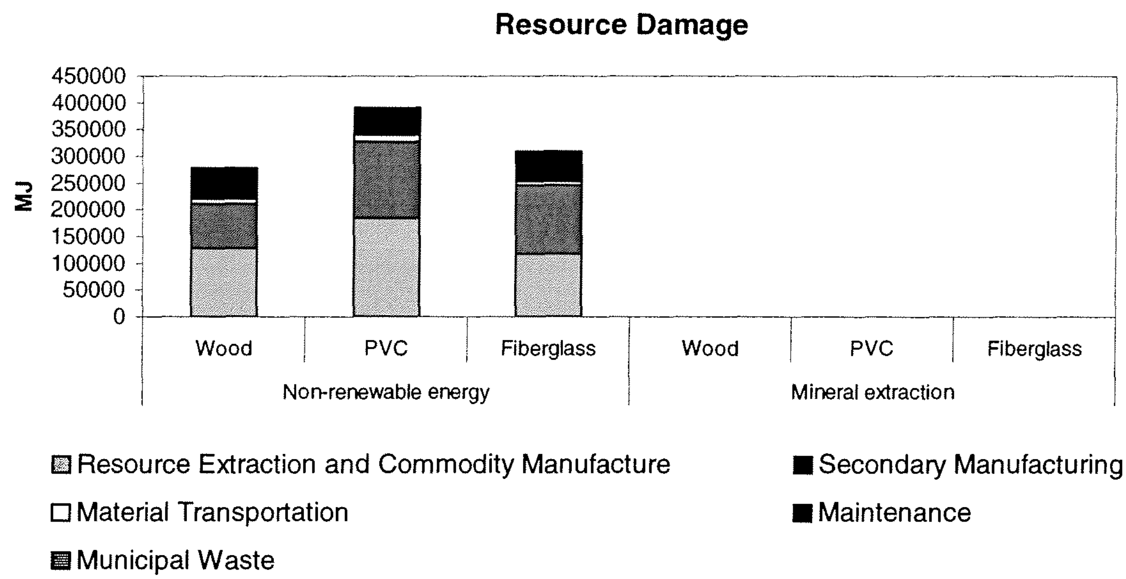

Figure 6.4: Resource damage resulting from different life stages of aluminum clad wood, PVC and fiberglass windows shown as mid-point damage categories

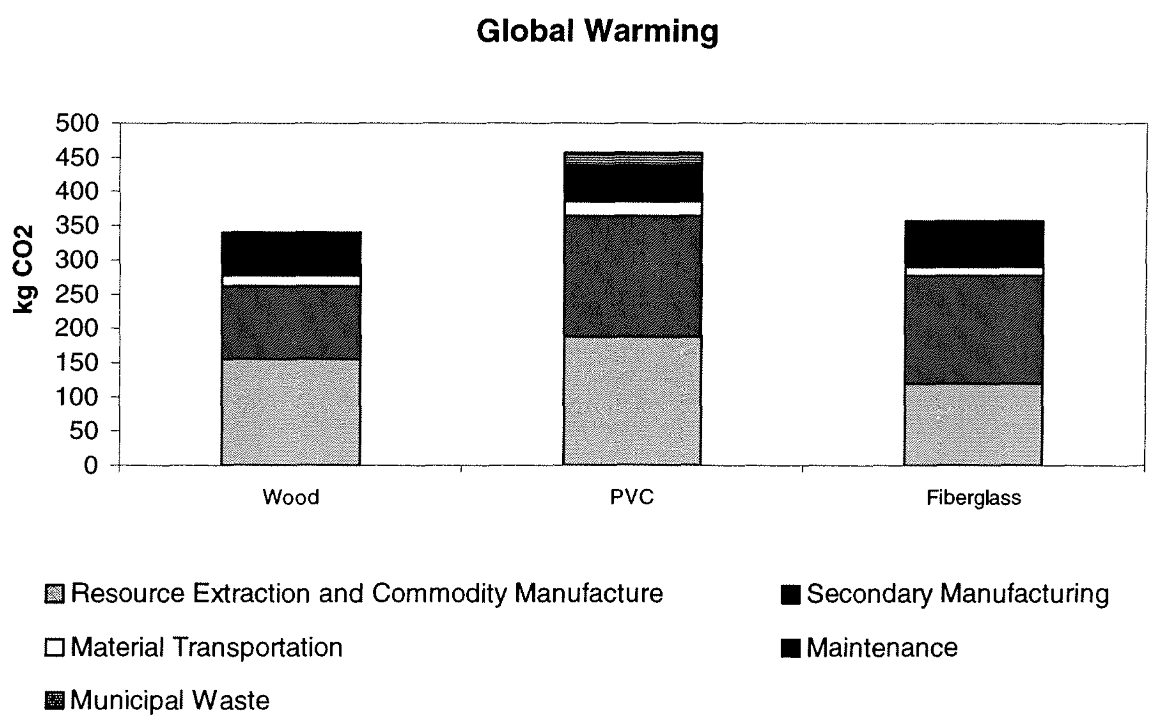

Figure 6.5: Global warming resulting from different life stages of aluminum clad wood, PVC and fiberglass windows shown as mid-point damage categories

After completing the damage analysis it is clear that the impacts on respiratory inorganics, terrestrial acidification/nitrification, non-renewable energy use, and global warming impacts required the greatest scrutiny as these caused the greatest damage. Aquatic ecotoxicity was also selected for further analysis as the wood window was significantly worse than the other two in this category.

Process contribution analysis revealed that the four most significant impact categories were all dominated by the burning of fossil fuels. The burning of coal and natural gas were the most significant processes in each of these categories. The cradle to gate manufacture of the various materials was also found to be significant, but the system levels of these data prohibited investigating the individual cradle to gate processes.

Recognizing that in the non-renewable energy graph that the amounts required to produce the window materials is closely related to the contribution of this stage in the other categories, it is reasonable to conclude that these impacts were caused primarily from burning fossil fuels as well.

The aquatic ecotoxicity values were not related to the aforementioned fossil-fuel dominated processes. The aquatic ecotoxicity was highest in the disposal of the aluminum clad wood window which suggests that some material unique to that type leaches during waste treatment. It was found that 80% of the total aquatic ecotoxicity in the wood window life cycle resulted from the disposal of aluminum, and subsequent release of aluminum to air and water.

6.4 Cradle to Gate Findings

The primary goal of this LCA was to compare the life cycles of the three frame materials. For this reason, the cradle to gate window manufacture was disaggregated to show the influence of the primary frame material, cladding and steel for the wood and PVC windows, sealed unit, all other materials, secondary manufacturing energy, and transportation of materials to the manufacturer. Figures 6.6, 6.7, 6.8, and 6.9 show the contribution to damage of the aforementioned window materials and cradle to gate processes.

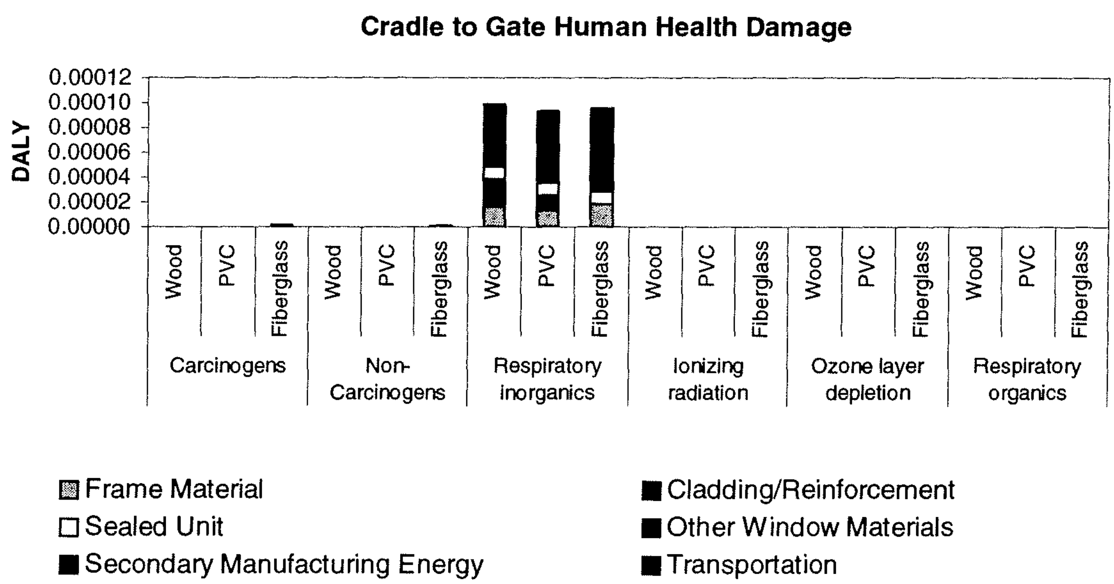

Figure 6.6 Human health damage from cradle to gate materials and processes of aluminum clad wood, PVC and fiberglass windows: mid-point damage categories

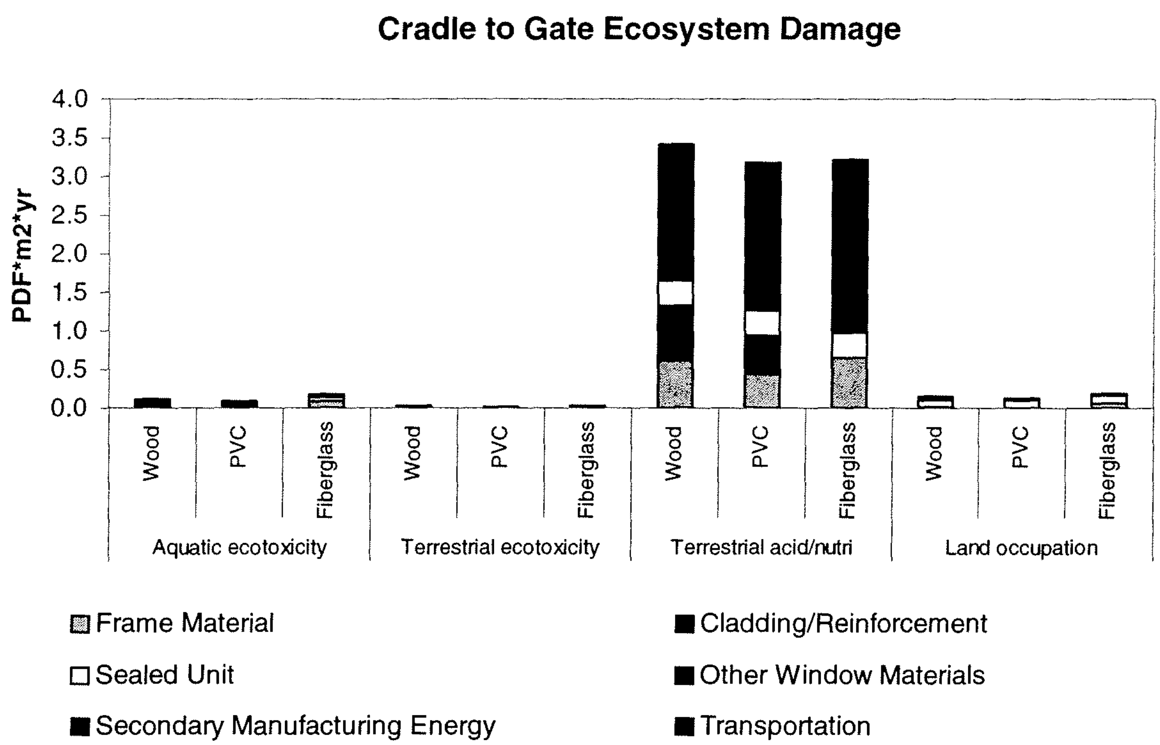

Figure 6.7: Ecosystem damage resulted from cradle to gate materials and processes of aluminum clad wood, PVC and fiberglass windows: mid-point damage categories

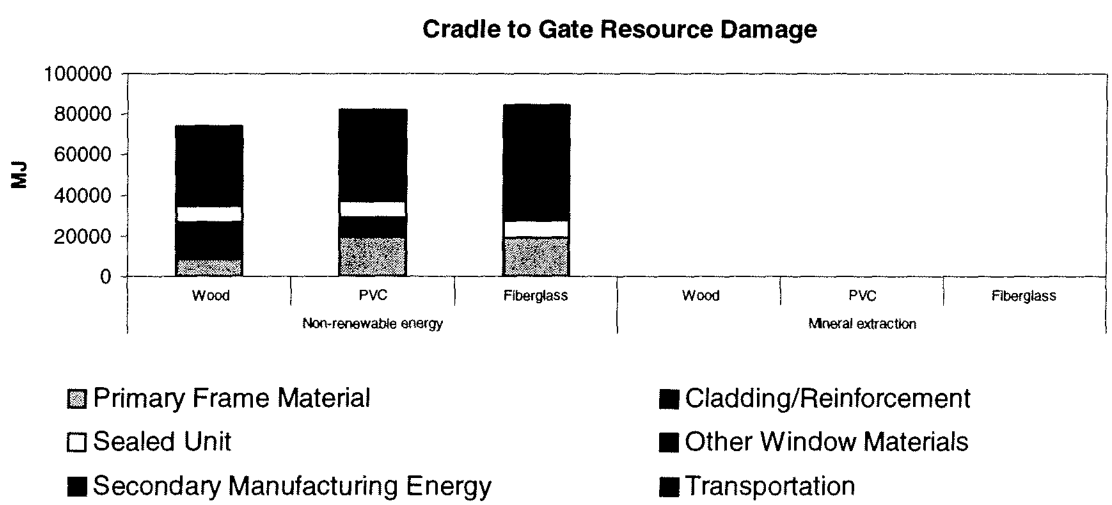

Figure 6.8: Resource damage resulted from cradle to gate materials and processes of aluminum clad wood, PVC and fiberglass windows: mid-point damage categories

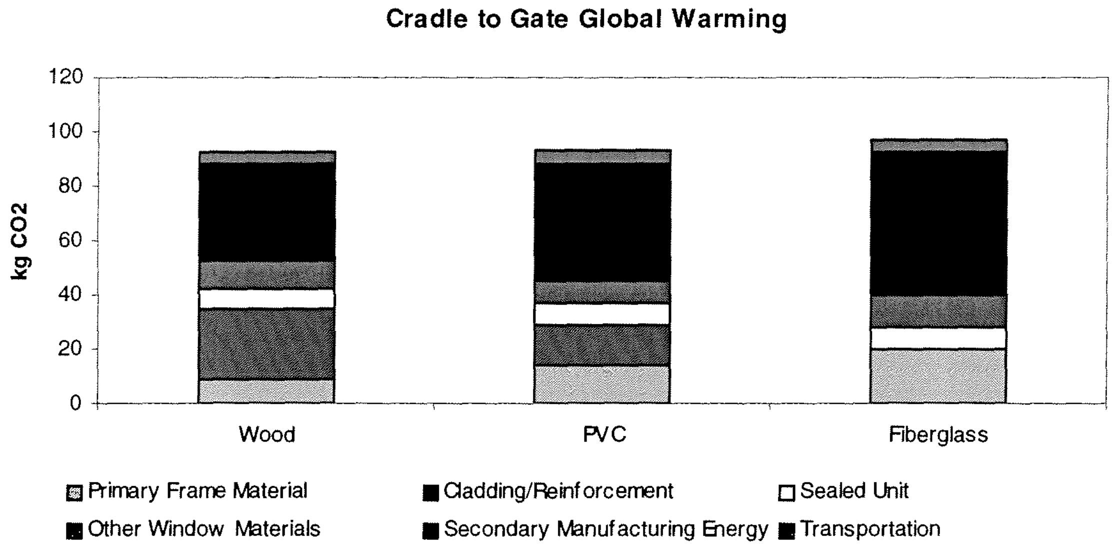

Figure 6. .9: Global warming resulted from cradle to gate materials and processes of aluminum clad wood, PVC and fiberglass windows: mid-point damage categories

The cradle to gate results provide several significant insights. First, the wood and PVC materials both use less energy and cause less acidification/nitrification, and emissions of respiratory inorganics, and greenhouse gas than the fiberglass materials alone. The aluminum and steel however, cause the total frame impacts to be greatest for these materials. This is particularly noticeable for the wood window frame, in which a majority of frame impacts are caused by the aluminum cladding.

The resource use graph also illustrates the role of renewable energy sources in the wood window and the use of non-renewables that are not burned in PVC manufacture. The wood life cycle uses burned wood waste for energy, which causes a reduced level of non-renewable resource use relative to the other effects of burning wood fuel, respiratory inorganics, acidification/nitrification, and greenhouse gasses. The use of oil in the production of PVC causes an elevated level of nonrenewable resource use while the effects are not seen in the categories related to burning this fuel.

CHAPTER 7: SENSITIVITY ANALYSES

Sensitivity analyses were performed to test several of the underlying assumptions in the model. These included the service life of the windows, the datasets that were used, and the effects of the specificity of using virgin scrap aluminum. In these tests, the impact values were recalculated based on the assumption of shorter and longer service lives, alternative datasets, and alternative cladding scenarios.

In accordance with the stated focus on the differences between frame materials, the sensitivity of the data used to represent their processing was considered. Alternative datasets were compared for wood, aluminum, PVC, steel, and polystyrene. The sensitivity to the glass dataset was also tested to ensure that the relative causation of different materials that was found is accurate.

Another significant contributor to cradle to gate impacts in the life cycle of the aluminum clad window was the cladding. Wood windows are commonly available with PVC or fiberglass cladding as an alternative to aluminum. Recycled aluminum may also be used without performance loss. The substitution of these three materials for the virgin aluminum was tested.

Finally, the effects of installation and resource location assumptions were tested as well as the use phase maintenance and service life estimations. Two specific cases were identified and the sensitivity to their assumptions was tested. In both cases, the resource locations were modeled based on the locations of suppliers to the three manufacturers that were studied. Minneapolis and Atlanta, the locations of the CORRIM house case studies (Winnestorfer et al. 2005), were selected as representative installation locations and the transportation, service life, and maintenance specific to them were considered. The case of extending the service lives beyond that which was assumed in the model was also tested.

7.1 Commodity Material Data

Alternative data sets were substituted for the default inventory values and the impacts recalculated to show the potential difference caused by data variation. It should be noted that the data used in the default case was most representative to the three product systems and that any changes to rankings are only illustrative of the model's variability.

7.1.1 Wood

CORRIM data were used for the default in this study. Two alternative datasets were available for cradle to gate wood manufacturing, Franklin and ETH (Ecoinvent). Figure 7.1 shows the recalculated life cycle impacts of wood windows with these datasets as well as the default values.

The ETH wood dataset showed significant differences to the default CORRIM data. Values were considerably higher for ionizing radiation, ozone layer depletion, aquatic ecotoxicity, and land occupation while the value for global warming was less than half of the default life cycle value. This illustrates differences in boundary definitions that exist in the accounting of these emissions, particularly for global warming when carbon sequestration is considered.

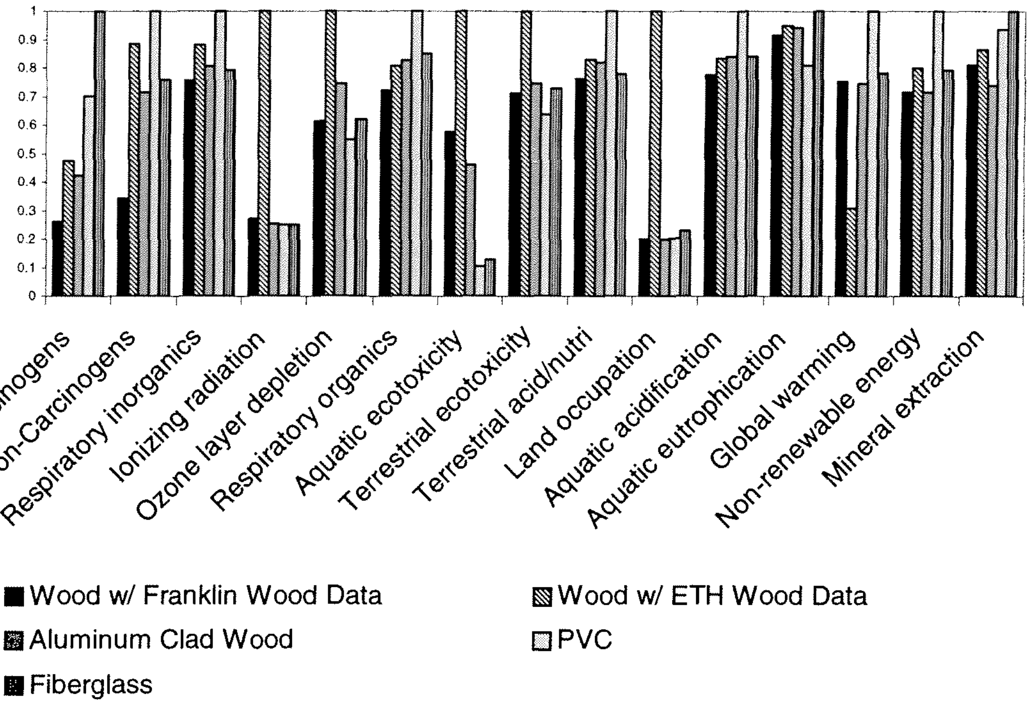

Figure 7.1 Wood Data Sensitivity Test from Substitution of Franklin and ETH Wood Data

7.1.2 Aluminum

Franklin data was used as the default in this study. Two European-specific datasets were available, ETH (Ecoinvent) and RER (Ecoinvent), and Figure 7.2 shows the sensitivity of the life cycle impacts to their substitution.

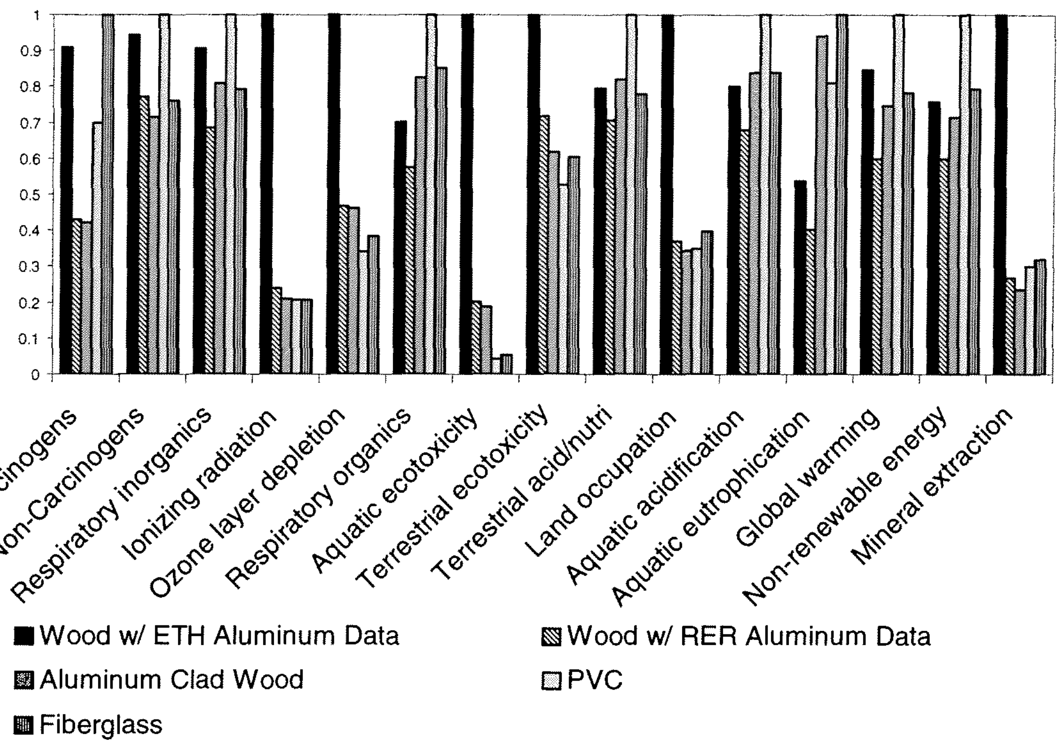

Figure 7.2: Aluminum Data Sensitivity Test from Substitution of RER and ETH Aluminum Data

The ETH data also caused significant differences in the results when it was substituted for the default Franklin aluminum data. The impact categories carcinogens, ionizing radiation, ozone layer depletion, aquatic and terrestrial ecotoxicity, land occupation and mineral extraction were all significantly higher than the default case. The consistently higher values for ETH for wood and aluminum cast doubts as to its comparability with the Franklin and Ecoinvent data that comprise the default life cycle model.

7.1.3 PVC

Ecoinvent data was used as the default in this study. Two alternative datasets were available, Franklin and APME (Ecoinvent). Figure 7.3 shows the sensitivity of the life cycle impacts to their substitution.

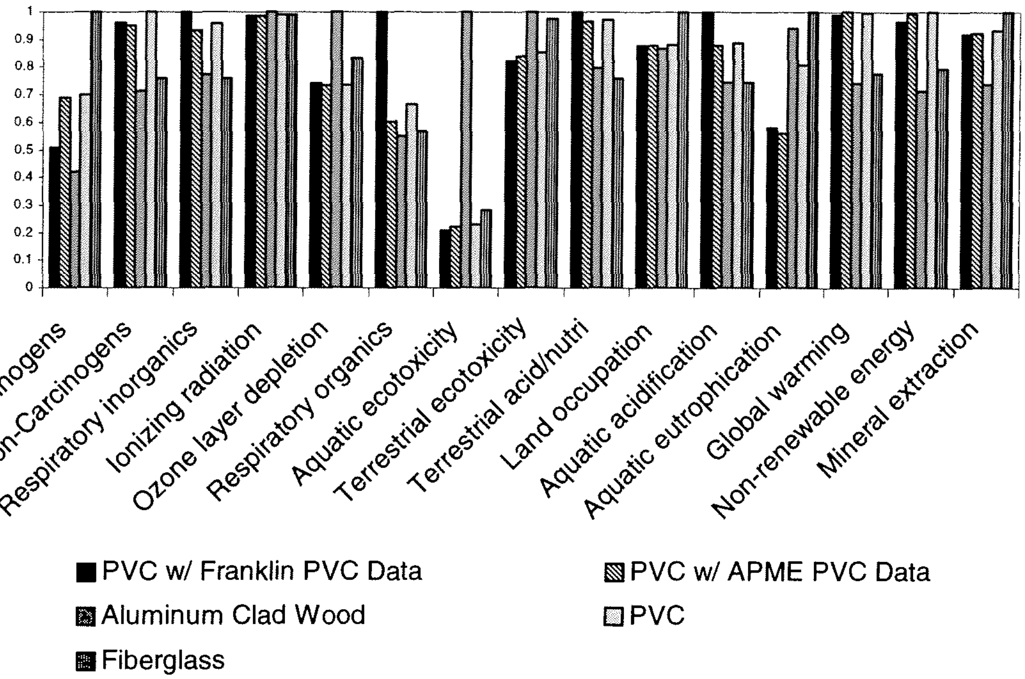

Figure 7.3: PVC Data Sensitivity Test from Substitution of Franklin and APME PVC Data

The PVC datasets are relatively homogeneous. The life cycle impacts were all within 40% of the default values for all categories besides respiratory organics, for which the Franklin data doubled the default life cycle value.

7.1.4 Steel

The steel data in the model was assumed as coming 50% from a blast oxygen furnace, (BOF) mill and 50% from an electric arc furnace (EAF) mill. Figure 7.4 shows the sensitivity of the PVC window life cycle results to the alternative cases of 100% from either an EAF mill or a BOF mill.

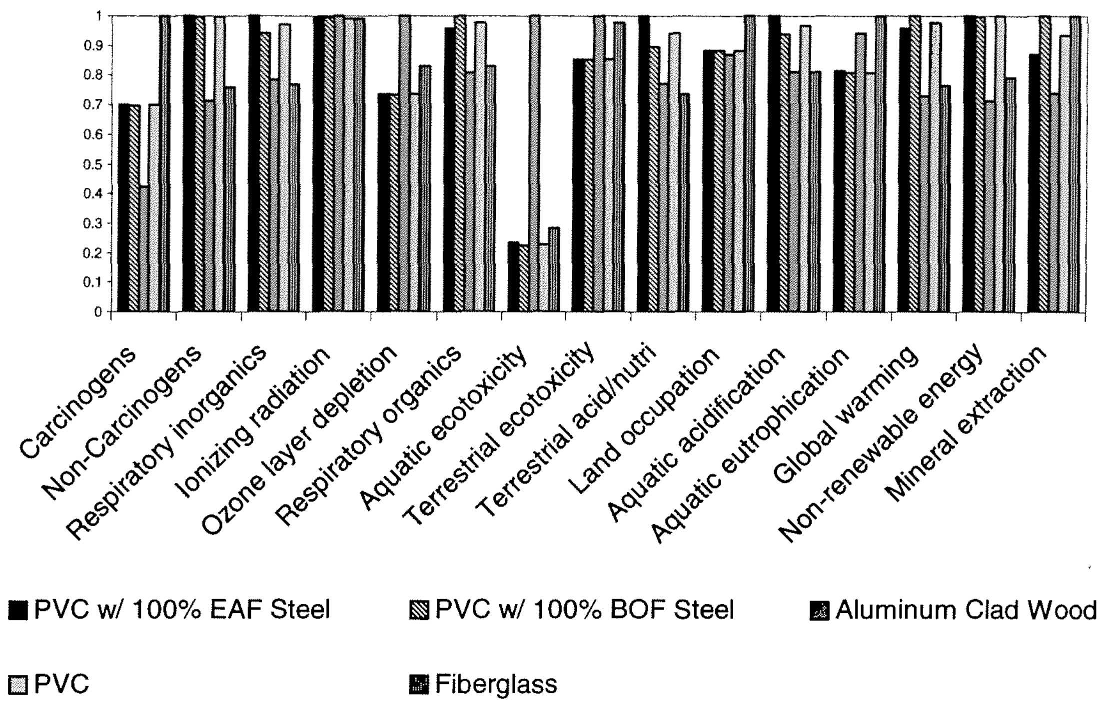

Figure 7.4: Steel Mill Type Sensitivity Test from Substitution of EAF and BOF Mills

Substituting 100% allocation to either steel mill type did not affect the life cycle results or the relative rankings of the three windows.

7.1.5 Polystyrene

The data for the manufacture of plastics was taken directly from the various resins that were used in the pultrusion process. While no alternative datasets exist for these constituent materials, RER (Ecoinvent) did publish LCI data for the manufacture of polystyrene plastic. The sensitivity of substituting this data for the resin data is shown in Figure 7.5.

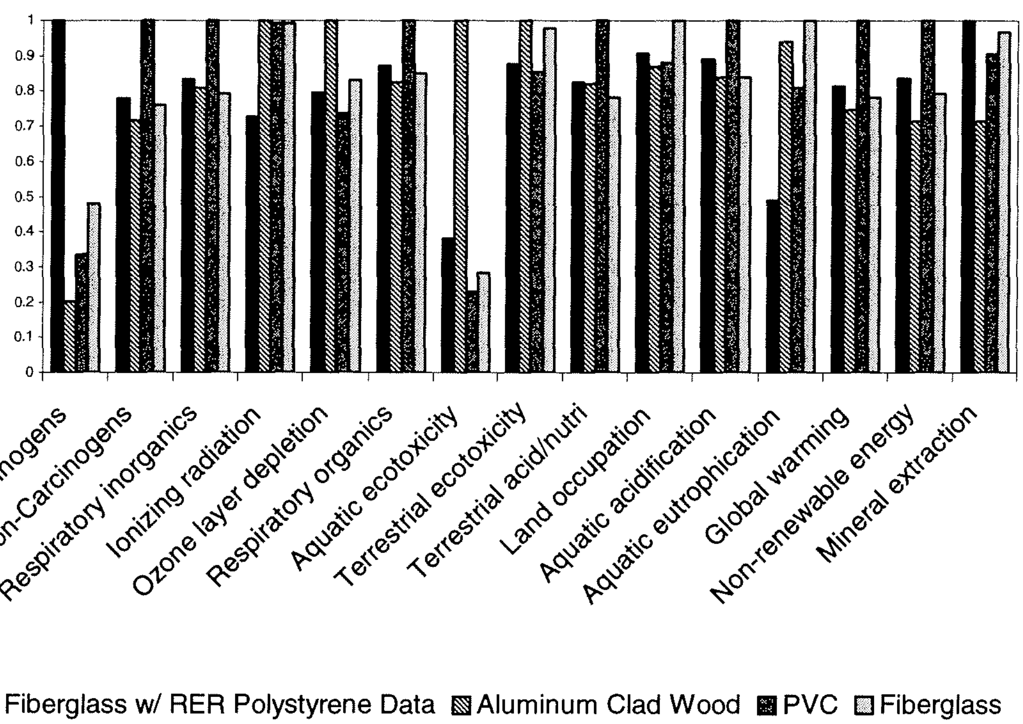

Figure 7.5: Polystyrene Data Sensitivity Test from Substitution of RER Polystyrene Data

Substituting the case specific data with generic polystyrene production data caused greater values for carcinogen release while causing less aquatic eutrophication.

7.1.6 Glass

The glass material was common to all three window types and thus the sensitivity of the glass data is not as critical to the stated goals. However, to ensure the results accurately depict the relative causation of a window's subassemblies, the sensitivity of the results to alternative datasets, ETH (Ecoinvent) and Franklin, was tested. The results are shown in Figures 7.6 and Figure 7.7. Both glass datasets produce results similar to the default case.

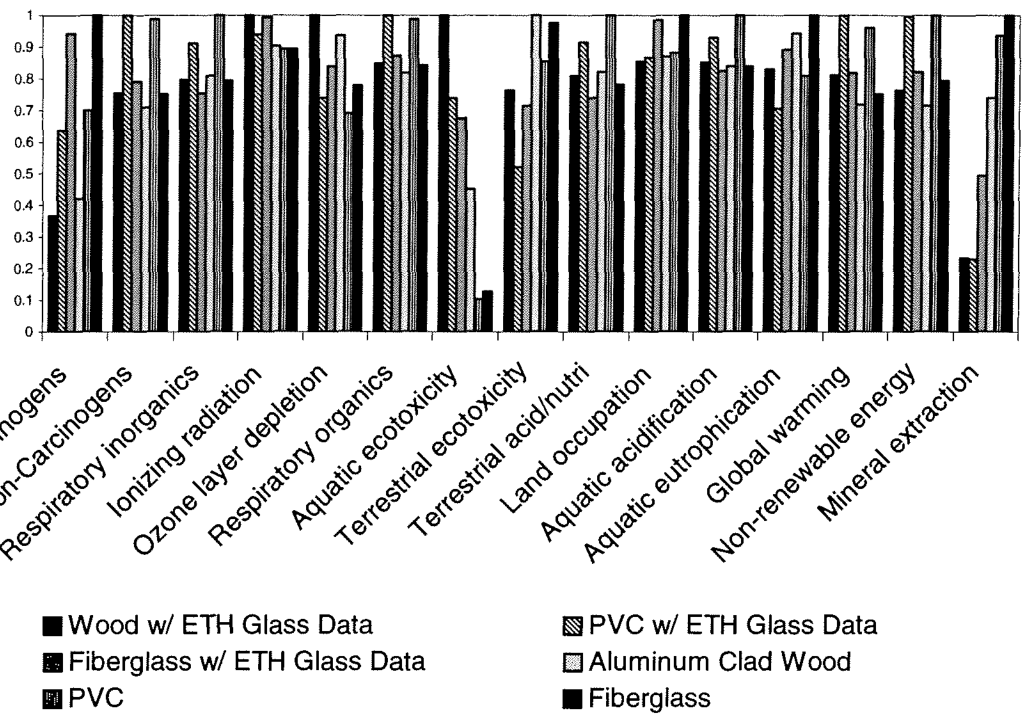

Figure 7.6: Glass Data Sensitivity Test from Substitution of ETH Glass Data

The ETH glass dataset caused greater aquatic ecotoxicity and less mineral extraction than the default case but did not affect any relative rankings. The Franklin data also led to less mineral extraction, land occupation, and terrestrial ecotoxicity.

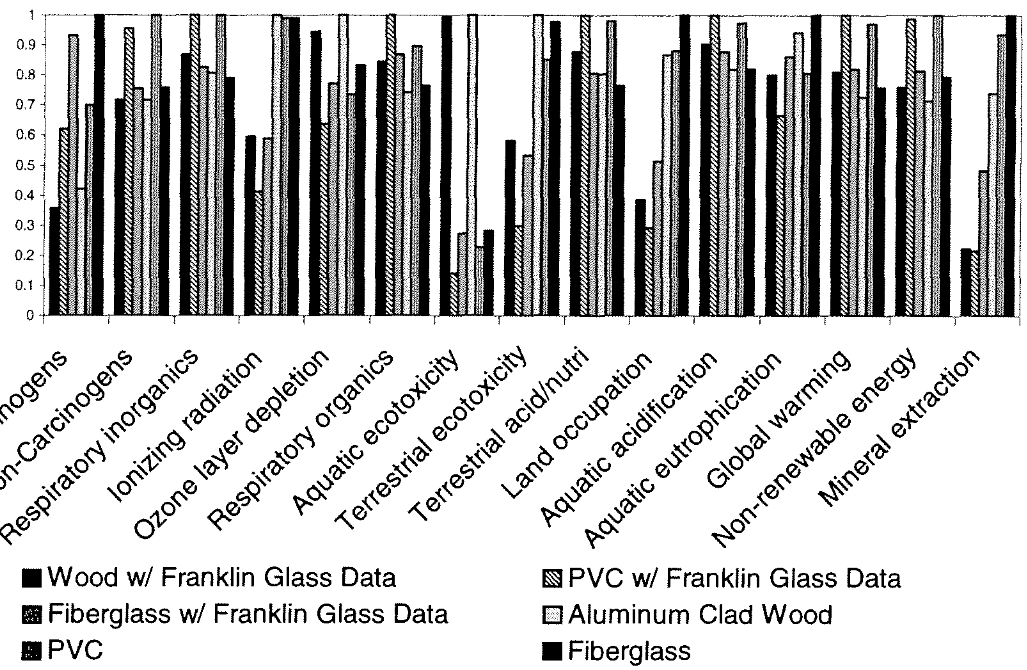

Figure 7.7: Glass Data Sensitivity Test from Substitution of Franklin Glass Data

7.2 Cladding Material

In building the cradle to gate model the aluminum cladding supplier indicated that they had previously used recycled ingot, with no degradation in quality, but were unable to locate a suitable supplier. Additionally, Pella Windows, another major North American window manufacturer states on their website[8] that they use aluminum with 95% recycled content. The energy savings attributable to using recycled aluminum are well known.

PVC and fiberglass were also considered as potential cladding materials in the sensitivity analysis. Anderson Windows, a third major North American window manufacturer, offers their wood windows clad with PVC. The wood window manufacturer consulted in this study also uses fiberglass for a small number of cladding

---

[8] http://www.pella.com/about/environment.asp

profiles. Figure 7.8 shows the sensitivity to cladding material selection and considers recycled aluminum, PVC, and fiberglass.

Wood windows are also available without cladding at all. This eliminates the contribution of aluminum in the cradle to gate analysis but does use more wood and materials allocated based on wood volume (preservatives, adhesives, energy). Wood windows without cladding are rare in the market as the lifespan of these are only 16 years, and they need repainting every 7 years. Based on these differences the sensitivity of the results were also tested for the case of non-clad wood. The unclad window was worse than the clad window in all impact categories, despite causing lower cradle to gate impacts by forgoing the aluminum manufacturing.

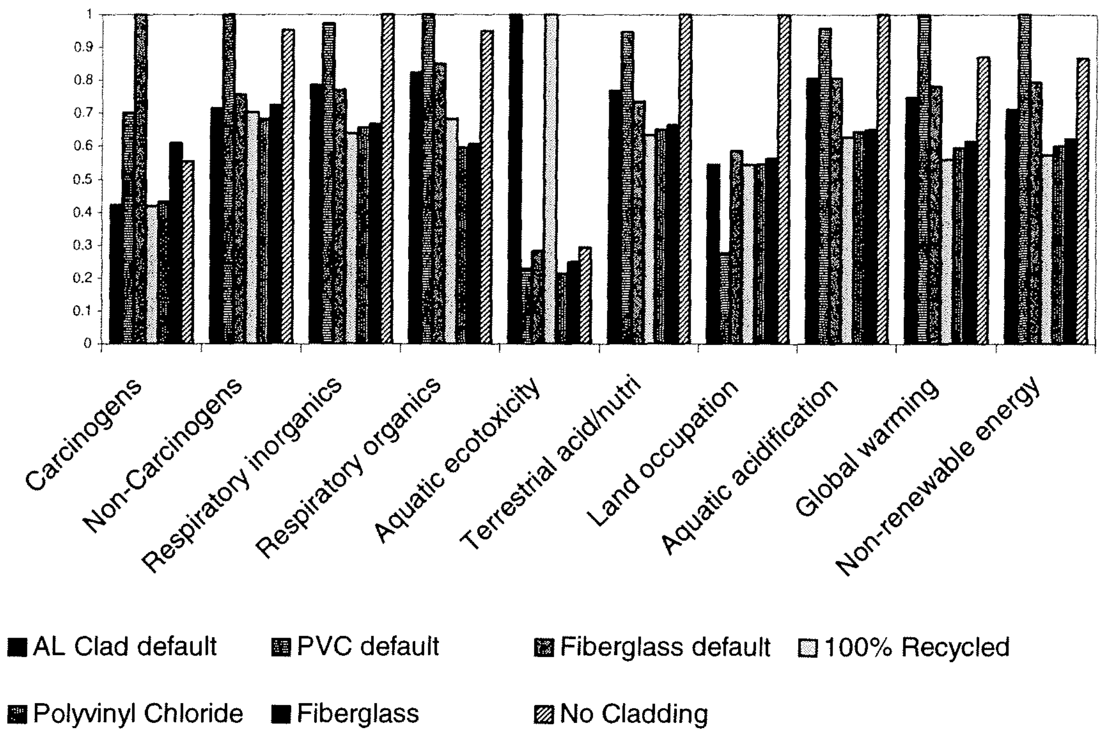

Figure 7.8: Cladding Material Sensitivity from Substitution of Recycled Aluminum, Fiberglass, PVC, and no Cladding for Virgin Aluminum

Changing the cladding material to any of the three alternative materials, significantly improved the impacts of the clad window. Removing the cladding caused increased impacts due to the higher replacement frequency and subsequent need to produce, ship, and dispose of more window materials.

7.3 Specific Location Case Studies

The transportation of window materials to the manufacturer and from the manufacturer to the installation site were assumed as averages in the SimaPro model. The specific locations were known for the wood manufacturer's supplier of wood (Vancouver), the

PVC manufacturer's PVC source (West Virginia), as well as the supplier of glass fibers to the fiberglass window manufacturer (China).

The installation location was also assumed as an average in the default model, with transportation distances based on an average from Statistics Canada and service life and maintenance assumptions taken as the average of ATHENA's city specific data. For the sensitivity test for the specific case studies, the locations Atlanta and Minneapolis were selected as representative. Figures 7.10 and 7.11 show the results of these two specific cases.

Besides the differences to the PVC life cycle caused by more frequent (Minneapolis) and less frequent (Atlanta) replacement frequencies, little differences exist when the life cycles are considered as specific cases. The changes to transportation distances, although in some cases greater than 10 times the average data values, did not influence the rankings of the three windows or the conclusions that may be drawn.

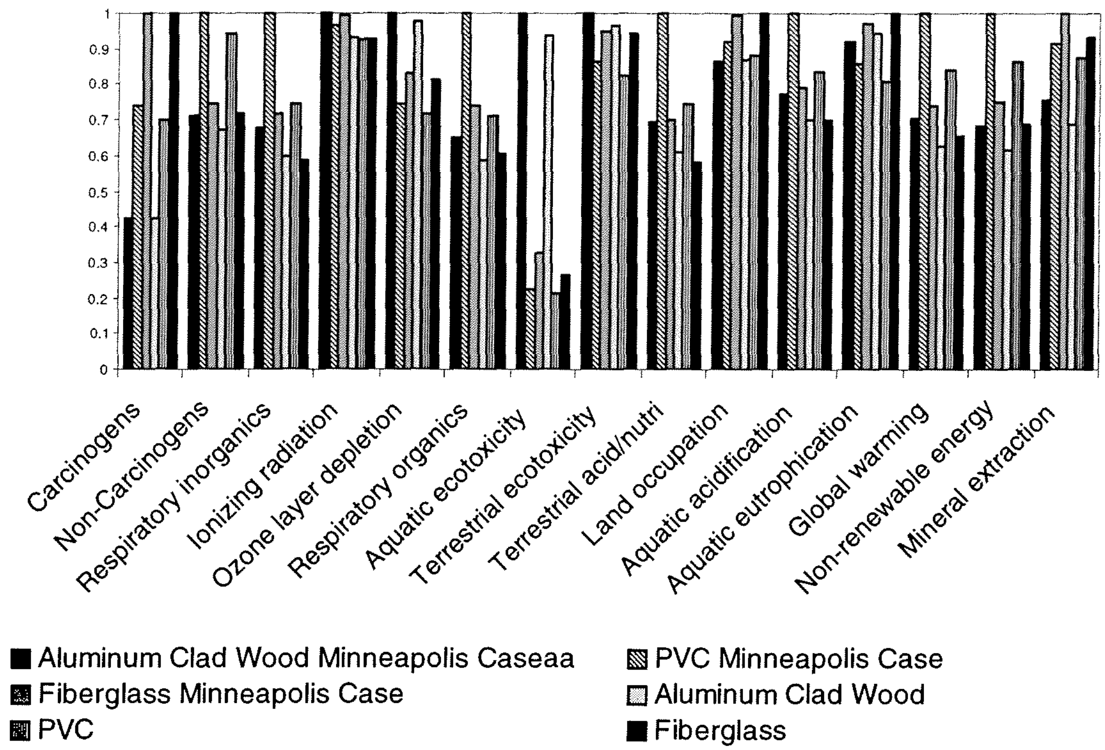

Figure 7.9: Minneapolis Case Sensitivity

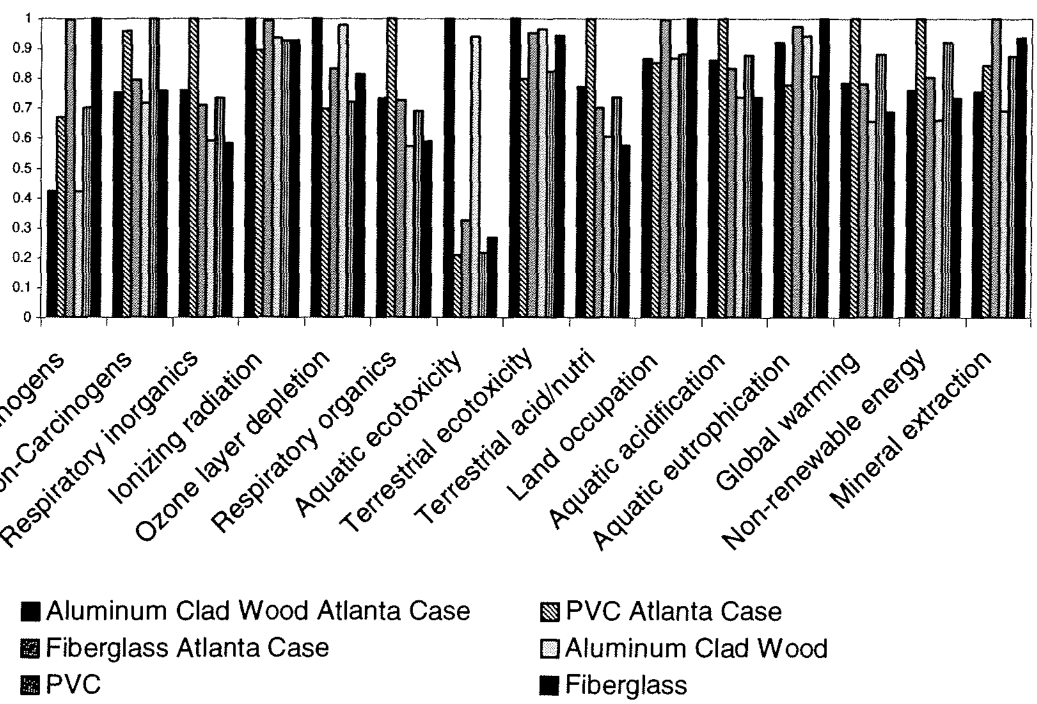

Figure 7.10: Atlanta Case Sensitivity

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The results of this research accomplish the objectives that were established. The impacts and differences between the three life cycles were found; the significant life stages and processes were identified; and the results were also presented such that the sensitivity and uncertainty are apparent.

As is the case with all LCAs, the goal and scope of this research required reconsideration during both the LCI and LCIA phases. In completing the LCI, it was determined a case study was required as finding industry average manufacturing data was deemed impossible. In completing the LCIA it was found that the results indicated an inability to decisively claim environmental superiority of any one window type. Thus, the second goal, recognizing key contributors over the life cycle for the purpose of directing abatement, then became the primary focus. The two areas in the windows' life cycles that were identified as most significant were the high proportion of secondary manufacturing energy to total energy use (and their related impacts) and also the energy intensiveness and potential savings of choosing a cladding material. The first finding suggests that the manufacturers may improve the environmental performance of their products by utilizing energy efficient lighting and heating, the primary energy draw in a plant, and also by improving process efficiency. The second finding speaks to the influence of material selection by the secondary manufacturer and to their ability to affect the environmental impacts of their products by sourcing recycled aluminum, PVC, or fiberglass cladding.

8.1 LCIA and Sensitivity Analyses Conclusions

8.1.1 Life Cycle Impacts

The fiberglass and aluminum clad wood windows used the least non-renewable energy during their life cycles. This caused them to be superior in the four categories most relevant to the ultimate damage caused by the three life cycles: respiratory inorganics, terrestrial acidification/nitrification, global warming, and non-renewable energy. The primary contributor to greenhouse gasses in the three life cycles were the cradle to gate commodity manufacture and secondary manufacturing energy.

The sensitivity analysis revealed that while several categories were significantly affected by the selection of data sources, the four non-renewable energy related categories were unaffected with an exception to assumptions regarding carbon sequestration.

The results are in accordance to the literature that was reviewed. However, no direct comparison can be made to this study and those done previously as the functional unit and system boundaries were defined differently in each case. The results of Entec (2000), that the PVC used 3 times the nonrenewable energy of the unclad wood, are supported by the finding in this research that PVC uses greater than double the nonrenewables (Figure 6.8). Significant differences were found between the results of Asif et al. (2002) and this research. Asif et al. (2002) did find that the aluminum manufacture was highly energy intensive, but not that this significantly affected the results for the aluminum clad wood window, which was found to be lower than the one made of PVC. Asif et al. (2002) also found that the PVC material manufacture used 13 times the energy of the wood, which is well beyond the disparity between the materials found in this study.

8.1.2 Differences in the cradle to gate manufacturing

The cradle to gate manufacturing of the three windows required similar levels of non-rewnewable energy. This indicates that the fundamental differences between the damage associated with the use of the three windows lies with the service life that is assumed. The cradle to gate analysis showed that the wood and PVC materials alone, actually use less non-renewable energy than fiberglass, but the requirement for cladding and steel reinforcement caused the total frame impacts to be greater.

The wood life cycle uses burned wood waste for energy, which resulted in a reduced level of non-renewable resource use relative to the other effects of burning wood fuel, respiratory inorganics, acidification/nitrification, and greenhouse gasses. Conversely, the use of oil in the production of PVC causes an elevated level of nonrenewable resources while the effects are not seen in the categories related to burning this fuel.

8.2 Potential Improvements

8.2.1 Use Alternative Cladding Material

As was discussed in Chapter 7, recycled aluminum, fiberglass, and PVC are three alternatives that are currently offered by North American and World leaders in window production. It was found that substituting for either of these three materials reduced greenhouse gas emissions.

No assertion is made here as to the comparability of a vinyl clad wood window and one clad in aluminum. In fact, the shorter service life of PVC frames indicates that they are not comparable. However, the sourcing of recycled aluminum and fiberglass are saving decisions that are being made within the industry and were shown to significantly affect the results.

8.2.2 Reduce Manufacturing Energy

The manufacturing energy was found to be a significant contributor to the life cycle impacts. The great majority of energy consumed by the manufacturer is dedicated to lighting and heating the facility. Window manufacturers may utilize energy efficient technologies such as improved thermal insulation and low wattage lighting.

8.2.3 Extend Service Life

Extending the service life of an installed window reduces the need to replace windows, and thus reduces the impacts from manufacturing, resource extraction, and disposal. The sensitivity analysis demonstrated how extending the service life of the PVC window to 25 years, the same as the other two window types, made the PVC window comparable to the other two types in regards to fossil fuel usage and its related categories. Extending the service life of the fiberglass and aluminum clad wood window beyond 25 years makes each the environmentally preferable window type.

8.3 Limitations of Research

The findings in this research are influenced to some extent by the uncertainty of the results that were found and by the lack of treatment of certain processes that were deemed to lie outside the scope of the LCA. The following were found to limit the arguments that may be made based on the results.

- Representational accuracy of model and data
- Differences between cases and average production

Uncertainty is present in the results in both quantifiable and non-quantifiable terms. The sensitivity analysis elucidated the variability of the results to numerous key assumptions and datasets. These only provide an indication to the potential sensitivity, however, as the product system for the windows in this case may be quite different than those included in the model.

8.3.1 Representational accuracy of model and data

Many assumptions were made in modelling the product system with representative processes and datasets. Decisions were made between different data sets when there were multiple available process data and surrogate data was required when there were none. This data also required allocation assumptions as the materials and energy were used for the manufacture of numerous products. Every allocation that was used (the list is found at the end of the Appendix) introduces uncertainty into the model.

The sensitivity of the results to commodity material data indicates further uncertainty of its accuracy. While the use of different datasets were found to negligibly alter the results, some data in the model includes European specific transportation and energy use. These could not be corrected, or the impact of which understood, as the data were only available on a system level and did not note the contribution of individual processes.

8.3.2 Differences between cases and average production

The analysis looked specifically at the life cycles of the windows produced by the three facilities. The potential for differences between the case study and average production exist in every piece of first hand data that was collected. The transportation differences to the manufacturer were provided in the sensitivity analysis and did affect the results but not as significantly as some other assumptions because the relative impact of transportation over the life cycle was small.

The main limitation of expanding the case study to the whole market is the uncertainty of manufacturing energy and the demonstrated significance of the aluminum cladding on recycled content. These data were found to significantly affect the results by noting that assuming recycled content in the cladding and equal heating requirement based on hypothetically placing the manufacturers in the same location, changes the relative ranking in greenhouse gasses so that the aluminum clad wood window is superior in this category from cradle to gate and over the whole life cycle to PVC and fiberglass. Therefore, the results presented in Figure 4.2 and 4.4 should be considered with caution as this highly plausible example of average practice shows a completely different result.

8.4 Further Research

Based on the recognized limitations of the current research, further research is needed to improve the applicability of these results. While this case study has gained an understanding as to the impacts caused by the observed processes, its lack of applicability to the average situation may be improved by performing an industry-wide survey designed to capture the key modelling assumptions that may vary from manufacturer to manufacturer. Also, a use phase simulation may be performed to test the advantages of the different window types in the current work with those caused by superior thermal efficiency.

8.4.1 Focused Industry Wide Survey

The research in this thesis only considered the manufacturing of windows at the three facilities. In this analysis the key assumptions were found and may now be used to reconfigure the model as it applies to average production.

It may be assumed that the design of windows across industry is relatively uniform, although the average amount of material/frame length should be determined. It may also be assumed that PVC and fiberglass window assemblies generate similar lineal waste as these processes are simply the cutting of frame pieces from 6 meter lengths of material. Differences are expected in the amount of wood waste that is produced and the amount of energy that should be allocated to manufacturing a single window. Process specific energy inputs may be established through power consumption meters installed directly into the manufacturing machinery while the overhead requirements would need to be allocated based on the various processes. A potential survey would ask the amounts of fuel consumed over a given year and also a description of the processes that occur in the factors so that the correct allocation would be used. The energy used by assemblers would be allocated based on the quantity of units they produce while a physical or economic allocation may be applied for those that vary based on the specifications of the window produced.

8.4.2 Use Phase Simulation

As was noted in the limitations section and literature review, use phase energy may be used to place manufacturing, maintenance, and disposal impacts into the context of the total consequences of the decision of material selection. This is justified by the findings of all previous research (Weir and Muneer 1998, Citerhlet et al. 2000, and Kiani et al. 2004) that found the use phase to be the most significant life stage in terms of energy use.

A myriad of factors have been considered as influential to use phase energy requirements and numerous texts have been devoted to calculating daylighting and thermal loss and gain as functions of the materials used, the orientation within the structure, geographic location, and interaction with other systems such as HVAC. While this is of obvious concern to the LCA practitioner, the detailed calculation of these values is complex and requires specific expertise. Simulation programs have been developed that consider the significant factors in calculating performance and life cycle inventory values have been developed in this manner.

Use phase energy is typically found by considering several representative climates, by redefining the functional unit of comparison to include a built structure with or without the windows installed in it, and by simulating the thermal load difference caused by the window. CORRIM recently integrated LCI findings for wood based building envelope materials with a use phase simulation for the climates of Minneapolis and Atlanta that used Sima Pro energy process data to relate the results of the simulation software to inventory values and characterization factors (Winistorfer et al. 2005). This would be a straightforward exercise as the model is currently programmed in Sima Pro and use phase energy totals could be related directly to the totals found in the impact analysis presented in this paper. This analysis would further elucidate the differences between frame material impacts and recognize potential tradeoffs between cradle to gate savings and improved use phase energy performance.

REFERENCES

Asif, M., Davidson, A., and T. Muneer. 2002. Life Cycle of Window Materials – A Comparative Assessment. Napier University, School of Engineering, UK. Retrieved on August 23, 2007 from http://www.cibse.org/pdfs/Masif.pdf.

Ayers, R., and L. Ayers. 1999. The Life Cycle of Chlorine Part IV: Accounting for Persistent Cyclic Organo-Chlorines. *J. Ind. Ecol.* 3(2-3): 121-159.

Bare, J.C., Hofstetter, P., Pennington, D.W. and H.A. Udo de Haes. 2000. Life cycle impact assessment workshop summary: Midpoints versus endpoints, the sacrifices and benefits. *Int. J. Life Cycle Ass.* 5(6): 319-326.

Chevalier .JL, Krogh H., and M.Tarantini 2003. IEA-SHC Task 27: Environmental performance assessment of glazing and windows: context, overview, main concerns. Retrieved on August 23, 2007 from http://www.iea-shc-task27.org/

Citherlet, S., Di Guglielmo, F., and J.B. Gay. 2004. Window and advanced glazing systems life cycle assessment. *Energ. Buildings.* 32(3): 225-234.

Consoli F., Allen D., Boustead I., Fava J., Franklin W., and A. Jensen . 1993. A code of practice: Guidelines for life-cycle assessment. Oude, Parrish, Perriman, Postlethwaite, Quay, Seguin, Vigon, editors. SETAC: Pensacola, USA.Curran, A.M. 2004. The status of Life Cycle Assessment as environmental management tool. *Environ. Prog.* 23(4) : 277-283.

Ekvall, T. 1999. Key methodological issues for life cycle inventory analysis of paper recycling. *J. Clean. Prod.* 7(4): 281-294.

Entec UK Ltd. 2000. Life Cycle Assessment of Polyvinyl Chloride and Alternatives, Final Report. Retrieved on July 6, 2007 from http://www.defra.gov.uk/ENVIRONMENT/consult/pvc/

Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier R., Nemecek, T., Rebitzer, G., and M. Spielmann. 2005. The Ecoinvent Database: Overview and Methodological Framework. *Int. J. Life Cycle Ass.*, 10(1): 3-9.

Heijungs, R., Guinée, J.B., Huppes, G., Lankrijer, R.M., Udo de Haes, H.A., and A. Wegener, 1992. Environmental life cycle assessment of products. Vol. I: Guide and Vol. II: Backgrounds. , CML Centre for Environmental Studies, Leiden University, The Netherlands.

International Standards ISO 14040:2006. 2006. Environmental management – life cycle assessment – principles and framework.

International Standard ISO 14041. 1998. Environmental management – life cycle assessment – goal and scope definition and inventory analysis.

International Standard ISO 14042. 2000. Environmental management – life cycle assessment – life cycle impact assessment.

International Standard ISO 14043. 2000. Environmental management – life cycle assessment – life cycle interpretation.

International Standard ISO 14044:2006. 2006. Environmental management – life cycle assessment – requirements and guidelines.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., and R. Rosenbaum, 2003. IMPACT 2002+: A New Life Cycle Assessment Methodology. *Int. J. Life Cycle Ass.*, 8(6): 324-330.

Kiani, M., Ip, K., and A. Miller. 2004. Evaluate the Whole Life Environmental Impact of Glass in a Fully Glazed Commercial Building. World Sustainable Building Conference, Tokyo, 2005.

Klopffer, W. 2005. The Critical Review Process According to ISO 14040-43. *Int. J. Life Cycle Ass.* 10(2): 98 – 102.

LCA 101. Retrieved on July 6, 2007 from ww.w.epa.gov/NRML/lcaccess/lca101.htm

Lenssen and Roodman, 1995, "Worldwatch Paper 124: A Building Revolution: How Ecology and Health Concerns are Transforming Construction," Worldwatch Institute. Retrieved on August 23, 2007 from http://www.worldwatch.org/node/866

LeVan L. S. 1996. Life Cycle Assessment: Measuring environmental impact. *Life cycle environmental impact analysis for forest products*. Forest Products Society. In proceeding of the 1995 Annual Meeting of the Forest Products Society. Wisconsin, Madison. pp. 7-16.

Lindeijer, E. 2000. Biodiversity and Life Support Impacts of Land Use in LCA. *J. Clean. Prod.* 8(4): 273-281.

Lucier, A. 1996. Understanding relationships among forest products, resource renewability, and global carbon cycle. In proceeding of the 1995 Annual Meeting of the Forest Products Society.Wisconsin, Madison. pp. 46-49

McHugh, A., Gough, A. and J.L. Innes, 2005. Indicators of Sustainable Forest Management: Review of Potential Indicators. University of British Columbia, Faculty of Forestry, Sustainable Forest Management Lab. Retrieved on August 23, 2007 from http://sustain.forestry.ubc.ca/Site/C%20and%20I.htm

Menzies, G. and T. Muneer. 2003. A life cycle assessment of multi-glazed windows. NorDan UK, Ltd. Retrieved on August 23, 2007 from http://www.nordan.co.uk/features/features_assets/life_cycle.pdf

National Association of Homebuilders. 2007. Housing Statistics. Retrieved on November 15, 2007 from http://www.nahb.org/category.aspx?sectionID=819.

Norris, G. 2003. SimaPro Database Manual: The Franklin US LCI Library. Retrieved October 1, 2007 from www.pre.nl/download/manuals/DatabaseManualFranklinUS98.pdf

Peereboom, E., Kleijn, R., Lemkowitz, S., and S. Lundie. 1998. Influence of Inventory Data Sets on Life Cycle Assessment Results: A Case Study on PVC. *J. Ind. Ecol.* 2(3): 109-130.

PE Europe GmbH. 2004. Life Cycle Asessment of PVC and of Principle Competing Materials. Commissioned by the European Commission, Retrieved on June 15, 2007 from http://ec.europa.eu/enterprise/chemicals/sustdev/pvc-final_report_lca.pdf

Pennington, D. W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T. and G. Rebitzer. 2004. Life Cycle Assessment Part 2: Current Impact Assessment Practice. *Env. Int.* 30(5): 721-739

Perez-Garcia, J., B. Lippke, D. Briggs, J. Wilson, J. Bowyer, and J. Meil. 2005. The Environmental Performance of Renewable Building Materials in the Context of Residential Construction. *Wood Fiber Sci.* 37(1): 3-17.

Rebitzer, G., Ekvall, T., Frishknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W. P., Suh, S., Weidema, B. P. and D. W. Pennington. 2004. Life Cycle Assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Env. Int.* 30(5): 701-720.

Recio, J.M.B, Narvaez, R.P., and P. J. Guerrero. 2005. Estimate of energy consumption and CO_2 emission associated with the production, use and final disposal of PVC, aluminium, and wooden windows. Department de Projectes d'Engineyeria, Universitat Politecnica de Catalunya, Environmental Modelling Laboratory Barcelona, Spain. Retrieved on August 23, 2007 from http://www.aboutpvc.org/recursos/12recurso.pdf

Richter, K. 1995. Life Cycle Analysis of Wood Products, Life Cycle Analysis. *Life Cycle Analysis: A Challenge for Forestry and Forest Industry, EFI No. 8,* Hamburg, Germany: University of Hamburg.

Scheuer, C., and G. Keoleian. 2002. Evaluation of LEED Using Life Cycle Assessment Methods. Prepared for National Institute of Standards and Technology, US Department of Commerce. Retrieved on July 5, 2007 from http://www.lcacenter.org/library/pdf/LEED-LCA-Wyly.pdf

StatCan 2000. Statistics Canada, Trucking in Canada, Catalog # 053-222, Ottawa, Ontario, Canada. Retrieved on May 29, 2007 from http://www.statcan.ca/english/freepub/53-222-XIB/0000053-222-XIB.pdf

StatCan 2002. Statistics Canada, Trucking in Canada, Catalog # 253-222, Ottawa, Ontario, Canada. Retrieved on May 29, 2007 from http://www.statcan.ca/english/freepub/53-222-XIB/0000253-222-XIB.pdf

StatCan 2003. Statistics Canada, Trucking in Canada, Catalog # 353-222, Ottawa, Ontario, Canada. Retrieved on May 29, 2007 from http://www.statcan.ca/english/freepub/53-222-XIB/0000353-222-XIB.pdf

Steel Construction Institute (SCI). 2003. Recycling of architectural flat glass. Retrieved on June 26, 2007 from http://scinews.steel-sci.org/Publish_Article.asp?Src=a0000162.xml

Syrrakou, E., Papaefthimiou, S. and P. Yianoulis. 2005. Environmental assessment of electrochromic glazing production. *Sol. Energ. Mat. Sol. C.* 85(2) : 205–240.

Totsch, W. and T. Gaenssle, 1992, Polyvinylchloride, Environmental Aspects of a Common Plastic. Elselvier Publishing, NewYork, NY.

Trusty, W. and S. Horst. 2002. Integrating LCA tools in green building rating systems. Proceedings: USGBC Greenbuilding International Conference and Expo, Austin. Retrieved on April 11, 2007 from http://www.athenasmi.ca/publications/publications.html

Trusty, W., and J. Meil. 1999. Building Life Cycle Assessment: Residential Case Study. ATHENA Sustainable Materials Institute. Retrieved on August 23, 2007 from http://www.environmental-expert.com/articles/article1157/ATH_AIA_paper.pdf

Udo de Haes, H.A., Jolliet, O., Finnveden, G., Hauschild, M., Krewitt, W. and R. Mueller-Wenk. 1999. Best available practice regarding impact categories and category indicators in life cycle impact assessment: Part 1. *Int. J. Life Cycle Ass.* 4(2): 66–74.

United States Department of Energy. 2006. Buildings Energy Data Book. Retrieved April 23, 2007 from http://buildingsdatabook.eren.doe.gov/default.asp?id=view_book&c=5

United States EPA (USEPA). 1997. Characterization of Construction and Demolition Debris in the United States. 1997 Update. Retrieved on June 26, 2007 from http://www.epa.gov/epaoswer/non-hw/debris/about.htm.

United States EPA (USEPA). 2006a. 2005 Facts and Figures. Document number EPA530-R-06-011. Retrieved on June 26, 2007 from www.epa.gov

United States EPA`(USEPA). 2006b. Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2004. Retrieved on June 26, 2007 from http://www.epa.gov/climatechange/emissions/downloads06/06_Complete_Report.pdf

United States Green Building Council. 2007. USGBC's Life Cycle Assessment Group Produces First Set of Recommendations. Press Release dated 1/26/2007. Retrieved on June 26,2007 from http://www.usgbc.org/News/PressReleaseDetails.aspx?ID=2892

Weir, G. and T. Muneer. 1998. Energy and Environmental Impact Analysis of Double-Glazed Windows. *Energ. Convers. Manage.* 39(¾): 243-256.

Winistorfer, P., Z. Chen, B. Lippke, and N. Stevens. 2005. Energy Consumption and Greenhouse Gas Emissions Related to the Use, Maintenance and Disposal of a Residential Structure. *Wood Fiber Sci.* 37(2): 128-139.

APPENDIX: MANUFACTURING INVENTORY CALCULATIONS

This document provides the calculation details of the manufacturing process inventory values for the three window types. The three facilities were visited, at which time documents were provided that allowed the calculation of inventory values caused by the manufacturing of one window. Multiple-output allocations were required in several cases as the individual causation of cumulative flows were not always recorded or measurable. The result is a detailed bill of materials for a finished aluminum clad wood, PVC, and fiberglass window, the amounts of all materials present in the finished product, along with the waste and resource use associated with this production.

The basis of the investigation is an operable 600mm wide x 1200mm tall awning/casement window, of standard profile and a design specific for the North American market, and assembled with a double glazed sealed unit. Note that this is not the functional unit as there is no time component. The vertical integration of the three companies varied, with The wood window manufacturer producing frames from un-planed lumber and sealed units from sheets of float glass, The fiberglass window manufacturer producing pultrusion lineals in house and assembling with externally sourced sealed units, and The PVC window manufacturer outsourcing the production of lineals and sealed units. It follows that the integration of these results into life cycle inventories must assume the differences in the boundaries of this process data and ensure comparability.

The wood windows are available with or without protective aluminum cladding, although the vast majority of windows sold include the cladding option. The following calculations are presented for both options. The flows of the following materials were recognized as significant and were accounted for:

Frame and Sash

- Kiln-dried Douglas Fir
- Aluminum Cladding
- Wood Preservatives
- Adhesives
- Polymer Weatherstripping
- Paint

Sealed Unit

- Low E Glass
- Argon Gas
- Aluminum Spacer Bar
- Sealants (Primary, Secondary, and Caulk)
- Desiccant

The processing of wood, glass, aluminum, and argon resulted in waste. The quantities of these wastes were determined as were the amounts that are recycled, sold as co-products, emitted to air, and landfilled as solid waste.

It was determined that the most efficient way to determine the amount of each material in a finished product was to use the assembly instructions. This document was chosen over their bill of materials because it referred directly to CAD files that specified the amount of each material for the available sizes.

Kiln-dried Douglas fir

The manufacturer uses Kiln-dried Douglas fir in the production of their windows. This material is logged, milled, and dried in the Pacific Northwest region and is shipped to them on flatbed trailers. After arrival, the wood is stored in a staging area where its moisture content is allowed to stabilize. From this stock, wood is sent through ripsaws and cross-cut saws that use laser scanners and planning algorithms that extract the maximum amount of usable product. The off-cuts from these processes are finger-jointed and edge-glued to increase the utilization by using this material for hidden pieces. The cut pieces are then sent to the shaping department where they are cut to the profiles of the various pieces required to make a window.

The assembly instructions provided the length of each profile that is needed to make different size windows. The lengths of the lateral pieces were given as a function of the width of the window, while the vertical pieces were a function of the unit height. The assembly instructions also referred to the CAD drawings of each profile. These CAD drawings allowed the calculation of the cross-sectional areas for each irregularly shaped profile. After the cross sectional areas were known, the amount of wood in the final product became a function of the height and width of the unit. The sill block and sash block are of fixed length and the volume of each piece was also recorded. The sizes of the wood pieces differ depending on whether the window is clad or not and Tables A.1 and A.2 show the calculated volume of wood for both options. The tables include the name of each piece, the quantity and length adjustment (difference from height or width) as specified by the assembly instructions, the cross sectional area determined from the CAD drawings, and the volume calculated for a .72 m^2 window with a 2/1 height/width ratio (600mm x 1200mm).

	QUANTITY	AREA (mm^2)	LENGTH DIFFERENCE (mm)	VOLUME (mm^3)
Lateral (w + length adj.)				
Top Rail	1	1204.7	-54	657766.2
Bottom Rail	1	1404.7	-54	766966.2
Head Jamb/Sill	2	3108.49	-32.5	3528136.15
Head Jamb Moulding	1	792	-89	404712
Sill Cover	1	670.2	-70	355206
Sash Glazing Stop	2	141.3	-123	134800.2
Jamb Extension	2	727	-16	849136
Vertical (h + length adj.)				
Stile	2	1204.7	-54	2761172.4
Side Jamb Moulding	1	792	-97	873576
Side Jamb	2	3108.49	0	7460376
Sash Glazing Stop	2	141.3	-128	302947.2
Jamb Extension	2	727	-16	1721536
Other		*Volume*		
Sill Block	1	12635		12635
Sash Block	6	1614		9684
			Volume (mm^3)	19838649.35 00
			Volume (m^3)	0.0198

Table A.1: Volume of Wood in Window

	QUANTITY	AREA (mm²)	LENGTH DIFFERENCE (mm)	VOLUME (mm³)
Lateral (w + length adj.)				
Top Rail	1	1447.9	-54	790553.4
Bottom Rail	1	1662.9	-54	907943.4
Head Jamb/Sill	2	3108.49	-32.5	3528136.15
Head Jamb Moulding	1	792	-89	404712
Sill Cover	1	670.2	-70	355206
Sash Glazing Stop	2	141.3	-123	134800.2
Jamb Extension	2	727	-16	849136
Brick Mold Head	1	1294.2	70	867114
Sill Nosing	1	675.2	80	459136
Vertical (h + length adj.)				
Stile	2	1447.9	-54	3318586.8
Side Jamb Moulding	1	792	-97	873576
Side Jamb	2	3108.49	0	7460376
Sash Glazing Stop	2	141.3	-128	302947.2
Jamb Extension	2	727	-16	1721536
Brick Mold Side	2	1294.2	27	3175966.8
Other		<u>*Volume*</u>		
Sill Block	1	12635		12635
Sash Block	6	1614		9684
			Volume (mm³)	25172044.95
			Volume (m³)	0.0252

Table A.2: Volume of Wood in Non-Clad Window

Because wood is machined in-house, it was also necessary to calculate the amount of waste that is generated in creating the pieces shown above. Because the wood window manufacturer makes many different products that use the same wood components, it was not possible to track a single board from its arrival at the plant to the final product. A factor of 29% was provided as an estimate of the wood window manufacturer's wood utilization. This means that for every m^3 of wood that arrives at the wood window manufacturer, .29 m^3 is left in the finished window frame while .71 m^3 is emitted as co-products and waste. By using the calculations above that .0198 m^3 and .0252 m^3 of wood are present in the final products with the 29% utilization assumption, it was determined that 0.0684 m^3 of wood were needed to produce the clad window and 0.0868 m^3 of wood were needed to produce the non-clad one. The differences of these two figures are .0486 m^3 and .0616 m^3 and represent the amount of co-products and waste produced for a 600mm x 1200mm clad and non-clad window.

Wood waste is collected by the wood window manufacturer through an efficient bagging system, emitting just 0.2% of all that is collected to the atmosphere. This waste is then burned to heat the facility in winter months and the remainder is bagged. Documents were provided that show the total amounts that are combusted for heat annually and also the total amount of wood used in 2004. The ratio of burned waste to total wood use was assumed to be uniform over all manufacturing and allowed the calculation of wood burned in making a 600mm x 1200mm window.

This calculation is shown below.

$$wb = \frac{WB}{W} * w$$

WB: wood burned in 2004
wb: wood burned in 2004 allocated to one window
W: wood used in 2004
w: wood used in 2004 allocated to one window

Equation A.1: Burned Wood Waste Allocation Formula

$$\text{Clad: } 15.089 \text{ kg} = \frac{6244547 \text{ kg}}{11692315 \text{ kg}} * 28.253 \text{ kg}$$

$$\text{Unclad: } 19.146 \text{ kg} = \frac{6244547 \text{ kg}}{11692315 \text{ kg}} * 35.845 \text{ kg}$$

The remainder from the production of windows is bagged, a portion of which is sold as animal bedding. Table A.3 shows the total use of wood in making a 600mm x 1200mm aluminum clad and non clad window.

	NONCLAD		**AL CLAD**	
	m^3	kg	m^3	kg
In Final Product	0.02517	10.396	0.019839	8.193
Total Input	0.087	35.848	0.068	28.253
Total Waste	0.062	25.452	0.049	20.060
Sawdust To Air		*0.012*		*0.009*
Burned For Energy		*19.146*		*15.089*
Bagged		*6.295*		*4.961*

Table A.3: Use of Wood in Making a Window

Cladding

This portion of the material use is only attributable to windows produced with the cladding option and is not included in the calculation of material usage for non-clad windows. The use of these components was calculated in a manner similar to the calculation used for the wood parts. The assembly instructions provided the length of each piece, once again as a function of height for the vertical pieces and width for the lateral pieces. CAD profiles were also made available for these pieces so that the cross sectional area of each could be computed. These CAD files also provided the weight of each profile per their length that saved the step of calculating mass as a function of volume and density of the alloy. Table A.4 shows the calculation of cladding for the 600mm x 1200mm window.

	kg/m	LENGTH ADJ.	VOLUME (mm3)	WEIGHT (kg)
Lateral Components (w+LA)				
Top Rail Cladding	0.301	-144.75	50988	0.13703
Bottom Rail Cladding	0.32	-144.75	54174.75	0.14568
Frame Cladding	0.433	0	96600	0.2598
Nailing Flange	0.304	60	74580	0.20058
Vertical Components (h+LA)				
Stile Cladding	0.301	-48.5	128968	0.3466
Frame Cladding	0.433	0	193200	0.5196
Nailing Flange	0.304	60	142380	0.3829
			Total	1.992

Table A.4: Volume & Weight of Aluminum Cladding in Window

The cladding waste is either recycled or sent to the landfill. The percentage of input that is recycled (1.1%) and the percentage that is landfilled (25.8%) were provided. The remainder (73.1%) is present in the final product and is assumed to be sent to the landfill after the window's service. These assumptions resulted in the values found in Table A.5.

6060 T5 Alloy	In Final Product	1.9922
	Total Input	2.7288
	Waste	0.7047
	Recycled	0.0319

Table A.5: Use of Aluminum Cladding in Window

Steel Hardware

The wood manufacturer uses steel as fasteners and to give the window operability. The assembly instructions specified the particular pieces of hardware that were used. These specifications included pieces that were a function of the unit's size as well as pieces such as handles and corner fasteners that were the same regardless of the window's size. Their windows are also available with several hardware options and for this study the most common combination of hardware was chosen. Each of these pieces was weighed by hand and the total weight of hardware was calculated for the various window sizes that they offers. For the fasteners, the specifications for the double hung window were used because the assembly instructions for the awning/casement windows did not include fasteners. The waste of this material was not calculated as none of the hardware pieces received any alteration and any waste in their manufacturing is accounted for in studies specifically dealing with those processes. Table A.6 and A.7 show the tabulation of hardware for the 600mm x 1200mm window.

WINDOW TYPE	PART	kg	QUANTITY
Casement			
	Entrygard	0.538	
	Sash Hook	0.02	
	16" Maxim	0.66	
	Operator Track	0.068	
	14" Hinge	0.108	
Awning			
	Dual Arm Operator	0.432	
	Casement Stud Bracket	0.022	
	Operator Hinge	0.108	2
	Casement Estutcheon	0.064	2
	Keeper	0.014	2
	Tie Bar	0.106	
	Tie Bar	0.142	0
Both			
	Sash Lock	0.108	2
	Keeper	0.02	2
	Limit Device	0.06	
	Handle	0.07	
	Snubber	0.008	
	Awning Hardware (kg)	1.788	
	Casement Hardware (kg)	1.460	

Table A.6: Hardware Used in Window

PART	#/WINDOW	g	TOTAL/WINDOW g
1 1/8" nail	24.00	0.63	15.08
1 1/8" nail	8.00	0.63	5.03
7/8" staple	24.00	0.29	7.00
1 1/4" nail	24.00	0.80	19.17
1" nail	8.00	0.52	4.14
1/2" nail	12.00	0.26	3.11
1" nail	36.00	0.52	18.64
#7 x 7/8" srew	2.00	1.48	2.96
#7 x 1 1/4" screw	2.00	1.87	3.74
#7 x 1 1/4" screw	4.00	1.87	7.47
1" nails	24.00	0.52	12.43
#6 x 1 1/4" screw	2.00	1.56	3.12
#6 x 1 1/4" screw	2.00	1.56	3.12
#6 x 1 1/4" screw	2.00	1.56	3.12
#6 x 1 1/2" screw	2.00	1.74	3.48
#6 x 1" screw	2.00	1.38	2.76
#6 x 1" screw	2.00	1.38	2.76
#6 x 1" screw	2.00	1.38	2.76
#6 x 1 1/8" screw	4.00	1.47	5.88
2" staple	16.00	0.62	9.92
#8 2" screw	8.00	2.62	20.98
#7 x 1 1/4" screw	4.00	1.87	7.47
#4 x 1/2" screw	1.00	0.47	0.47
		Weight (kg)	0.16

Table A.7: Fastener Use in Window

Wood Preservative

Every wood component is dipped in a tank of a wood preservative to protect the product from moisture permeation and subsequent decay. The tanks of this preservative, called Woodlife, are large enough that entire pallets of components can be dipped at one time. The nature of this process prevents the direct calculation of this material use. Instead, it was assumed that the absorption of preservative was uniform across the volume of all pieces. By taking the total amount of preservative used in 2004 and dividing this number by the volume of wood used in that year, a ratio of preservative/wood use was established. Then, by multiplying this ratio by the amount of wood used to create the window, the amount of preservative used could be calculated. Because the amount of preservative used relates directly to the amount of wood used to make the window, the amount of preservative for the clad and non-clad windows differed. The calculations for both are shown below. For the 600mm x 1200mm windows, .250 liters of preservative is used to produce the clad window and .317 liters of preservative were required for the non-clad one.

$$pr = \frac{PR}{W} * w$$

PR: preservative used in 2004
pr: preservative used in 2004 allocated to one window
W: wood used in 2004
w: wood used in 2004 allocated to one window

Equation A.2: Preservative Allocation Formula

$$\text{Clad: } 0.288\ \text{l} = \frac{152558\ \text{l}}{28311\,\text{m}^3} * .0684\ \text{m}^3\ \text{clad}$$

$$\text{Unclad: } 0.365\ \text{l} = \frac{152558\ \text{l}}{28311\,\text{m}^3} * .0868\ \text{m}^3\ \text{unclad}$$

It was also assumed that waste was minimal because all of the preservative that is not absorbed remains in the container. The only waste of this process is evaporated mineral spirits that are periodically replaced to maintain the proper concentration of the solution. The total use of mineral spirits for 2004 was also provided which allowed the amount of waste for the given window to be calculated using the same logic of weighting as was done for the preservative. The result that less than .3ml of evaporation can be attributed to a single 600mm x 1200mm window indicates that this liquid evaporates slowly. The following shows these calculations.

$$ms = \frac{MS}{W} * w$$

MS: mineral spirits used in 2004
ms: mineral spirits used in 2004 allocated to one window
W: wood used in 2004
w: wood used in 2004 allocated to one window

Equation A.3: Mineral Spirits Allocation Formula

$$\text{Clad: } .3479 \text{ ml} = \frac{1441}{28311 \text{m}^3} * .0684 \text{ m}^3$$

$$\text{Unclad: } .4415 \text{ ml} = \frac{1441}{28311 \text{m}^3} * .0868 \text{ m}^3$$

Adhesives

The utilization of wood is maximized by making use of the off-cuts from the ripping and cross cut processes. Edge-gluing and finger jointing have been implemented to convert smaller volumes of acceptable wood into usable pieces. These pieces are hidden by ones of continuous grain in order to maintain the aesthetics of the window.

Like the preservative, it is impossible to calculate the amount of adhesives in the final product by direct measurement. The numerous sizes and options made available by The wood window manufacturer also prevented the tracking of these pieces through the production process. Therefore, the assumption was made that the ratio of glued to non-glued material in a window was uniform across all product lines. The use of adhesives for a single window could then be calculated in the same manner as was the use of preservatives with the knowledge of 2004 Adhesive use, which was provided. Similar to the preservative, the amount of adhesives used differed for the clad and non-clad window. For the 600mm x 1200mm window, the calculations that follow show the amount of adhesives used to make a clad and non-clad window.

$$ad = \frac{AD}{W} * w$$

W: wood used in 2004
w: wood used in 2004 allocated to one window
AD: adhesive used in 2004
ad: adhesive used in 2004 allocated to one window

Equation A.4: Adhesive Allocation Formula

$$0.154 \text{ kg} = \frac{46409 \text{ kg} + 8746 \text{ kg} + 7955 \text{ kg}}{28311 \text{ m}^3} * .0684 \text{ m}^3$$

$$0.195 \text{ kg} = \frac{46409 \text{ kg} + 8746 \text{ kg} + 7955 \text{ kg}}{28311 \text{ m}^3} * .0868 \text{ m}^3$$

Polymer Weatherstripping

Weatherstripping is used in all of the wood window manufacturer's operable windows to ensure a proper seal of the unit when it is in the closed position. Two weatherstripping profiles are used in each window. One of these is applied to the frame, the fixed portion, and the other to the sash, the part that moves. The cross sectional areas of these extrusions were made available through the CAD specifications supplied by the vendor. The CAD specifications included the use of two different polymers, a flexible thermoplastic for the contact surfaces and rigid polypropylene to maintain the components orientation in the window. Similar to the wood and cladding components, the length of each piece of weatherstripping is specified by the assembly instructions and is a function of the height and width of the window. The density of the two polymers was provided in the material safety data sheet for both materials. Waste was also deemed to be negligible as the pieces are cut to length as needed from stocks that are stored on spools and only result in waste at the end of the roll. Table A.8 shows the calculations for weatherstripping used for a 600mm x 1200mm window.

	LENGTH DIFFERENCE (mm)		AREA (mm^2)	DENSITY (g/cm^3)	
PPE Frame	-54	-54	16.28	1.06	
TPE Frame	-54	-54	12.99	0.965	
PPE Sash	-54	-54	16.71	1.06	
TPE Sash	-54	-54	15.22	0.965	
			TOTAL AREA	VOLUME (mm^3)	TOTAL WEIGHT (g)
					118.33
					92.11

Table A.8: Volume and Weight of Weatherstripping in Window

Paint

Priming is available as an option on all windows with some surfaces receiving a coat on every finished unit. The jamb on all metal-clad awning/casement, transom door, and access windows receives a coat of primer. Also, 9% of clad awning/casement window receive an interior coat of primer. Of non-clad awning/casements, 79% receive an exterior coat and 19% receive a coat on the interior surface. It was assumed that these ratios could be extended across all product lines, that the interior and exterior surfaces were roughly equal in size, and that the primed jambs were roughly half the area of those surfaces. By using these assumptions, it was calculated that 42752.5 surfaces of awning/casement windows were primed. By extending this figure across all product lines, this value becomes 84431 and is equal to the number of surfaces that were primed in 2004. This calculation is shown below.

$$S = \left(\left(\frac{S_{ac}}{Q_{ac}}\right) * Q\right) + \frac{J}{2}$$

S: surfaces painted in 2004
S_{ac}: surfaces of awning casement windows painted in 2004
Q_{ac}: quantity of awning casement windows produced in 2004
Q: quantity of all windows produced in 2004
J: jambs painted in 2004

Equation A.5: Surfaces Painted Formula

$$84431 = \left(\left(\frac{13820}{73759}\right) * 198327\right) + \frac{94542}{2}$$

This figure relates to 84431 average sized interior or exterior surfaces and needed to be scaled to relate to the perimeter of wood used in each frame. The calculation of average window perimeter was shown in the calculation of spacer bar waste. By assuming a linear increase in use with perimeter length, it was found that .159 liters of primer were used for painting one surface the 600mm x 1200mm window. This amount would double if it both the interior and exterior surface was painted. For clad windows it can also be assumed that .0782 liters are used to paint the jamb of every window.

$$pa = \frac{PA}{\overline{PE} * S} * pe$$

PA: paint used in 2004
pa: paint used in 2004 allocated to one window
pe: perimeter of window
$\overline{PE}$: average perimeter of windows in 2004
S: surfaces painted in 2004

Equation A.6: Paint Allocation Formula

$$.1563\ \mathrm{l} = \frac{14454\ \mathrm{l}}{3942.714\ \mathrm{mm} * 84431} * 3600\ \mathrm{mm}$$

Low E glass

A document was provided that showed the total number of lites, 7ft x 12ft sheets of glass, that were used in 2004. This document stated a utilization of 92.3%, which means that for every 1 m^2 of glass that arrives at the wood window manufacturer, .923 m^2 is left after the cutting process. The assembly instructions provided the area of glass that was needed to produce a window of given size. Similar to the wood components, this specification was a function of the height and width of the finished product as shown in Table A.9.

	Quantity	Height Difference (mm)	Width Difference (mm)	Area (mm^2)
Glass	2	-132	-153	954792

Table A.9: Area of Glass in Window

From this calculation, and the assumption of 92.3% utilization, the amount of waste could be calculated similarly to that of the wood components. For the window described above, the waste was .0797 m^2. All of the glass waste was returned to the manufacturer.

Spacer Bar

The manufacturer uses an aluminum spacer bar to separate the glazings in multiple paned sealed units. This bar is installed in the perimeter of the sealed unit and its mass was calculated based on this perimeter and the known density 37 g/m. The result is shown in Table A.10.

Height Difference (mm)	Width Difference (mm)	Sealed Unit Perimeter (mm)	g/m	Spacer bar (g)
-132	-153	3030	37	112.11

Table A.10: Volume and Weight of Aluminum Spacer Bar in Window

The utilization of this material was determined from direct measurements of daily waste recorded at the bending and cutting machines. This gave the total amount of waste in 2004. To allocate the correct amount of spacer bar waste to this window, the total perimeter of all sealed units produced in 2004 was needed. The calculation of the total perimeter relied on several assumptions. The first was that it was reasonable to estimate the average perimeter of all units produced as the perimeter of a unit of average area. This assumption was made despite the recognition that upon inspection the estimation slightly inflates the value of average perimeter. A second assumption, a 2:1 height to width ratio, was made to convert this average area to the corresponding perimeter. Ian and others ensured that this was a reasonable estimation.

These assumptions led to the following equation as a solvable function to determine the average sealed unit perimeter:

$$SUW * SUH = SUA$$

SUW: average sealed unit width
SUH: average sealed unit height
SUA: average sealed unit area

Equation A.7: Sealed Unit Dimensions

$$(x - 132) * (2x - 153) = 609787.63$$

The solution to the above equation is that x = 657.12. This means that the width of the window with an average sealed unit area is 657mm and the height is 1314. From this it was established that the dimensions of the average sealed unit were 525mm and 1161mm. Uniform waste across all products was assumed in the calculation shown below. Note that the 2004 perimeter spacer bar waste is used in this calculation to isolate this waste from that resulting from grill production.

$$sbw = \frac{SB}{SUP} * sup$$

sbw: spacer bar waste allocated to one window
SUP: perimeter of sealed units produced in 2004
sup: perimeter of sealed unit
SB: spacer bar used in 2004

Equation A.8: Spacer Bar Waste Allocation Formula

$$0.0127 \text{ kg} = \frac{3770.08 \text{ kg}}{896318981.78 \text{ mm}} * 3030 \text{ mm}$$

Sealants (Primary & Secondary)

Sealants are used to secure the spacer bars to the glass, to seal the argon filled chamber, and to make the bond between the wooden sash and glass sealed unit weather resistant. The waste of sealants at The wood window manufacturer was deemed to be negligible because their application seldom results in spillage. Data regarding the flow rates, usage/bond length, of these three materials was not available. It was noticed that the sealants are applied to the perimeter of the sealed unit. This recognition led to a weighting based on the total perimeter of all sealed units in 2004 following similar logic as that of the other materials that were impossible to measure directly.

The average sealed unit perimeter was calculated to be 3.3372 meters. This calculation was described in the calculation of spacer bar waste. By multiplying this figure by the total number of sealed cavities produced in 2004 (twice the number of triple glazed sealed units plus the number of double glazed), the total perimeter sealed in that year was obtained.

With the knowledge of the total sealed perimeter in 2004 and the perimeter of the sealed unit specified by the assembly instructions, the calculation of the sealant uses can be performed with the calculations described below.

$$se = \frac{\text{sup}}{SUP} * SE$$

SUP: perimeter of all sealed units in 2004
sup: perimeter of sealed unit
SE: sealant used in 2004
se: sealant used in 2004 allocated to one window

Equation A.9: Sealant Allocation Formula

$$\left(\frac{3030 \text{ mm}}{896318981.8 \text{ mm}}\right) * \begin{matrix} 93770.352 \text{ kg Thiover} \\ 8476.42 \text{ kg Th. Hardener} \\ 1157.85 \text{ kg PIB} \end{matrix} \qquad \begin{matrix} .317 \text{ kg Thiover} \\ .029 \text{ kg Th. Hardener} \\ .0040 \text{ kg PIB} \end{matrix}$$

Argon gas

=

To calculate the amount of argon that is present in the finished window, the volume of the sealed chamber was calculated as the area of the glass panes described above multiplied by the depth of the chamber, 12mm. Because the argon is not injected under pressure, it was assumed that its state in the final product is close to standard temperature and can be calculated by multiplying the volume of the chamber by the density of argon at STP. This is shown in Table A.11.

Height Difference (mm)	Width Difference (mm)	Area (mm^2)	Depth (mm)	Density (kg/m^3)	m^3	kg
-132	-153	954792	12	1.784	0.005729	0.01022

Table A.11: Volume and Weight of Argon in Window

The process of filling the sealed unit creates a high percentage of waste. This is because the machine that performs this task fills a large chamber with argon, seals the unit within the chamber, and then releases the waste before repeating the process on the next unit. The total use of argon was found by comparing the total usage of argon in 2004 with the total volume of all sealed units in that year. The total volume of all sealed units was found by first multiplying the total area of glass used in 2004 by utilization of 92.3%. This value, the amount of glass present in final products, is then divided by the number of glass panes produced in 2004 with the provided knowledge of the number of double and triple glazed units produced in that year. It was then assumed that the average glazing area of double and triple glazed windows was the same. This resulted in an average glazing area of 609787.63 mm^2. By multiplying this average glazing area by the depth of the sealed units produced at The wood window manufacturer, 12mm, the average volume of a sealed chamber was obtained. The assumption of 12mm is reasonable as over 90% of The wood window manufacturer's production uses this spacing. It was understood that triple glazed windows have two sealed chambers and thus double the argon volume of double glazed ones. Next, the ratio of 2004 argon use to 2004 sealed unit volume was multiplied by the volume of the sealed unit under examination to find the total amount of argon needed to make that window. This calculation is shown below:

$$ar = \frac{AR}{SUV} * suv$$

AR: argon used in 2004
ar: argon used in 2004 allocated to one window
SUV: sealed unit volume in 2004
suv: sealed unit volume of window

Equation A.10: Argon Allocation Formula

$$0.189 \text{ kg} = \frac{64114.8 \text{ kg}}{1944.66 \text{ m}^3} * 0.0057 \text{ m}^3$$

This calculation revealed that for the 600mm x 1200mm window, 0.189 kg was required to fill a sealed unit that holds .01kg of argon. The 97% waste of this material may be insignificant to The wood window manufacturer's operations as it is relatively inexpensive and benign.

Desiccant

In making windows using multiple glazing, there is concern as to the buildup of moisture in the sealed chamber. To accommodate for this, desiccant absorbent is injected into the spacer bars that separate the multiple panes. It was assumed that this desiccant is uniformly applied across the length of spacer bar used in the window. To calculate the amount of desiccant in a given window, the ratio of spacer bar used/total spacer bar used in 2004 was multiplied by the amount of desiccant used in 2004. The waste of desiccant was obtained from direct measurement at The wood window manufacturer, a total of 329.9 kg in 2004, and was used to calculate the amount of waste attributable to a single window. The calculation of desiccant usage in the 600mm x 1200mm window is shown below.

$$d = \frac{sb}{SB} * D$$

D: dessicant used in 2004
d: dessicant used in 2004 allocated to one window
SB: spacer bar used in 2004
sb: spacer bar used in one window

Equation A.11: Desiccant Allocation Formula

$$0.1680 \text{ kg} = \frac{3030 \text{ mm}}{896318981.784 \text{ mm}} * 49761.18 \text{ kg}$$

Summary Table

Wood		*Metal Clad*	
		m3	kg
	In Final Product	0.0198	8.1934
	Total Input	0.0684	28.2530
	Total Waste	0.0486	20.0596
	Sawdust To Air		0.0062
	Burned For Energy		8.8045
	Bagged		11.2488
Preservative			
		l	kg
	Woodlife	0.2500	0.1950
	Mineral Spirits	0.000236	0.0002
Adhesives			
			kg
	Adhesive 42-2100		0.0760
	Adhesive 42-2150		0.0143
	Adhesive 42-2162		0.0130
	Wood Filler		0.0007
	Total Adhesives		0.1041
Paint			
		l	kg
	Primer (jamb)	0.0782	0.0985
	Primer (1 surface)	0.1563	0.1970
	Primer (2 surfaces)		
Aluminum Cladding			
			kg
6060 T5 Alloy	In Final Product		1.9922
	Total Input		2.7288
	Waste		0.7047
	Recylced		0.0319
Weather Strip			
		cm3	g
	In Final Product	111.6317	118.3296
	In Final Product	95.4457	92.1051
Hardware (Steel)			
			kg
	Awning		1.7880
	Casement		1.4600
	Fasteners		0.1646

Continues on the next page

Glass			
		m2	
	In Final Product	0.9548	
	Total Input	1.0344	
	Waste	0.0797	
Argon Fill			
		m3	kg
	In Final Product	0.0057	0.0102
	Total Input	0.1059	0.1889
	Waste	0.1001	0.1787
Polysulphide-sealant			
		l	kg
	Thiover	0.1791	0.3170
	Thiover Hardener	0.0179	0.0287
PIB Sealant			
			kg
	Amount Consumed		0.0039
Spacer Bar (Aluminum)			
			kg
	In Final Product		0.1121
	Waste		0.0127
	Total Input		0.1249
Desiccant			
			kg
	Amount Consumed		0.1682
	Waste		0.0011
	Total Input		0.1671

Table A.12: Manufacturing Inventory for Clad and Non-Clad 600mm x 1200mm Awning/Casement Window

PVC Manufacturer

The PVC window's production involves fewer materials than does the wood one due to the lack of in-house sealed unit production and the nature of PVC windows design. . The following materials were recognized as significant and were accounted for:

- PVC
- Steel reinforcement
- Steel fasteners
- Weatherstrip
- Sealed Unit

PVC

PVC is the primary material used by the manufacturer to construct windows. The shapes needed for the frame and sash are purchased as finished extruded pieces in 6 meter lengths. The required lengths are cut from these pieces based on the output of their optimization software. The cuts are made at 45 degree angles and waste results from the first cut, waste 1, the pieces between usable lengths, waste 2, and the portion at the end of the piece that is too small to be usable, waste 3. Figure A.1 shows the 3 wastes.

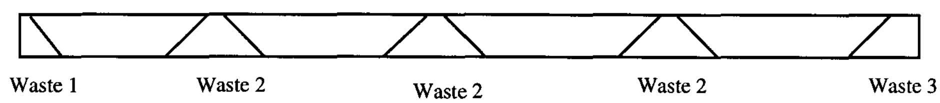

Figure A.1: PVC waste from cutting usable lengths

Offcuts were taken from the production line and weighed. The weights of the three waste types are shown in Table A.14.

Table A.13: PVC Waste Offcuts

Waste 1 (g)	*Waste 2 (g)*	*Waste 3 (g)*
25.03	50.07	75.10
19.37	38.73	58.10
3.50	7.01	10.51

The waste from the initial cut and the unusable portion at the end were averaged over the 6 meter length and the pieces between the required portions were multiplied by a factor between 3 and 3.66 related to the size of the frame pieces. This is due to the fact that the number of these waste pieces is one less than the number of lengths cut out of a given lineal. The largest window produced is approximately 1.4 meters wide. This results in 3 waste portions, as is shown in the example in Figure A.1. The smallest windows are approximately .4 meters on each side and for the 12 usable pieces in the 6 meter length, 11 waste pieces would be cut, or 3.66/ window for the 3 windows that are produced under this scenario. Thus, the number of waste pieces is between 3 and 3.66 for each window based on its dimensions. For a 600mm x 1200mm window, the average number of usable pieces cut from 6 meter lineals is 6.38, which results in 5.38 waste 2 pieces, and 3.37 for the 4 frames pieces caused by this production. The total waste is 3.37 waste 2, 4/6.38 waste 1, and 4/6.38 waste 3. Table A.15 shows the result of this calculation for a 600mm x 1200mm window:

	In Window (kg)	*Waste (kg)*	*Total Used (kg)*
Sash	2.82752	0.179	3.00652
Frame	3.65472	0.231	3.88572
Glazing Bead	0.612	0.032	0.644
Total PVC	7.09424	0.442	7.53624

Table A.14: PVC use in 600mm x 1200mm window

Steel Reinforcement

The manufacturer adds steel reinforcement bars to improve the rigidity of their windows. This is common practice in North American window manufacturing. The weight/length of the steel bars was given and the process of cutting them to length results in roughly 6 inches of waste for each 6 meter piece (2.54%). This amount is than multiplied by 4/(# usable lengths) to find the amount attributable to one window and Table A.16 shows this calculation.

	In Final Product	*Waste*	*Total Used*
Sash	2.898	0.04984	2.94784
Frame	3.204	0.05511	3.25911
Steel Reinforcement	6.102	0.10495	6.20695

Table A.15: Steel use for a 600mm x 1200mm window

Steel Hardware

The manufacturer uses steel screws to hold the window together and parts purchased from Truth hardware to make the windows operable. Each window receives a fixed number of fasteners and hardware kit that does not significantly change with window size. The steel hardware for a particular window was weighed directly. The fasteners weighed 0.08 kg and the operability hardware weighed 1.83 kg

Weatherstrip

The weight/length of the weatherstrip was found by direct measurement. Negligible waste results from the cutting of weatherstrip. For the 600mm x 1200mm window in question, 183.26 g of weatherstrip was used.

Sealed Unit

The manufacturer purchases finished sealed units and snaps them into the frames they produce using a pressure fitting. The area of glass was found from the product drawings that were provided. For the 600mm x 1200mm window, .48 m^2 of glass was used for each glazing, or .96 m^2 for a double glazed window. It is also noteworthy that the manufacturer purchases sealed units with a foam spacer bar, coined "warm edge" in the market.

Summary Table

In Final Product			*Waste*		*Total Used*	
Fasteners	0.08	kg				
Operator	1.83	kg				
Steel Hardware	1.91	kg			1.91	kg
Steel Reinforcement	6.102	kg	0.16	kg	6.261	kg
PVC	6.65	kg	0.44	kg	7.09	kg
Caulk	20.00	mL			20.00	mL
Glass Area	0.96	m2			0.96	m2
Weatherstrip	183.261	g				

Table A.16: Materials used for a 600mm x 1200mm PVC window

Fiberglass Manufacturer

The fiberglass window manufacturer's operations center around their technological capability to produce consistent fiberglass lineals. Their finished window production arose as a support of their primary focus of selling lineals to other assemblers, the machines that produce fiberglass lineals, and the patented technology that they have gained through experience. In their assembly department, the following materials were recognized as significant and were accounted for:

- Fiberglass
- PVC
- Polyester
- Steel fasteners
- Weatherstrip
- Glass (finished sealed units)

Fiberglass

Fiberglass is the primary material used to construct windows. The shapes needed for the frame and sash are produced in 6 meter lengths in their in-house extrusion department. Similar to operations at The PVC window manufacturer, the required lengths are cut from these pieces and an algorithm is used to maximize the amount of usable material in each piece. The same offcuts were also generated. In this case, a bin of offcuts collected over a shift was provided and the average was found by weighing a representative set. The result is within 1% of that found for The PVC window manufacturer. The results are shown in Table A.17.

In Final Product			*Waste*		*Total Used*	
Fiberglass	6.564	kg	.486	kg	7.050	kg

Table A.17: Fiberglass use in 600mm x 1200mm window

Fiberglass lineals are composed of glass mats, glass roving, and a resin mixture. The resin comprises about 39% of the lineal. The resin formula is a trade secret and will not be disclosed in this document.

PVC

For the glass stops, The manufacturer uses purchased PVC. This comes in 6m lengths and the corners are butt jointed, cut at right angles. Therefore, the waste that results is the length of lineal at the end of the six meters that is too short to be used. Table A.18 shows the calculation for PVC use in the fiberglass window.

	kg
In Final Product	0.489
Total Input	0.497
Total Waste	0.008

Table A.18: PVC Use in Fiberglass Window

Polyester

The manufacturer uses polyester components to bind the corners of window frames and prevent sheer. Each operable casement window has one in each corner of the frame, and one in each corner of the sash. These do not change with window size. 369.64 grams of polyester are required for each operable window.

Steel Hardware

The manufacturer uses steel screws to hold the window together and parts purchased from Truth hardware to make the windows operable. The hardware used is identical to that used by The PVC window manufacturer and The wood window manufacturer. The operating hardware was estimated at 1.80 kg. Also identical to The PVC window manufacturer, but different from The wood window manufacturer, each window receives a fixed number of fasteners and hardware kit that does not significantly change with window size. The steel hardware for a particular window was recorded and the result shown in Table A.19.

Fasteners	0.08	kg
Operator	1.80	kg
Steel Hardware	1.88	kg

Table A.19: Steel hardware

Weatherstrip

The weight/length of the weatherstrip was found by direct measurement. Negligible waste results from the cutting of weatherstrip. For the 600mm x 1200mm window in question, 121.97 g of weatherstrip was used.

Glazing Tape (Foam)

The manufacturer applies foam tape between the sealed unit and the frame to improve the seal. This tape was measured directly and the amount of foam required relates to the perimeter of the sealed unit. For the 600mm x 1200mm window, 32.07 g of foam were used.

Sealed Unit

The manufacturer purchases finished sealed units and snaps them into the frames they produce using a pressure fitting. The area of glass was found from the product drawings provided at The PVC window manufacturer. For the 600mm x 1200mm window, .523 m^2 of glass was used for each glazing, or 1.05 m^2 for a double glazed window. This is slightly more glazing area than the other two frame types.

Summary Table

Fiberglass		*kg*	
	In Final Product	6.564	
	Total Input	7.050	
	Total Waste	0.486	
PVC		*kg*	
	In Final Product	0.489	
	Total Input	0.497	
	Total Waste	0.008	
Polyester		*g*	
	In Final Product	369.640	
Weather Strip		*g*	
Thermal Plastic Elastomer	In Final Product	121.97	
Glass		*m2 (Single)*	*m2 (Double)*
	In Final Product	0.523	1.046178
Glazing Tape(foam)			*g*
	In Final Product		32.07
Hardware (Steel)			*kg*
	Casement		1.88

Table A.21: Materials used for a 600mm x 1200mm Fiberglass window