The effect on climate change impacts for building products when including the timing of greenhouse gas emissions

by

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ABSTRACT

Greenhouse gases (GHGs) trap infrared radiation emitting from the Earth's surface to generate the "greenhouse effect" thus keeping the planet warm. Many natural activities including rotting vegetation emit GHGs such as carbon dioxide to produce this natural affect. However, in the last 200 years or so, human activity has increased the atmospheric concentrations of GHGs mostly from burning fossil fuels resulting in climate change (i.e. additional warming).

Global warming potential (GWP) measures the impact from climate change but does not consider the timing of the GHG emissions. Traditional (static) life-cycle assessments (LCAs) use GWP. However, GHG emissions for building products may occur decades after initial product production and installation. A new dynamic methodology was created for long-lived products using wood flooring as an example over a 100-year time horizon.

The new methodology demonstrated the time-dependent climate change impact metric using cumulative radiative forcing. Similar to the concept of net present value, time-zero equivalent (TIZE) generates a single value where future negative and positive radiative forcing impacts are brought back to year zero. $TIZE_{100}$ values for fossil carbon dioxide, methane, and nitrous oxide were found for two wood flooring products, prefinished solid strip hardwood (SSHF) and prefinished engineered wood (EWF). Results were reported in kg CO_2-eq per functional unit of product for $TIZE_{100}$ and GWP_{100}. The functional unit was one m^2 of installed flooring in service for 80 years. The service life for SSHF and EWF are 80 and 40 years, respectively.

$TIZE_{100}$ values were less than the GWP_{100} values. For SSHF, GWP_{100} and $TIZE_{100}$ values were 20.9 and 15.6 kg CO_2-eq per functional unit, a 25% decrease. For EWF, GWP_{100} and $TIZE_{100}$ values were 34.7 and 28.9 kg CO_2-eq per functional unit, a 17% decrease. SSHF had the greatest reduction for TIZE mainly because of its longer service life resulting in less GHG emissions at end-of-life.

Including timing of GHG emissions by using the TIZE (dynamic) methodology provides greater precision on the impacts of climate change than GWP (static) does. Additionally, because TIZE and GWP use the same reporting unit, kg CO_2-eq TIZE could be an alternative to GWP.

DISSERTATION OVERVIEW AND ORGANIZATION

My dissertation focused on developing a time-dependent climate change impact metric. The dissertation is organized in the journal-style format. This format is different from the traditional format. Consider the four papers included in the dissertation separately from the general document itself. The general document includes an abstract, traditional introduction, literature review, and methodology. The general document discusses the methodology for the development of the life-cycle inventory for manufacturing prefinished engineered wood flooring (EWF) as well as the traditional and dynamic life-cycle assessments (LCAs) for the two flooring products. Papers #3 (traditional) and #4 (dynamic) have more detail than the general document. Paper #4 focuses on the new methodology, the time-dependent climate change impact metric. I created a new metric called the time-zero equivalent (TIZE).

The four papers included in the dissertation provide details found in any scientific paper. Details include abstracts, introductions, methodologies, results, conclusions, and any recommendations. Of the four papers included within my dissertation: two are published peer-reviewed papers on life-cycle inventory analysis of EWF by Bergman and Bowe and two are draft unpublished papers on traditional (static) and dynamic (temporal) life-cycle assessments for building products using two wood flooring products as the example. The first paper is referred to as a "CORRIM Report". CORRIM stands for the Consortium for Research on Renewable Industrial Materials (www.corrim.org). CORRIM Reports provide life-cycle inventory analysis on many wood products covering forest resources, resource transportation and manufacturing across the United

States. CORRIM Reports are detailed and comprehensive reports that show how the individual life-cycle stages are developed. In order to construct a full LCA, the first step is developing individual life-cycle stages as shown in paper #1 for EWF. Paper #2, a journal article is a condensed version of the CORRIM Report (Paper #1) and provides additional analysis on solid strip hardwood flooring (SSHF).

Paper #4 builds on the traditional life-cycle analysis demonstrated in paper #3. In paper #3, results focus on quantifying GHGs per cubic meter, square meter and functional units of EWF and SSHF for the various life-cycle stages. In addition, because GHGs and GWP values were reported per life-cycle stage, paper #3 provides the background LCA data for determining the timing of the GHG emissions incorporated in the new methodology (paper #4). The GHGs studied included fossil $CO_{2,}$ methane, and nitrous oxide. Paper #4 provides a literature review on the determination of climate change impacts through global warming potentials including GHG decay rates and radiative efficiencies. Additionally, the paper #4 evaluates the relative importance of the three GHGs studied on their overall impacts to climate change. Furthermore, paper #4 introduces and describes the new dynamic methodology for calculating the time-zero equivalent (TIZE) values using the concept of cumulative radiative forcing for the 100-year time horizon. TIZE values for the three GHGs were compared to the widely accepted GWP (100-year time horizon) metric. TIZE reports in the same units as GWP does (kg CO_2-eq). The general document, paper #3 and paper #4 each have their own glossaries with the general document containing definition of all terms. I have provided a list of original articles and proceedings papers that supports my dissertation research.

LIST OF ORIGINAL ARTICLES

This dissertation includes information from the following publications. Papers #1 and #2 are the two peer-reviewed papers included in the dissertation.

1. **Bergman RD**, Bowe SA (2011b) Life-cycle inventory of manufacturing prefinished engineered wood flooring in the eastern United States. CORRIM Phase II Final Report. Module N. University of Washington, Seattle, WA. 56 pp.

2. **Bergman RD**, Bowe SA (2011a) Life-cycle inventory of manufacturing prefinished engineered wood flooring in the eastern United States with a comparison to solid strip wood flooring. Wood and Fiber Science 43(4):421-441.

3. **Bergman RD**, Bowe SA (2008) Environmental impact of producing hardwood lumber using life-cycle inventory. Wood and Fiber Science, 40(3), 2008, pp. 448 – 458

4. Puettmann ME, **Bergman RD**, Hubbard S, Johnson L, Lippke B, Wagner F (2010) Cradle-to-gate life-cycle inventories of US wood products production – CORRIM Phase I and Phase II Products. Wood and Fiber Sci 42(CORRIM Special Issue):15-28.

5. **Bergman RD**, Bowe SA (2010a) Environmental impact of manufacturing softwood lumber in northeastern and north central United States. Wood and Fiber Science, 42(CORRIM Special Issue), 2010, pp. 67–78

6. **Bergman RD**, Bowe SA (2010b) Life-cycle inventory of manufacturing prefinished engineered wood flooring in the eastern United States. Society of Wood Science and Technology 53rd International Convention. Geneva, Switzerland. October 11 - 15, 2010.

7. **Bergman RD**, Bowe SA (2010c) Life-cycle inventory of hardwood lumber manufacturing in the southeastern United States. CORRIM Phase II Final Report. Module L. University of Washington, Seattle, WA. 61 pp.

8. **Bergman RD**, Taylor A (2011) Environmental product declarations of wood products. Forest Products Journal 61(3):1-12.

9. **Bergman RD**, Gu H, Napier TR, Salazar, J Falk RH (2011) Life cycle primary energy and carbon analysis of recovering softwood framing lumber and hardwood flooring for reuse. American Center for Life-cycle Assessment XI Conference. Chicago, IL. October 4-6, 2011. pp. 1-6.

10. **Bergman RD**, Bowe SA (2012) Life-cycle inventory of hardwood lumber manufacturing in the southeastern United States. Wood and Fiber Science 44(1):71-84

11. **Bergman RD**, Salazar J, Bowe SA (2012) Developing a dynamic life-cycle carbon emission inventory of wood construction for two different EOL scenarios. International Symposium of LCA and Construction 2012. Nantes, France. July 10-12, 2012 (accepted March 9, 2012).

TABLE OF CONTENTS

TABLE OF FIGURES

Section 1: Life-cycle analysis concepts

1 INTRODUCTION

1.1 Environmental performance of products

Products made of wood, concrete, plastic, and steel compete in the marketplace in other ways besides by price; e.g., wood studs compete with steel framing in residential housing. Products are increasingly evaluated based on their environmental performance including their carbon profile. In addition, products made of the same material compete for market share; oriented strand board competes with plywood as a sheathing material and prefinished engineered wood flooring (EWF) competes with prefinished solid strip hardwood flooring (SSHF) as a flooring material. Life-cycle research is one way to conduct fair and scientifically sound evaluations. Methods have been developed to determine the environmental burdens associated with the creation, transportation, use, and disposal of products, processes, and services. Accurately detailing carbon emissions for products is vital for a low carbon society.

1.1.1 Life-cycle assessment

Life-cycle assessment (LCA) is a well-established methodology used worldwide to evaluate a product or suite of products for their environmental performance. LCA considers all of the inputs and outputs for a process, product, or service of its whole life cycle from extraction to disposal (i.e. cradle-to-grave). Developing a LCA requires data on the product, process, or service. Data may be collected directly from raw material extraction and manufacturing processes (primary data), secondary data drawn from literature or tertiary data drawn from existing commercial or government life-cycle inventory (LCI) databases depending on the study goal and scope. Typically, LCA data developers collect primary data from manufacturing facilities using questionnaires (surveys). The surveyed data usually covers a pre-determined region and time period. Typically using a spreadsheet algorithm, the survey data are weight averaged on a per functional unit basis. Then the data developers use LCA software to model the weighted-average primary data per functional (production) unit. The LCA software links the primary process data collected and secondary background processes (e.g., electricity generation and delivery) to generate the LCI. LCIs measure all the raw material and energy inputs and outputs to manufacture a particular product, process, or service on a per unit basis within carefully defined system boundaries (i.e. a detailed mass and energy balance). With the inventory complete, the next step in the LCA process is to prepare a life-cycle impact assessment (LCIA) of the modeled system(s) – to find the environmental burdens from the various inputs and outputs throughout the product life cycle. Partial LCIAs typically examine two indicators – primary energy and global warming potential (GWP).

1.1.1.1 ISO Standards

Primary data collection follows International Organization of Standardization (ISO) standards (ISO 2006a; b) and other similar protocols such as Society of Environmental Toxicology and Chemistry (SETAC) (de Beafort-Langeveld et al. 2003). A standardized and transparent approach ensures data quality and representation necessary to provide the most accurate state of the industry for the given product, process, or service. Collecting primary data directly from the studied item is preferred.

1.1.1.2 Scope

Evaluating a group of competing products on their environmental performance using LCA requires that each studied product cover the same scope. The scope covers the starting and ending point of the life-cycle study. To make a comparative analysis following ISO 14040 standards, the products ought to start for example at extraction and end at disposal (ISO 2006a; b). A comparative analysis shows the environmental advantage if any of one product over its competing alternative. Therefore, eco-labeling has become a way to communicate environmental attributes for products.

1.1.1.3 Environmental product declaration (eco-labeling)

Environmental product declarations (EPDs) are a LCA-based eco-label. Using LCA data in conjunction with product category rules, EPDs are created. EPDs for products provide a way to communicate LCA results to businesses and consumers in a standardized format, somewhat similar to nutritional labels on food (ISO 2006c; 2007). LCAs along with EPDs provide decision-makers including government, environmental non-government organizations (eNGOs), academia, and industry with environmental information to make sound scientific judgments on competing products (Bergman and Taylor 2011). EPDs provide a listing of the LCIA results including GWP in kg CO_2-eq per functional unit of product. GWP is how to measure climate change impacts now by aggregating individual GHGs. However, the new methodology developed in the present study provides a more precise value for the climate change impact from greenhouse (GHG) emissions by incorporating when the GHGs are released into the atmosphere. Different products have different GHG fluxes.

1.1.2 GHG emissions

GHG emissions (i.e. GWP) are a major focus of LCAs partially because of climate change implications. However, traditional LCAs only record the total of carbon emitted for the whole life cycle but do not include the timing of carbon or non-carbon GHGs. As a result, some life-cycle research has begun to examine the impact of climate change from the timing of GHG emissions. Researchers have studied emissions timing on biofuel to aid policy-makers on determining whether biofuels are less carbon emitting than fossil fuels (Levasseur et al. 2010; Cherubini et al. 2011; Schwietzke et al. 2011). However, current climate change metrics have not investigated the warming potential for building materials and products by including the timing of GHG emissions over the whole life cycle.

1.2 Problem Statement

Determining the impacts from the timing of GHG emissions on climate change for buildings products offers new insight into how to mitigate climate change. Werner et al. (2010) stated, "An increased use of wood products and an adequate management of forests can help to mitigate climate change". Forests and forest products help mitigate carbon (C) to the atmosphere through sequestration, storage, and release with energy recovery (substitution for fossil fuels). However, a more comprehensive method is necessary to solve the problem that includes the timing of GHG emissions for building products because traditional LCA through GWP, a static approach does not account for when GHG fluxes occur. For example, during the life cycle of a building product, GHG emissions sometime occur decades after initial product production and installation. Current climate change metrics such as GWP do not quantify the timing of GHG emissions for a given product, process or service. To aid in understanding the timing of GHG emissions more accurately, this study will answer the following question. What is the effect of GHG emissions timing on climate change impacts for the cradle-to-gate manufacturing, use and disposal?

1.3 Justification

Climate change continues to present itself as one of the most vexing environmental problems facing our society today. Since the industrial age started, carbon dioxide (CO_2) levels have increased significantly becoming the major cause of climate change (Schneider 1989, Ryan et al. 2010, IPCC 2007). Traditional LCAs track GHG emissions but more work is necessary to incorporate emissions timing. Traditional LCAs estimate GHG emissions but do not consider when the emission occurs during the life cycle, a significant shortcoming (Reap et al. 2008a). In traditional LCA framework, systems provide a snapshot so to incorporate GHG fluxes other methods are necessary. Therefore, a greater determination of the timing of GHGs and their dynamic affects will provide a more accurate assessment of a building product's climate change impact.

1.3.1 Inconsistent time period

Climate change impacts in traditional LCAs use the GWP metric discussed by the International Panel on Climate Change (IPCC) (Forster et al. 2007; Ramaswamy et al. 2001). GWP is dependent upon the time horizon chosen to estimate the GWP for a particular GHG. Most LCA studies use the 100-year time horizon to estimate the GWP. However, selection of a set time horizon results in an inconsistency between the environmental outputs such as GHGs from the time period chosen and the time period of the LCA study itself (Levasseur et al. 2010).

1.3.2 Carbon footprint

Environmental performance including the carbon footprint of building products is important for developing sound environmental policies. Carbon footprint is usually defined as the sum of GHGs emitted during the life of a product over a given timeframe. In particular, the GHG fluxes of the residential and commercial building sectors are significant and are dependent on energy consumption. Building sectors consume up to 20 to 40% of primary energy available for developed countries (Pérez-Lombard et al. 2008). For 2008, the buildings share of United States primary energy consumption was 39.9% (40.0 quads). By 2035, the commercial and residential building sector could consume 46.9 quads (USDOE 2011). Building materials make up a small but significant effect on total building material utilization and energy consumption. Therefore, building material impacts will matter more as buildings themselves become energy efficient.

To support building practices that lower carbon footprint; the building industry, building rating systems, policy makers, and consumers need information from scientific studies to evaluate carbon footprint claims. Previous studies have helped determine the environmental and energy burdens of producing and using wood compared to non-wood building components. For example, Consortium for Research on Renewable Industrial Material (CORRIM) research examined the environmental burdens associated with making and using alternate products - wood, steel, and concrete -- for framing in housing in the U.S. North and U.S. South (Lippke et al. 2004). However, the individual LCI studies did not include the time-dependent effects of GHG emissions.

1.3.3 Status of life-cycle studies for the two wood flooring products

This study will include the estimation of climate change impacts from the timing of GHG emissions for two wood flooring products. To evaluate the two products for the time-dependent effects, the first thing to do is construct traditional LCAs by linking individual LCIs together for SSHF and EWF. The LCAs quantify GHG emissions per life-cycle stage. LCI (i.e. life-cycle stage) is the tracking of material and energy flows across a system boundary in order to develop the environmental flux. A LCI is similar to a detailed mass and energy balance for a particular product or process. The two wood flooring products require LCIs to construct the full LCA. Additionally, for some wood products including SSHF, their production considered secondary manufacturing originates from primary products. Therefore, primary manufacturing precedes secondary manufacturing. SSHF is made from rough dry hardwood lumber. To develop the SSHF manufacturing LCI, Hubbard and Bowe (2010) built on the hardwood lumber LCI (Bergman and Bowe 2008). The cradle-to-gate LCI on SSHF has been completed in the United States (Puettmann et al. 2010). The cradle-to-gate LCI includes information on embodied energy and GHG emissions associated with resource extraction, resource transportation and manufacturing. Adding on the gate-to-grave LCIs from product transportation through construction and use to final disposition constructs the cradle-to-grave LCI. The resultant LCI flows derived from modeling primary data provide emission data to estimate the CO_2-equivalent emissions and other environmental impacts to air, water, and land for a functional unit of the product or process. As for constructing the traditional LCA for EWF, Bergman and Bowe have developed the LCI on manufacturing EWF in the eastern United States (Bergman and Bowe 2011a; Bergman and Bowe 2011b).

1.3.4 Importance of LCAs

Flooring LCAs are important to manufacturers, consumer groups and policy-makers. Consumers make daily choices to buy or use products made from metal, wood, plastic, or concrete. They base their product selection on a spectrum of attributes including price, quality, aesthetics, and intended service application. In recent decades, the burdens that a particular product may place on human health and the physical environment are receiving greater consideration. To make informed product choices consumers need transparent, scientifically verified, non-biased information. To this end, a statistically sound method put forth by the CORRIM has resulted in regional-based life-cycle data for an array of wood products in the United States (Puettmann and Wilson 2005; Puettman et al. 2010).

Policy-makers need scientific data developed using dynamic LCAs to understand the timing of GHGs for building products in mitigating climate change. Wood products store carbon. Therefore, carbon storage affects the timing of GHG emissions. Therefore, carbon storage can aid in mitigating climate change (Werner et al. 2010; Lippke et al. 2011; Eriksson et al. 2012). Fixing carbon in long-lived (durable) wood products prevents or delays its release into the atmosphere thus not adding to atmospheric carbon dioxide levels. Long-lived wood products such as flooring do store carbon but their impact on climate change needs to be studied. In addition, forest management practices such as harvest rotation affect carbon sequestration potential in forests. For example, EWF and SSHF use some of the same wood species; however, EWF uses less raw wood to make the final product and uses a greater variety of wood species than SSHF(Hubbard and Bowe 2010, Bergman and Bowe 2011b). However, EWF requires a higher rate of replacement than SSHF because of its lower durability. Therefore, more frequent harvesting of raw material occurs to make EWF. In the present study, forest carbon dynamics were not considered and are a limitation of the study. Future work will incorporate the forest carbon dynamics introduced by Bergman and Salazar (2012).

1.4 Objectives of this dissertation

To answer how to incorporate the impacts to climate change from the timing of GHG emissions. The following study objectives were completed:

1. Develop a gate-to-gate manufacturing LCI for EWF (Papers #1 and #2),
2. Develop full traditional LCAs for SSHF and EWF including the GHG fluxes (Paper #3), and
3. Create a new methodology to estimate the impacts on climate change on the timing of GHG emissions for building products using wood flooring as an example (Paper #4). The method will illustrate the difference between traditional and dynamic LCA.

2 LITERATURE REVIEW

The following literature review is relevant to the objectives listed above including how traditional LCA does not incorporate the impact on climate change from the timing of GHG emissions.

The purpose of life-cycle research is to determine the environmental burdens—emissions, effluents, and solid wastes—associated with production and use of particular products. The final measurements of life-cycle environmental performance are in units of environmental output released per functional unit of final product, e.g. kilograms of fossil carbon dioxide emissions per cubic meter of softwood plywood. LCA is a well-established scientific method for estimating and assessing the environmental burdens assigned to the whole life cycle of a product. LCA is a relative approach based on a functional unit thus differing from other approaches such as risk assessment, environmental performance evaluation, and environmental impact assessment. For example, risk assessment deals with a single element or compound whereas LCA deals with an array of elements and compounds (SAIC 2006). For building materials, life-cycle research is a systematic and transparent approach that ensures the validity and quality of results. However, traditional LCA only tracks the individual GHGs as a single aggregated value without considering emission timing. Not including impacts from emission timing is just one of several shortcomings in traditional LCA (Reap et al. 2008a; 2008b).

This study examines the durability of the various flooring materials in conjunction with its maintenance over the expected life of a house. How long a product lasts prior to disposal, replacement, or refurbishing provides greater insight into the product total impact over the expected lifetime of a house. The expected life of a house provides a sound basis for selecting a flooring product. For example, one would expect SSHF to last as long as a house and to outlast carpet by a factor of seven to ten times (Peterson and Solberg 2004). EWF lasts only half as long as SSHF. In addition, SSHF and EWF require refurbishing of its coatings about every 20 years unlike carpet. Coatings are similar for the two wood flooring products.

2.1 Background

2.1.1 Life-Cycle Assessment

A LCA is comprised of four stages (phases) as defined by the ISO. These are 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (Figure 2-1). A LCA study includes all stages but a LCI studies does not include stage 3 (SAIC 2006, ISO 2006a, b).

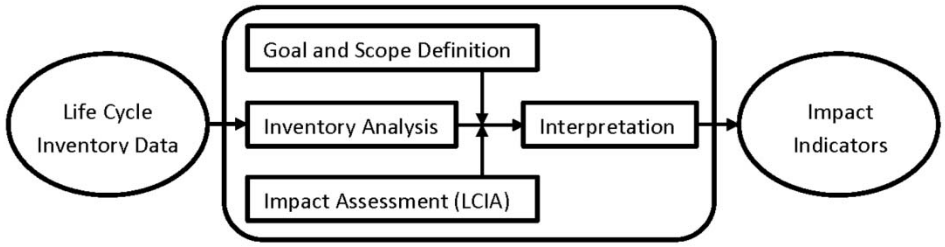

Figure 2-1: Life-cycle assessment stages

Applications of LCAs include environmental process improvement, green building rating systems/codes/standards, EPDs for public policy making and (green) marketing, and building national LCI database. Green building standards such as the National Green Building Standard (NGBS) for residential housing are updated every few years. For the NGBS ICC-700, builders accumulate points when prescribed activities are performed. The more points a builder collects, the higher the rating of the building. Performance levels are Bronze, Silver, Gold, and Emerald. For example, originally published in 2008, the NGBS ICC-700 provided points just for completing a LCA on a building product. Now, in 2012, the updated standard will require having an environmental performance improvement for a building product or assembly based on a LCA to alternatives to get points.

2.1.1.1 Goal and scope

Goal and scope of a LCA study describes a product system for a functional unit and system boundary. The goal and scope section also provides the basis for any study. Defining the system boundary determines the boundary between nature and the studied technology. Nature includes raw materials such as grass, iron ore, carbon dioxide (in air), crude oil, and trees. Setting the system boundary defines what unit processes are to be included in the study. A functional unit (a reference unit) is a quantity of a studied product. The functional unit provides a reference unit to compared alternative products capable of performing the same task for a pre-determined service life. Functional units for products are typically measured in physical units such as volume, area, or mass of the product. Examples of product systems include dairy products.

Examples of a functional unit for dairy products are one gallon of ready-to-consume packaged milk leaving the dairy or 100 pounds of ready-to-consume packaged butter leaving the dairy. The system boundary may start with milking the cows at the dairy farm or start when the raw milk arrives at the dairy for processing into dairy products. The start of the system boundary is stated in the goal and scope section of the life-cycle study.

The scope describes the depth of the study and shows that the intention of the study can be satisfied given a set of assumptions and limitations. In addition, the scope assigns which environmental impacts of the product are to be evaluated such as water usage, GWP, or primary energy consumption and what other products are the results compared to. Furthermore, the scope determines if system expansion or some other sort of allocation is necessary such as mass, energy, or economic.

Some technologies produce co-products along with the final product being studied especially wood products. When co-products are produced along with the product, the system is referred as a multi-output process. Many wood product facilities are multi-output processes . Therefore, material flows and energy consumption for the process including the environmental burdens must frequently be assigned (allocated) to the final product and associated co-product(s). Allocation is recommended to be made according to a given procedure: 1) Wherever possible, allocation should be avoided. 2) Where allocation is not avoidable, inputs and outputs should be partitioned between its different functions or products in a way that reflects the underlying physical relationships between them, and 3) If the latter is not possible, allocation should be carried out based on other existing relationships (e.g. in proportion to the economic value or mass of products and co-products).

Allocation methods resolve issues where co-products are generated along with the final product and are not consumed within the manufacturing process being studied. For example, corn stover is produced as a co-product during corn grain production and the corn stover is made into cellulosic ethanol. One approach for allocation is to assign all of the energy and material to corn grain production and not consider corn stover at all. Therefore, corn stover would not have any environmental burdens assigned to it prior to harvesting the material. Another allocation method called system expansion would involve the entire ethanol production chain for both corn grain and stover from cradle-to-gate, a much more costly and time-consuming study than the alternative approaches to allocation. However, system expansion does avoid allocation of material and energy flows between the final product and associated co-product(s). Another approach is to assign energy and GHG burdens based on how much ethanol using current technology is made from the corn grain and corn stover generated per acre of land for 2012 in Wisconsin, an energy allocation method. This allocation approach covers time, geography, and technology.

Reliability of the outcome from LCA studies depends largely on the degree to which data quality requirements are met. The following parameters ought to be considered: 1) technology coverage, 2) geographical coverage, 3) time-related coverage 4) consistency and reproducibility of the methods used throughout the data collection, 5) accuracy, completeness and representativeness of the data, and 6) uncertainty of the data gaps and information. Reproducibility is strongly dependent on data documentation.

2.1.1.2 Inventory analysis

A LCI measures all the raw material and energy inputs and outputs to manufacture a particular product, process, or service on a per unit basis within carefully defined system boundaries (ISO 2006b). For the product manufacturing stage, this is often referred to as a gate-to-gate LCI. Quite simply, a LCI is a detailed mass and energy balance on a given process or product. For example, EWF manufacturing falls within the product manufacturing stage of a cradle-to-grave LCI (Figure 2-2). A LCI tracks all material and energy flowing across the system boundary as an input or output in relation to the functional (production) unit.

Material and energy inputs and outputs cover a wide spectrum depending on the product being made. Material inputs include such raw materials as trees, grass, crude oil, natural gas, and iron ore or intermediate products such as rolled steel, pellets, gasoline, or green lumber. Energy inputs include wood fuel, fuel oil, propane, and electricity. Material outputs include products, co-products, waste by-products either recycled or landfilled, and environmental outputs to air and water (CORRIM 2010). Inventory analysis is data-intensive and time-consuming. In addition, the overall quality of a LCI or LCA study depends mostly on the quality of primary (input) data used to model the product (De Smet and Stalmans 1996).

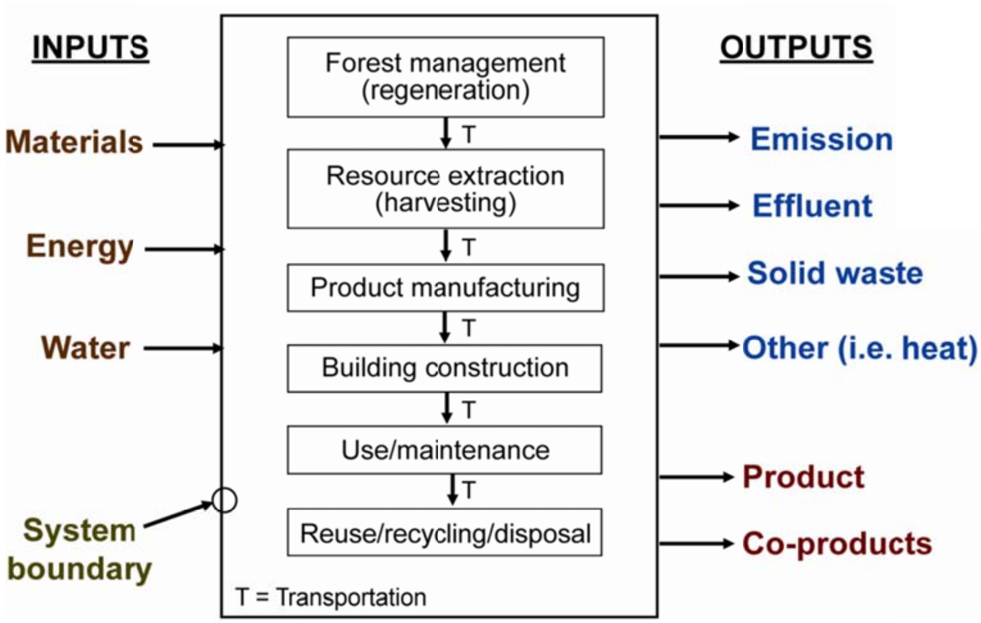

Figure 2-2: Complete life cycle from regeneration of trees to disposal of wood materials

(Source: Based on Fava et al. 1994)

Primary (survey) data collection is the most resource- and time-consuming part of the LCI. Reusing secondary data from other studies or LCI databases can simplify the work. However, using secondary data requires significant care so that the data are representative enough to meet the goal and scope of the project.

2.1.1.3 Life-cycle impact assessment

LCIAs can use LCI flows to explore impacts for the following four areas: human and social health, resource depletion, and ecosystem (Pennington et al. 2004, Bowyer et al. 2005). LCIA gives insights for architects, engineers, and designers on raw materials, product choices, and disposal methods. Learning the LCIA of a particular material if results are transparent allows stakeholders to make informed choices based on science rather than anecdotal evidence. LCIAs are part of a LCA study but not a LCI study (ISO 2006b).

2.1.1.4 Interpretation

Interpretation occurs at each stage of the life cycle. Sensitivity analysis may be conducted to examine decisions to replace material such as adhesive with an alternative on an environmental basis to aid decision-makers within a company or industry. A LCA practitioner may want to conduct a comparative analysis on alternative products. For a LCI study, results can be conclusive for product alternatives where one product shows higher material and energy consumption. For a LCIA, environmental trade-offs between the alternatives may play a factor because an impact category such as climate change may weight more heavily than say toxicological impacts. In addition, other impact categories such as land use are not well defined. Other well-established impact categories include stratospheric ozone depletion, photo oxidant formation (smog), eutrophication potential, acidification potential and respiratory effects (Pennington et al. 2004).

2.1.2 Process LCAs

In the past decade, many environmental impact studies have presented considerable differences on the LCAs used. Various LCAs include process LCAs such as attributional and consequential and commodity/industry level input/output (I/O). Depending on the process LCA used, the study has important distinctions concerning process modeling (Rebitzer et al. 2004).

2.1.2.1 Attributional life-cycle assessment

“Attributional” LCA (ALCA), the focus of this study, uses a process-modeling method to find the critical environmental impacts for a particular product referred to as “cradle-to-grave” (raw material extraction to waste disposal) analysis. ALCA is a linear approach. Therefore, the magnitude of the functional unit (m^2 or thousand m^2 of flooring) does not affect the result (Rebitzer et al 2004). This assessment includes the environmental and energy costs on a per unit basis using LCI data from individual LCI studies. LCI studies include resource extraction, transportation, primary and secondary processing, final product use, maintenance, and final disposal for a particular product.

Figure 2-2 shows an example of the life-cycle stages for a typical wood product. Results from the LCI assess environmental impact (Bowyer et al. 2005). ALCA can locate “hot spots” of environmental impacts within the product system (cradle-to-gate) to provide information for manufacturers (decision makers) regarding process improvements and design (Thomassen et al. 2008, Gaudreault et al. 2010). ALCA does not include unit processes that fall outside the system boundary (Ekvall and Andrae 2006). If necessary and unable to divide unit processes sufficiently to track impacts, ACLA studies use allocation methods to assign environmental burdens to products and co-products. Common allocation methods include mass, energy, and economic allocations (ISO 2006a; b).

2.1.2.2 Consequential life-cycle assessment

"Consequential" LCA (CLCA) is another process-modeling method that attempts to describe the (indirect) consequences of a particular decision. CLCA estimates system-wide changes in (material and energy) resource flows and environmental burdens that result from different levels of production of the functional unit based on decisions. It is the decision that affects the technology activity (Ekvall and Weidema 2004). Unlike an ACLA, a CLCA does not try to allocate the environmental burdens to the studied product, service, or process (Gaudreault et al. 2010). CLCA studies use system expansion to describe the consequences instead of allocation. In addition, this method examines the effects on marginal electricity consumption for a change in production whereas ACLA evaluates environmental impacts based on modeling average technologies to create a "composite" technology. However, CLCA is not capable within the product system of locating "hot spots" as an ALCA is (Rebitzer et al. 2004; Thomassen et al. 2008; Gaudreault et al. 2010). Additionally, conducting a CLCA versus an ALCA usually results in greater uncertainty to an individual study reducing its usefulness.

2.1.2.3 Differences of attributional and consequential life-cycle assessments

Figure 2-3 and Figure 2-4 highlight the differences between ALCA and CLCA. An ALCA (Figure 2-3) stays within carefully defined boundaries whereas a CLCA does not (Figure 2-4). CLCA activities may fall outside the original system boundary. For example, a sawmill produces sawn lumber as its final product while producing co-products such as sawdust as a co-product (Bergman and Bowe 2012). The sawdust is burned for fuel on-site or sold off-site. In an ALCA, material is not tracked once it crosses the system boundary. An ALCA examines the situation at a moment of time or a "snap-shot" while the basis for a CLCA could be a market decision to sell more sawdust to particleboard manufacturers at a higher price and buy cheap natural gas to fire the boilers to dry the lumber. Selling the sawdust affects the environmental profile of the auxiliary energy generation process and the two downstream unit processes after sawing, drying and planing. Figure 2-4 highlights the new system boundary for the studied process.

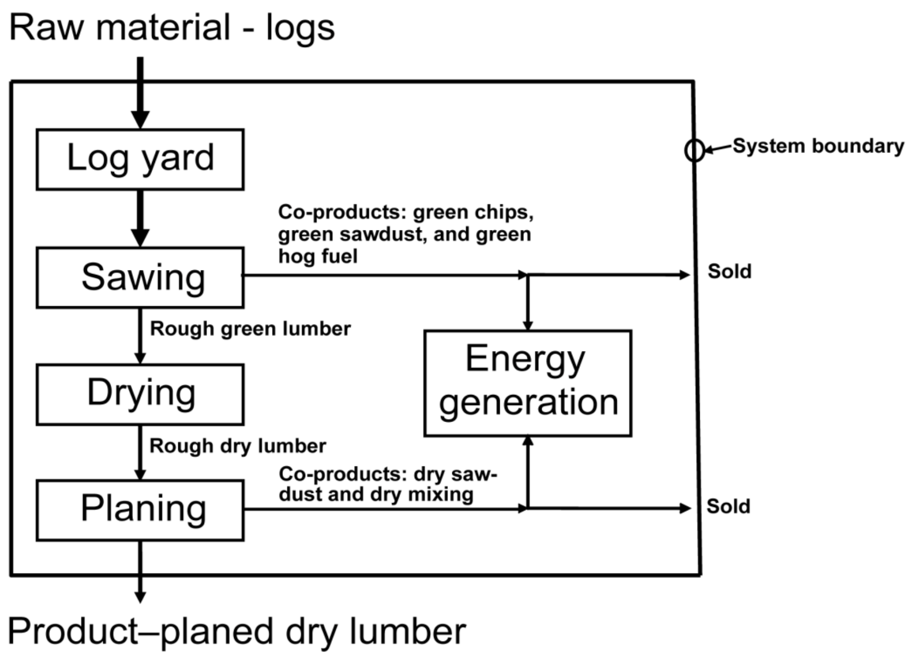

Figure 2-3: Unit processes for an attributional LCA approach on hardwood lumber manufacturing

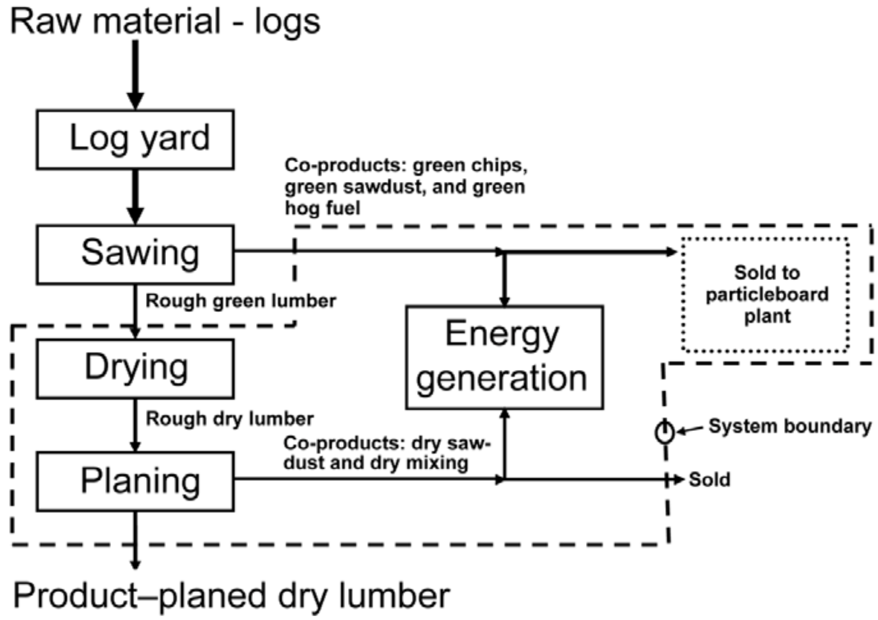

Figure 2-4: Unit processes for consequential LCA approach on hardwood lumber manufacturing when selling sawdust and burning natural gas for energy generation

2.2 History and Evolution

2.2.1 When and Why Life-Cycle Research Developed

Learning how societies affect our environment has interested and motivated people for hundreds, perhaps thousands of years (e.g. collapses of old civilizations). Past societies have declined for various reasons, one of which was the lack of available resources or the lack of understanding about availability and how to manage these resources (e.g. scarcity). Consumption of natural resources is a fundamental part of past and present societies. As the United States and world populations grow, the environmental impact of the products people manufacture, use, and dispose of becomes more critical for developing sustainable practices thus societies. Conducting life-cycle studies helps us provide the most informed choices for these products (Benedick 2000).

2.2.1.1 Early years

Life-cycle analysis began in different forms and started to formalize in the late 1960s (Guinée et al. 2011, Jensen et al. 1998). An early example of life-cycle practices involved Coca Cola and its use of glass bottles through a study in 1969 by Harry Teasley, Jr and the Midwest Research Institute. This study used the Resource and Environmental Profile Analyses (REAP) framework which studied products from cradle-to-grave using system analysis on the production chain. One part of this particular study examined the environmental impact of substituting single-use plastic bottles for refillable glass bottles. Contrary to popular opinion and expectation, the study showed single-use plastic bottles consumed less hydrocarbon raw material than did the returnable glass bottles (Duda and Shaw 1997; Hunt and Franklin 1996). Energy impacts, pollution controls, and raw material utilization motivated many of the earlier studies (Boyd et al. 1976, Vigon et al. 1993, Guinée et al. 2011).

In the 1970s, life-cycle analysis was an open field. Field practitioners continued to scrutinize the various methods, standards, and assumptions in the field. Life-cycle research was partially linked to the oil embargoes (Vigon et al. 1993).

Other methods to evaluate materials on their environmental burdens were used including REAP (Vigon et al. 1993) in the United States. Japan and some European countries implemented similar approaches to REAP. During the 1970s, interested in the life-cycle work waned in the United States whereas other countries such as Japan, Sweden, West Germany, The Netherlands, and Switzerland continued to put more and more resources into the field (Vigon et al. 1993).

2.2.1.2 Middle years

In the 1990s, organizations such as SETAC (Consoli et al. 1993) worked on consolidating and standardizing life-cycle methods. Duda and Shaw (1997) and Guinée et al. (2011) indicated the many shortcomings of LCA used to develop environmental impact data for policy-making before 1997. These shortcomings were noted prior to the release of ISO 14040 standards on environmental management (ISO 1998; ISO 2000a, ISO 2000b). These shortcomings include the lack of regional effects, the lack of transparency, uncertainty in energy conversion values for power plants, no framework for incorporating technological changes, and not incorporating transportation data into the LCA framework. The most significant issues were the lack of current primary data incorporated into these earlier LCA studies and the varying results even though the study objectives were the same.

2.2.1.3 Current years

SETAC (de Beafort-Langeveld et al. 2003) saw data collection as a vital factor in the area of LCA. A SETAC workgroup worked on data availability and quality. Key issues studied included improving data collection quality and efficiency, procedure to evaluate data quality, and procedure to aid LCI data presentation and exchange.

Some research organizations responded to these issues by providing guidance and ensuring compliance. The United Nations Environment Programme (UNEP) and SETAC launched the UNEP-SETAC Life-cycle Initiative (http://lcinitiative.unep.fr/) to establish the best practices on life-cycle research (Curran 2006). In addition, CORRIM developed research guidelines on forest products in 2001 during their Phase I LCI projects on US wood products to generate the highest data quality possible (CORRIM 2001). CORRIM research guidelines included methods to generate quality data included designating at least 5% of regional production from a minimum of four facilities. CORRIM updated their research guidelines' methodologies in 2010 (CORRIM 2010). Furthermore, the ISO continue to update the environmental management for LCA with ISO 14040 (2006a) and 14044 (2006b) standards to resolve any additional shortcomings. One distinction is the current use of critical reviews to ensure compliance particularly for peer-reviewed papers. Other researchers such as Rebitzer et al. (2004) state the necessity of including the basis (goal) for any detailed LCI study in the study itself. However, shortcomings are still present in LCA studies as reported in Reap et al. (2008a, 2008b). One continual problem is the lack of dynamic approaches necessary to evaluate the timing of emissions including carbon.

2.2.2 Consortium for Research on Renewable Industrial Materials (CORRIM)

In 1976, the National Academy of Science formed CORRIM to examine energy impacts of using renewable materials. CORRIM evaluated the energy issues for building materials and wrote a report that documented wood's energy efficiency (Boyd et al. 1976).

In 1997, CORRIM was re-formed to update the 1976 study using LCA methods to quantify and categorize environmental issues related to wood products. CORRIM is now comprised of 15 wood-related research institutions including the USDA Forest Service Forest Products Laboratory. CORRIM is helping develop a LCI database of peer-reviewed information quantifying both economic and environmental impacts of wood and non-wood building materials (USDA 2012). CORRIM developed rigorous guidelines for the researchers involved in conducting LCI studies on forestry and wood products (CORRIM 2001).

2.2.2.1 Phase I

CORRIM projects began in the Pacific Northwest (PNW) and the Southeast (SE) focusing on glulam, plywood, oriented strand board, softwood lumber, laminated veneer lumber, and trusses (Figure 2-5). These LCI studies are referred to as Phase I projects. The PNW and the SE are the largest structural wood products producing regions in the United States.

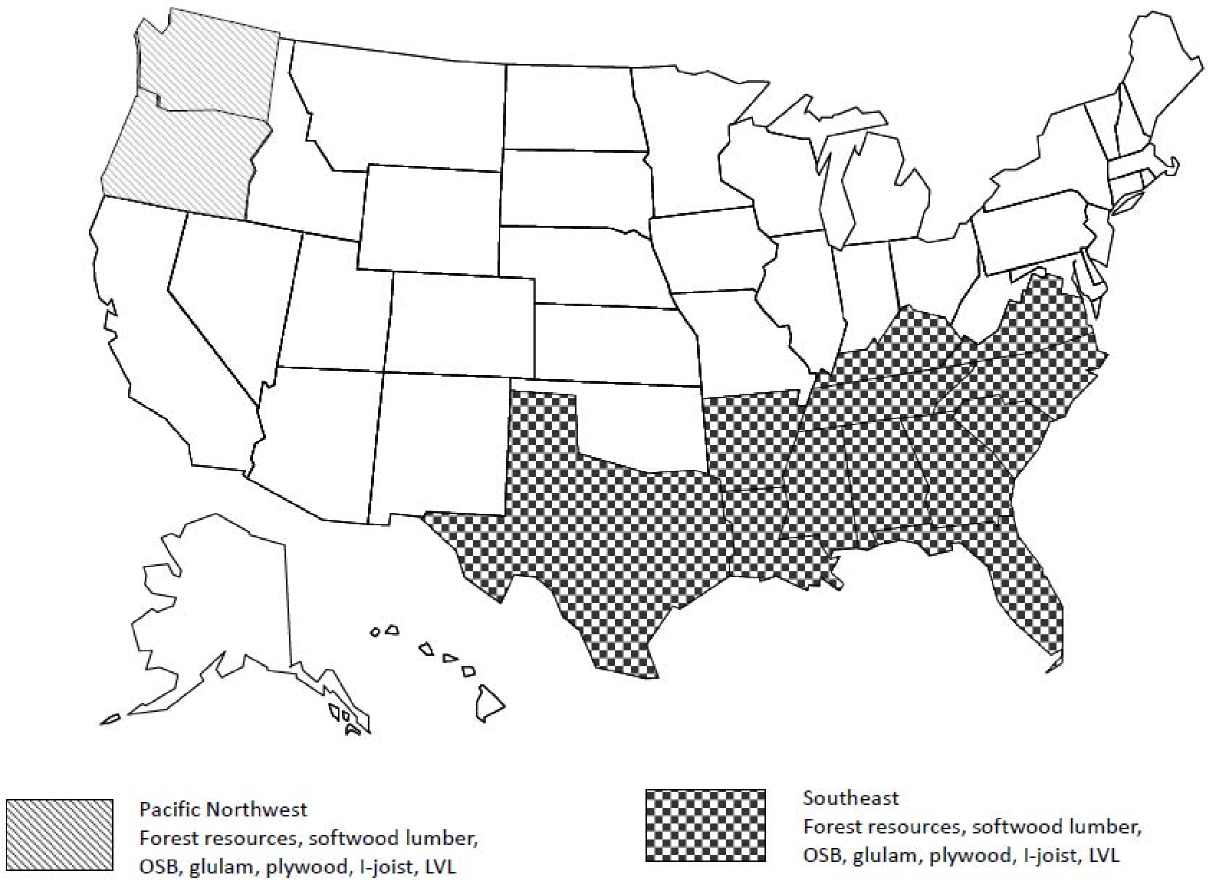

Figure 2-5: Survey regions for the production of glued-laminated timbers, lumber, laminated veneer lumber, plywood, and oriented strandboard produced in the Pacific Northwest and Southeast regions of the United States.

For Phase I, CORRIM released a study comparing the energy use and environmental load of construction and operation of a wood-framed house to a steel-framed house and a concrete-framed house in two different locations (Minneapolis and Atlanta) in the United States. The results mostly favored the wood-framed house in both locations when evaluated on five energy and environmental impact categories (Lippke et al. 2004). CORRIM's efforts are producing data to help establish environmental standards. Smaller regional wood product production centers including hardwood lumber were examined in Phase II.

2.2.2.2 Phase II

Phase II LCI projects focus mostly on the Inland West and the Northeast thus extending the geographic coverage examined in Phase I projects (Figure 2-6). Not considering geographical differences were major problems of earlier LCA studies. This effort focused on solving this problem for US wood products. The extension of the wood products life-cycle research into other regions is vital because of the sensitivity that LCI studies have regarding regional (spatial) factors such as the electrical grid composition, tree species, and harvesting practices. In the eastern US, coal generates most of the electrical power unlike the PNW that derives its power mostly from hydropower. This difference has a significant environmental impact on manufacturing processes that consume large amounts of electricity. These projects consisted of hardwood lumber and flooring, softwood lumber, and other forest resources (Bergman and Bowe 2008; Hubbard and Bowe 2010; Bergman and Bowe 2010a; Puettman et al 2010; Bergman and Bowe 2012).

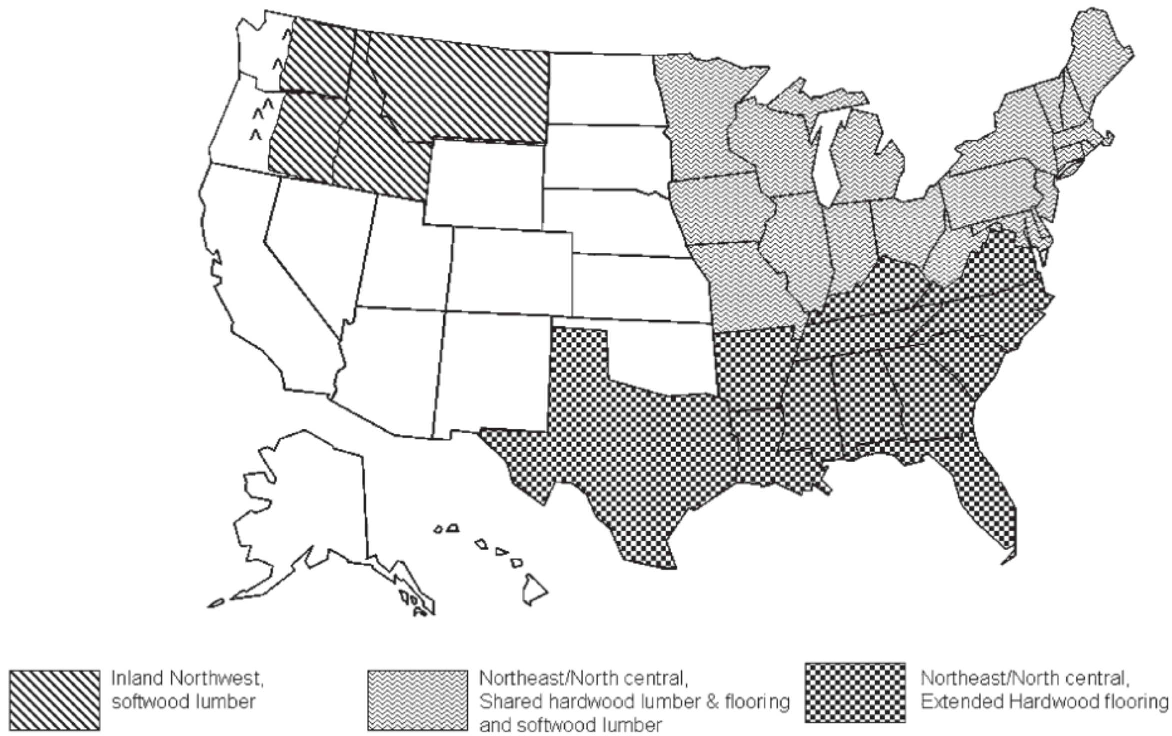

Figure 2-6: Resource and product manufacturing regions for CORRIM Phase II products; softwood lumber, hardwood lumber, and hardwood flooring.

2.2.3 Stakeholder Interest in Development

Several major stakeholders who have an interest in the application of LCA data include government agencies, the building industries, eNGOs, environmental consultants, and academia. Different stakeholders view and value life-cycle work differently but all have the following concerns when conducting LCI studies: confidentiality, improper assumptions and system boundaries, misuse or misunderstanding by others (i.e. green-washing), and poor data quality. Green-washing is wrongly stating environmental impact attributes when selling a product or service (Bergman and Taylor 2011). Confidentiality of the data provided by industry participants is necessary. Other barriers to effective LCI studies include lack of expertise, methodology development (search for common basis), and cost and time of the project (de Beafort-Langeveld et al. 2003). Regardless of any drawbacks, most stakeholders see LCI studies as opportunities. Industry values LCI studies because of the scientific basis used in examining the environmental impacts of products and the potential for process improvement and green marketing, while government and academia would use the resulting LCA as decision-making tools (de Beafort-Langeveld et al. 2003; Bergman and Taylor 2011). An example is the US Environmental Protection Agency utilizing LCA to categorize biofuels for their GHG reduction potential (EISA 2007).

2.3 Review of relevant LCI studies on flooring

2.3.1 Previous studies

Previous studies on flooring products included both US and Europe. Hubbard and Bowe (2008) evaluated unfinished solid wood flooring in the eastern US. About 86% of the total energy (including electricity) needed for making the flooring derived from biomass (wood residue). This result is consistent with other LCI studies on wood products that show a high percentage of process energy coming from biomass (Puettmann and Wilson 2005; Puettmann et al. 2010). Additionally, Gustavsson et al. (2010) found that substituting biomass residue from wood products for fossil fuels significantly lowered net CO_2 emissions. Gustavsson et al. (2010) assumes forests regenerate over an indefinite time period. Biogenic CO_2 emissions caused by burning wood are balance by the CO_2 uptake from the atmosphere in the growing trees. Therefore, biogenic CO_2 not counted toward CO_2 emissions but fossil CO_2 emissions are. Petersen and Solberg (2005) reviewed 14 LCA studies from Norway and Sweden, whereas Werner and Richter (2007) reviewed international research from the past 20 years. The main conclusion is that wood tends to have a favorable environmental profile particularly regarding GHGs compared with competing materials such as steel and concrete.

2.3.1.1 Sweden

In Sweden, Jönsson et al. (1997) reported that solid wood flooring showed significant environmental advantages compared with linoleum and vinyl flooring. Vinyl flooring had the greatest environmental impact. Raw materials in its natural state have no environmental burdens assign to them. However, selection of raw materials to make the final product is not without environmental consequences, e.g. the final product with the greatest impact tended to be the product using synthetics derived from fossil fuels. For example, polyvinyl chloride (PVC) used in vinyl flooring production is synthesized from ethylene made from crude oil. Another reason for the greater impact associated with vinyl flooring was that its production consumed the most nonrenewable energy resources. Wood flooring used the least nonrenewable energy resources because its main raw component was trees, a renewable resource.

2.3.1.2 Germany

A 2006 German study provided data on environmental impacts of types of prefinished wood flooring including solid wood, solid and multilayer parquets, and wood blocks (Nebel et al. 2006). Nebel et al. (2006) found that solvent use and energy consumption had the most effect on environmental performance of these products. This life-cycle study provided results from extraction of raw material to final disposal of material. One important factor was the expected lifetime of a given product and its ability to be refurbished. Wood blocks, wood floorboards, and 22-mm parquet flooring had an expected useful life of 50 years, which was at least twice the useful life of other wood flooring products such as multilayer parquet flooring. Wood block flooring is made from tongue and groove wood blocks that are 19-38 mm thick, up to 90-mm wide, and 150-380 mm long. In the Nebel et al. study, wood block flooring was 38-mm thick, nearly twice as thick as the wood floorboards. In addition, the 50 years corresponded to the expected useful life of the house. An environmental advantage was the air-drying of wood floorboards to 17% MC that decreased primary energy consumption to 25% of multilayer parquet. The reference flow was one m^2 of laid flooring for 50 years. Multilayer parquet had only an expected useful life of 10 yr. As other studies have shown, energy consumption during manufacturing was the highest of the individual life-cycle stages. In addition, burning the disposed material for energy lowered the flooring's impact at end of life. Solvents used in lay-up, prefinishing, and refurbishing had the largest impact in photo-oxidant formation, caused mainly by emissions of volatile organic compounds (VOCs).

2.3.1.3 United States

Bowyer et al. (2009) conducted a flooring study using life-cycle information from Building for Energy and Environmental Sustainability (BEES). National Institute of Standards and Technology (NIST) manages BEES (www.bfrl.nist.gov/oae/software/bees) (Lippiatt 2007). Bowyer et al. (2009) found that BEES has an extensive database that includes 25 flooring coverings for commercial buildings, however no life-cycle information on wood or bamboo flooring. The study did note that flooring derived from renewable materials such as natural cork parquet, plank flooring, and linoleum had the lowest environmental impacts of the ten flooring options evaluated. BEES does include LCI data from the US LCI Database (USDA 2012). One fault with the Petersen and Solberg (2005) study was the assumption that materials for subfloors were not included even though carpeting requires additional subfloor material than does SSHF and EWF. The BEES model does include subfloors as necessary (Bowyer et al. 2009).

2.3.1.4 Coatings

Some wood products use coatings, but the coating with the lowest environmental impact is not always obvious. Gustafsson and Börjesson (2007) found through a cradle-to-grave evaluation that a "green" wax produced from rapeseed oil has a greater overall environmental impact than the two ultraviolet (UV) light hardening lacquers, whereas the 100% UV lacquer shows the lowest environmental impact. In addition, Tufvesson and Börjesson (2008) found that wax ester made from rapeseed oil had about 3.5 times higher GWP than paraffin wax. Furthermore, cultivation of rapeseed oil causes soil emissions of ammonia and nitrous oxides, resulting in potential acidification and eutrophication. These results indicate that more research into finding coatings with minimal environmental impacts is necessary.

2.3.2 Lessons learned

The initial work of CORRIM examined structural wood building products used in residential home construction (Puettmann and Wilson 2005; Perez-Garcia et al. 2005; Lippke et al. 2004). In each of these studies, wood building materials are found to have smaller environmental impacts than competing non-wood materials such as steel and concrete. Current CORRIM efforts are focusing on biofuels and updating old LCI data from phase I wood products. Updated wood product LCI data will be used to develop EPDs. In addition, wood products tend to have lower environmental impact than competing wood products because biomass, considered carbon neutral, is used as a primary energy source in their production.

2.3.2.1 Useful life

The useful life of a product matters in its environmental impact. Some flooring products need to be replaced multiple times during the life of a house, whereas others are more durable. Some products are able to be refurbished more easily than others, and refurbishing flooring instead of replacing it decreases its overall environmental impact (Nebel et al. 2006).

2.3.2.2 "Green" coatings

Evaluating coatings requires caution for its environmental impacts to ensure that the whole life cycle of the material is covered. A "green" coating does not necessarily have less environmental impact than a competing product. Examining a product from the raw material stage to its final disposal (i.e., cradle-to-grave LCA) provides the most accurate evaluation of environmental impacts. For the present study, final disposal includes landfill operations.

2.3.2.3 Landfills

Landfills emit landfill gas whether the landfill is capped or not. Fugitive emissions are released on the edges of the cap because of gas buildup and are not captured. Petersen and Solberg (2004) assumed that no GHG emissions were released in the landfill once the material was disposed of. This is a common assumption that fails to evaluate the impacts from fugitive emissions such as methane, a potent GHG. Landfill capture technology usage varies greatly between countries (IEA 2009; De La Cruz and Barlaz 2010).

2.3.3 Flooring industry overview

SSHF and EWF are non-structural wood products. EWF is more dimensionally stable than SSHF because it is made up of cross-laminated veneers; this arrangement decreases shrinking and swelling in width that result from changes in moisture content (Bergman 2010). EWF as defined by the National Wood Flooring Association (NWFA) comprises several sheets of solid wood (veneer) bonded together with an adhesive under heat or pressure or both. Although plies with two, three, five, seven, or nine sheets are available, three and five are most common. EWF is one of many commercially available flooring products. EWF has competing products besides SSHF including laminated wood flooring, carpet, vinyl flooring, ceramic tile and laminated bamboo flooring.

2.3.3.1 US wood flooring production

In 2007, wood flooring manufacturers in the US produced 41.67 million m^2 solid wood and 36.36 million m^2 EWF for a total of 78.03 million m^2 (CRI 2008). Market percentage of EWF out of the total wood flooring market increased from 42.1% in 2004 to 46.6% in 2007 (CRI 2008). This increase in market share occurred although its production had actually decreased since about 2008 because of the severe decline in domestic housing construction (USDC 2012). However, hard surface flooring demand is expected to increase 2.8% annually from 2008 to 710 million m^2 by 2013, and the wood flooring market share is expected to increase whereas vinyl flooring continues to lose market share. As before the recession, the remodeling market will be the driving force for hard surface flooring consumption because new residential construction consumes only 20% (Freedonia 2009a). In addition, the market for wood coatings has also declined because of the downturn in the US housing market, although is it also expected to rebound.

An increase in wood flooring production results in an increase in wood coatings (protection) production. Total value of the wood protection and preservative market is forecast to be $3.3 billion by 2013. Although this value does include the treated wood market, the greatest increase in demand is expected to occur in interior wood applications such as flooring. The release of VOCs, including formaldehyde, during prefinishing and refurbishing will be an issue that is likely to affect market share. Coatings with improved formulation showing better environmental performance will gather a higher market share (Freedonia 2009b).

2.4 Climate Change

Because of different radiative properties and lifetimes in the atmosphere, GHGs vary in their warming influence (i.e. radiative forcing) on the global atmosphere. These warming influences are estimated through a common metric (index) based on the radiative forcing of CO_2 such as CO_2-equivalent emission (GWP) or CO_2-equivalent concentration. CO_2-equivalent emission is the amount of CO_2 emission that would cause the same time-integrated radiative forcing, over a selected time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs. The CO_2-equivalent emission is calculated by multiplying the GWP characterization factor of a GHG for the given time horizon by the amount of the GHG emitted to the atmosphere. For a mix of GHGs, the CO_2-equivalent emission is calculated by summing the CO_2-equivalent emissions of each GHG. Although the CO_2-equivalent emission has shortcomings especially in its uncertainity, it is a standard and practical metric for comparing emissions of different GHGs (Fuglestvedt et al. 2003). CO_2-equivalent concentration is the concentration of CO_2 that would cause the same amount of radiative forcing as a specified mixture of CO_2 and other non-CO_2 GHGs (IPCC 2007).

Radiative forcing is the amount of the influence a factor has in changing the equilibrium energy in the atmosphere and indicates the significance of the factor as a prospective climate change mechanism. Radiative forcing occurs from a perturbation such as GHG emissions from burning coal or a forest fire. In IPCC (2007) report, radiative forcing values are measured in watts per square meter (W/m^2) and are for changes relative to the preindustrial environment defined at year 1750. Radiative forcing is an effect of GHG emissions thus a trade-off exists between certainty and importance (Fuglestvedt et al. 2003).

2.5 Previous research on including emission timing

Previous studies have evaluated the effect of emission timing on climate change impacts. For carbon mitigation projects, the Lashof accounting method is one such approach by calculating cumulative radiative forcing (CRF) from GHG emissions within a given time period and reporting values in Mg-yr (Fearnside et al. 2000). The Lashof approach and other MG-yr approaches including the Moura-Costa approach uses the concept of radiative forcing to evaluate the impact of keeping carbon out of the atmosphere for a set number of years (Moura-Costa P et al. 2000). The resultant carbon credit can be used to counter other GHG emissions occurring during the given time horizon (Brandão and Levasseur 2010; Courchesne et al. 2010). These approaches are similar to the new methodology developed in this dissertation on building products by incorporating the timing of emissions to estimate the difference in climate change impacts with respect to the static LCA approach (i.e. GWP).

2.6 Weighting of radiative forcing

Estimating the impact of weighting radiative forcing over time is a complex issue (Forster et al. 2007). Several initial attempts have tried to define accurate impact functions. However, great uncertainty exists on the impacts from radiative forcing for the present atmospheric CO_2 concentration of 394 ppm versus a potential atmospheric CO_2 concentration of 550 ppm or higher (Forster et al. 2007; NOAA 2012). Therefore, the IPPC (2007) suggests the use of the following equation to estimate the impacts to climate change as developed by IPCC (1990) and adopted by the United Nations Framework Convention on Climate Change for the Kyoto Protocol (Forster et al. 2007).

$$GWP = \frac{\int_0^{TH} RF_i(t)dt}{\int_0^{TH} RF_r(t)dt} = \frac{\int_0^{TH} \sigma_i C_i(t)dt}{\int_0^{TH} \sigma_r C_r(t)dt} \qquad (1)$$

2.7 Carbon Storage

Carbon storage is a way of mitigating the climate change impact of fossil fuel emissions from fossil fuel power plants and vehicles to the warming influence. Interest in global cycling of carbon has been highlighted because of climate change. One issue requiring additional research is accurately estimating the effect of carbon storage on the global carbon cycle. However, Marland et al. (2010) provided results on evaluating carbon physically held in long-live harvested wood products (HWP) which demonstrated the carbon effects of HWP are not trivial. Additionally, Earles et al. (2012) provide carbon storage data on 169 countries showing countries that made more long-lived wood products than other wood products on a percentage basis have higher carbon storage rates. Storing carbon in durable wood products is a way to store carbon over a long time thus delaying the release of GHGs. Oven dried wood is roughly 50% carbon (Koch 1988). Traditional LCAs lack temporal information but dynamic LCAs consider the timing of each emission during the life cycle instead of determining a single aggregated number (Levasseur et al. 2010).

Carbon storage in long-lived wood products can offset carbon emissions released to the atmosphere during wood product production (Lippke et al. 2010; Sathre and Gustavsson 2009; Reid at al. 2004). Sathre and Gustavsson (2009) indicated that durable wood products such as wood flooring could affect the carbon balance positively because of wood's ability to store carbon. Thereby, detailing the necessity for future work on evaluating the effect of wood products on carbon storage.

Wood materials positively affect the carbon balance in several other ways besides carbon storage: 1) relatively low fossil fuel consumption when manufacturing wood building materials compared to non-wood building materials, 2) greater avoidance of fossil carbon emissions when manufacturing wood product by burning woody biomass for energy, and 3) substitution of biofuels made from wood residues for fossil fuels such as gasoline and diesel (Lipke et al. 2010). In construction material, substituting wood building material for fossil fuel based materials such as concrete and bricks may reduce CO_2 emissions up to 3.9 metric ton per ton dry wood used (RTS 2001, Sathre and O'Connor 2010). Despite the many positive environmental attributes of wood, wood building materials have lost market share to other building materials (Reid et al. 2004).

2.8 GHG emission standards development

PAS 2050:2011 (BSI 2011) is a specification that examines and categorizes GHGs of goods and service. PAS 2050:2011 is an update of an earlier 2008 version, both developed by the British Standard Institute and builds on previous internationally-recognize standards including ISO 14040 (ISO 2006a) and 14040 (ISO 2006b). The primary users are organizations wanting to quantify positive (additions to the atmosphere) and negative (removals from atmosphere) GHG emission profiles for their supply chains. GWP values are reported using the 100-year time-horizon in kg CO_2-eq per functional unit. Of special interest is the delay in carbon emissions due to carbon storage in products themselves. PAS 2050:2011 includes time weighting of GHG emissions that happen during the use phase 25 years after product production or at final disposition for specific and general cases. ILCD Handbook provides a similar analysis with respect to delayed emissions (ILCD 2010).

Another standard similar to PAS 2050:2011 is called the GHG Protocol Product Life Cycle Accounting and Reporting Standard (Bhatia et al. 2011). The World Resources Institute and the World Business Council for Sustainable Development collaborated on updating the standard designed for a corporate level approach versus PAS 2050 that focuses on a product level approach. Both PAS 2050:2011 and Bhatia et al. 2011 have been harmonized between their newest editions as well as to the draft carbon footprinting standard, ISO 14067 (ISO 2012).

2.9 Restatement of problem and need for research

Determining the impacts from the timing of GHG emissions on climate change for buildings products offers new insight into how to mitigate climate change. Werner et al. (2010) stated, “An increased use of wood products and an adequate management of forests can help to mitigate climate change”. Forests and forest products help mitigate carbon (C) to the atmosphere through sequestration, storage, and release with energy recovery (substitution for fossil fuels). However, a more comprehensive method is necessary to solve the problem that includes the timing of GHG emissions for building products because traditional LCA through GWP does not account for when GHG fluxes occur. For example, during the life cycle of a building product, GHG emissions sometime occur decades after initial product production and installation. Current climate change metrics such as GWP do not quantify the timing of GHG emissions for a given product, process or service. To aid in understanding the timing of GHG emissions more accurately, this study will answer the following question. What is the effect of GHG emissions timing on climate change impacts for the cradle-to-gate manufacturing, use and disposal.

3 METHOD

3.1 Objective 1: Gate-to-gate life-cycle inventory for manufacturing wood flooring

The gate-to-gate LCI for EWF involved a careful definition and identification of the manufacturing unit processes to be included. A literature review on the manufacturing wood flooring was necessary to understand the unit processes required. Once the unit processes were determined, the next step was defining the system boundary that covered all of the unit processes and a functional unit. To survey the EWF facilities, a detailed questionnaire was developed (Bergman and Bowe 2011b (Paper #1: Appendix 14-2)). This survey tracked all measurable raw material inputs (including energy), product and by-product outputs, and pertinent emissions to water, air, and land for those unit processes. The industry production unit from the survey was converted to a metric production unit (i.e. functional unit).

3.1.1 Sample size

A sufficient sample of production facilities was required to attain reliable and valid results to develop a "composite" EWF facility. CORRIM protocol targets the capture of a minimum of 5% of regional production for a given product but recommends between 10-50% of total production (CORRIM 2010; ISO 2006a, b).

3.1.2 Data collection

Collecting manufacturing data is the most challenging and time-intensive part of a LCI study. An average participating mill can invest up to 20 hours to provide the required production data. Therefore, the support of the NWFA to promote the merits of this project and clearly identify the cooperating mills was necessary for reliable data collection and project completion. Other CORRIM projects have shown a clear link between industry association support and a corresponding high level of mill cooperation and data quality.

3.1.3 Critical review

A critical review was conducted by a representative of CORRIM to ensure ISO 14040 compliancy of the survey instrument. In addition, other CORRIM scientists as well as experts at the Wisconsin Department of Natural Resources, the USDA Forest Products Laboratory, and the University of Wisconsin conducted a peer review of the survey instrument. Only data in aggregated form was released publicly to protect proprietary information. As required to fill primary (survey) data gaps, follow-up calls or site visits were conducted.

3.1.4 Weight-averaging survey data

Analyzed the primary data collected from industry using a spreadsheet algorithm, Microsoft Excel. Method of aggregation for primary data was weighted as in previous CORRIM reports (Milota et al. 2004) using the following equation

$$\overline{P}_{\text{weighted}} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i}$$

where $\overline{P}_{\text{weighted}}$ is the weighted average of the values reported by the mills, P_i is the reported mill value, and x_i is the fraction of the mill's value to total production for that specific value.

3.1.5 Life-cycle inventory analysis

Modeled the weight-averaged (aggregate) primary data on a per functional unit basis using SimaPro LCA software as outlined by the CORRIM guidelines (CORRIM 2010; PRé Consultants 2012). Completed wood mass and energy balances for the unit processes to meet CORRIM research guidelines (CORRIM 2010). Inputted the weight-averaged data into SimaPro for each unit processes and linked them together (Bergman and Bowe 2011b (Paper#1: Appendix 14-1)). SimaPro uses the internationally recognized and standardized LCI format to record and analyze the model data (ISO 2006a; ISO 2006b). Secondary data found in the US LCI Database and US Ecoinvent Database within SimaPro provided additional life-cycle data. The additional life-cycle data included generation and delivery of electricity and fossil fuel. LCI outputs from SimaPro included allocated raw material consumption, solid waste, and emission to air, water, and land. The mass allocation method assigned the environmental impact between the products and co-products. Estimated unallocated and allocated LCI flows to show the effect of the selected allocation method. Calculated carbon balance using the wood mass balance and wood carbon factors developed by Skog and Nicholson (1998). A comparison on energy comparison to other products was shown (Potting and Blok 1995; Jönsson et al. 1997; Werner and Richter 2007; Hubbard and Bowe 2010; Petersen and Solberg 2004). A critical review on the final report was completed by a representative of CORRIM to ensure compliance with ISO 14040 standards (Bergman and Bowe 2011b (Paper #1)).

3.2 Objective 2: Full traditional LCA

Full traditional (static) LCAs for SSHF and EWF from harvesting to disposal were constructed. Puettmann et al. (2010) completed a cradle-to-gate LCI for SSHF. Linked the forest harvesting and manufacturing LCIs together to complete the cradle-to-gate LCI for EWF. Forest harvesting LCI came from the US LCI Database (USDA 2012) and the manufacturing LCI from Bergman and Bowe (2011b (Paper #2)). For the two cradle-to-grave LCIs of the two wood flooring products, life-cycle stages of product transportation, installation, use, demolition, and disposal (i.e. landfill and biomass combustion) were developed. Used secondary data from previous studies that were similar on an area basis (square feet or square meter) and the installed flooring products served the same function as the functional unit selected in Objective 1 (Nebel et al. 2006; Petersen and Solberg 2004; Mahalle 2011) . These previous life-cycle studies helped develop the whole life cycle. SimaPro LCA software contains many LCI database libraries (tertiary data) within its framework including the US LCI Database (USDA 2012) and US Ecoinvent to further help to develop the end-of-life stage for the two wood flooring products.

3.3 Objective 3: Dynamic life-cycle assessment

I created a new method called the Time Zero Equivalent (TIZE) to quantify the impacts to climate change from incorporating the timing of greenhouse gas (GHG) emissions for building products. The static LCA approach quantified the GHG emission for the various life-cycle stages (Paper #3). The method illustrated the difference between traditional (static) and dynamic (temporal) LCAs (Marland et al. 1997; Levasseur et al. 2010; Kirkinen 2010; Schwietzke et al. 2011). Wood flooring products were used as the case study to illustrate the new method.

Traditional LCAs can effectively track GHG emissions. In traditional LCAs, an aggregated value for each emission is found. Examples include methane, particulate, VOCs, non-methane VOCs, fossil carbon dioxide, and biogenic carbon dioxide (Milota et al. 2004). Most LCI and LCA studies report this aggregate value without considering the timing of GHGs. The timing of GHGs falls outside the scope of the study. For example, Bergman and Bowe (2010a) reported biogenic and fossil carbon dioxide emissions from manufacturing softwood lumber in the northeastern and north central United States at 187 and 65.1 kg per cubic meter of planed dry lumber. Usually, just several weeks pass between the time the logs enter the mill and leave as planed dry lumber, the final products. However, linking life-cycle stages such as use and disposal stages that occur over several decades can be problematic when including the timing of GHGs for traditional LCA.

Objective 3 developed the new methodology to incorporate the timing of GHG emissions using the concept of radiative forcing over the whole life cycle of a building product. Levasseur et al. (2010) demonstrated the use of GWP for a given time horizon based on the radiative forcing concept for biofuels. As the Levasseur et al. (2010) and Schweitzer et al. (2011) studies focused on biofuels, building product LCA data such as wood decomposition in landfills into methane and biogenic CO_2 were not evaluated. The results from Levasseur et al. (2010) showed an inconsistency between traditional and dynamic LCAs that warrants further investigation in creating a new method for building products that includes the impacts of landfilling wood and replacement or refurbishment. Landfilling wood is a common occurrence in the United States compared to other disposal options (De La Cruz and Barlaz 2010). In addition, wood decaying in landfills occurs over many decades (Skog 2008). Used wood flooring products to illustrate the new dynamic LCA method.

Paper 1: CORRIM Report – "Life-cycle inventory of manufacturing prefinished engineered wood flooring in the eastern United States"

Paper #1 covers dissertation pages 45-100.

Final CORRIM Report

Module N

Life-Cycle Inventory of Manufacturing Prefinished Engineered Wood Flooring in the Eastern United States

February 2011

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Conversion Table

1 megajoule = 0.278 kilowatt-hour
1 megajoule = 948.8 Btu
1 kilowatt = 3,412 Btu per hour
1 kilogram = 2.205 pounds
1 meter = 3.281 feet
1 millimeter = 0.0394 inches
1 meter squared = 10.76 feet squared
1 meter cubed = 35.31 feet cubed (264.2 gallons)
1 meter cubed = 423.8 actual board feet (0.4238 actual MBF)
1 liter = 0.2642 gallons
1 kilometer = 0.621 miles
1 metric ton (1,000 kilograms) = 1.10 tons (2,205 pounds)

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Participating companies and individual mill respondents from the flooring industry for their time and effort in providing the data needed to make this project a success.

Executive Summary

This study summarizes the environmental performance of prefinished engineered wood flooring using life-cycle inventory (LCI) analysis. Using primary mill data gathered from manufacturers in the eastern United States and applying the methods found in Consortium for Research on Renewable Industrial Materials (CORRIM) Research Guidelines and International Organization of Standardization (ISO) standard for conducting life-cycle assessments, the environmental impacts in making engineered wood flooring were estimated. This study is a follow-up to the CORRIM Report Module G—Life-Cycle Inventory of Solid Strip Hardwood Flooring in the Eastern United States. Life-cycle impact assessment was beyond the scope of this study.

Engineered wood flooring is designed to be more dimensionally stable than solid strip wood flooring because it is less susceptible to width shrinkage from increases in moisture. Engineered wood flooring as defined by the National Wood Flooring Association consists of several sheets of solid wood (veneer) bonded together with an adhesive under heat and/or pressure. Although plies having 2, 3, 5, 7, or 9 sheets are available, 3 and 5 are most common. Thicknesses can range from 3/8 to 9/16 in. (9.5 to 14.3 mm). Typical manufacturing includes the following eight unit processes: log yard, debarking and bucking, block conditioning, peeling and clipping, veneer drying, lay up, trimming, sanding, sawing and moulding (profiling), and prefinishing. Inputs and outputs to these unit processes were collected from a survey of manufacturers. The multi-unit process approach is the preferred evaluation method because it helps identify possible process improvements by showing the energy and environmental contribution of each unit process.

We determined the environmental impacts based on resource and energy consumption and releases to air, water, and land for making prefinished engineered wood flooring in the eastern United States. Of the five companies contacted in the eastern United States, four companies (comprising four veneer mills and five flooring plants) completed the mill survey. These facilities well represented the industry as a whole, and their manufacturing technology was average. Primary data were collected for the production period January to December 2007. Input data collected included raw materials such as hardwood logs with bark and water, resins, electricity, fossil fuels, prefinishing materials, transportation distances for materials used onsite, and the breakdown of logs into co-products sold (not flooring) such as wood chips and wood fuel burned onsite to produce thermal energy. Allocation of environmental inputs was done on a mass basis because the highest volume product had the highest economic value. This was true for all unit processes. Production unit bases of 1 m^3 and 1,000 ft^2[1] were selected to standardize the results to alternative products.

Based on surveyed data from the eastern United States, flooring production of 64,840 m^2 (73,270 thousand ft^2) was found. This was approximately 19% of the total 2007 engineered wood flooring production in the United States of 346,400 m^2 (391,400 thousand ft^2). No U.S. wood flooring production data were available by individual states. Surveyed mill production exceeded the minimum CORRIM production data requirement of 5%. In addition, this study met the minimum number of product manufacturers (four). Detailed inputs and outputs of unit processes were collected from these manufacturers and weight-averaged to allow modeling in SimaPro 7.1.8 to estimate emissions to air, water, and land. Results also include a carbon balance of the entire process.

After developing a mass balance from inputs and outputs, an ovendry density of 656 kg/m^3 (40.9 lb/ft^3) prefinished engineered wood flooring including wood, resins, and finish (coatings) was estimated. Assuming a specific gravity at 6% MC of 0.656, the density was 695 kg/m^3 (43.4 lb/ft^3). At 0% MC, the largest component of the flooring is wood (578 kg) and represents 88.2% of the final product mass, resins

[1] 1,000 ft^2 equals 92.9 m^2.

(65 kg) are 9.8%, and the remaining 2.0% finishing material (13 kg). Hardwood plywood and prefinished engineered wood flooring had wood recoveries of 43% and 35%, respectively. These numbers were determined by the output of wood in the form of plywood as a percentage by weight of the wood input to the manufacturing facilities in the log form (white wood only).

Energy consumption and type have significant effects on the environmental performance of all products. In this LCI study, unallocated thermal process energy and electricity consumed was 6,418 MJ/m^3 (5.38 million Btu/thousand ft) [2] and 1,113 kWh/m^3 (985 kWh/thousand ft^2), respectively. Wood fuel at 300 ovendry kg or 6,263 MJ/m^3 (5.26 million Btu/thousand ft^2) contributed 97.6% of process thermal energy required with the remainder from propane (2.2%) and natural gas (0.2%). Results showed a cumulative allocated value of manufacturing prefinished engineered wood flooring starting with logs at the forest landing to the final product leaving the flooring plant of 22,990 MJ/m^3 (19.3 million Btu/thousand ft^2)[3]. Unfinished engineered wood flooring showed a cumulative allocated value of 13,600 MJ/m^3 (11.4 million Btu/thousand ft^2).

Tracking emissions is increasingly important in terms of applying proper emission controls. Two different scenarios were created to track emissions and involved system and onsite boundary conditions. First, the total (cumulative) system boundary covers both onsite and off-site emissions for all material and energy consumed. This includes the fuel resources used for the production of energy and electricity and is part of this LCI. Examples of off-site emissions are grid electricity production, transportation of logs to the mill, and fuels produced off-site but used onsite. The onsite system boundary covers emissions developed just at the prefinished engineered wood flooring facilities (i.e., onsite) from the seven unit processes. Environmental impact outputs from SimaPro were allocated to the production of 1 m^3 of prefinished engineered wood flooring. A certain portion of the environmental impacts were assigned to the co-products such as wood chips and were not included in the LCI output for prefinished engineered wood flooring.

Data quality is considered excellent based on the data collected from the manufacturing facilities. We developed detailed surveys (questionnaires) that were reviewed by a CORRIM representative before distribution. In addition, a CORRIM representative reviewed the SimaPro model for this report. Onsite visits to a veneer mill and flooring plant allowed for provides greater insight into the manufacturing process, thus providing higher quality data. The multi-unit process method allows for unit process improvements to be evaluated more precisely than a system process approach.

Modeling data estimated biogenic and fossil CO_2 emissions at 623 and 1,049 kg/m^3, respectively, and VOCs at 1.04 kg/m^3. A cubic meter of prefinished engineered wood flooring stores 1,096-kg CO_2 equivalents/m^3 as a final product.

The following main conclusions are based on the life-cycle inventory:

- The amount of carbon stored in prefinished engineered wood flooring exceeds the fossil carbon emissions by about 4%. Therefore, as long as prefinished engineered wood flooring and its carbon stay in products held in end uses, the carbon stored will exceed the fossil carbon emitted in manufacturing.

- A trade-off exists between prefinished and unfinished engineered wood flooring. The prefinishing unit process consumes a large amount of electricity from controlling emissions from staining and

[2] Process energy was calculated based on the following higher-heating values (HHVs) in MJ/kg: Ovendry wood 20.9, coal 26.2, distillate fuel oil 45.5, LPG 54.0, natural gas 54.4, gasoline 48.4, diesel 44.0, and uranium 381,000.
[3] Cumulative allocated value considers electrical efficiency of grid power provided.

coating the wood flooring in addition to the prefinishing. As a result, the environmental impact is significantly higher for prefinished engineered wood flooring than for unfinished engineered wood flooring. However, finishing the wood floor after installation in a residential or commercial building (an uncontrolled environment) would result in greater harm to the environment. This harm results from uncontrolled emissions released from the staining and coating process that are now captured or destroyed onsite at the flooring plant.

- Burning fuel for energy generates CO_2. Nearly all energy burned onsite for manufacturing prefinished engineered wood flooring comes from woody biomass. Burning biomass for energy does not contribute to increasing atmospheric CO_2 provided forests are growing and absorbing the emitted CO_2 on a sustainable basis.

- Increasing onsite wood fuel consumption would reduce fossil greenhouse gases but increase other gases, especially particulate emissions. Particulate matter can be captured prior to release to the atmosphere using commercially available technology but not without increased costs and additional inputs such as electricity.

Contents

Table of Figures

Table of Tables

1 Introduction

Environmental performance of products that are components of residential or commercial buildings is increasingly being examined because of concerns over the impacts of such structures on the environment. For example, some research claims the main cause of climate change is from burning fossil fuels (IPCC 2007). In addition, some building products consume large amounts of fossil fuels during their processing (Khatib 2009). However, wood building products typically consume more biomass than fossil fuels during their manufacturing, a significant environmental advantage (Puettmann and Wilson 2005a). Biomass carbon dioxide (CO_2) is considered carbon neutral because the CO_2 emitted from burning biomass will not increase total atmospheric CO_2 if the consumption of biomass is done on a sustainable basis (UNFCCC 2003, EPA 2003).

"Green building" is defined as the practice of improving the energy efficiency of materials, construction, and operation of buildings while reducing the overall environmental impact. The green building market including non-residential and residential is likely to almost triple from $36 to $49 billion in 2008 to $96 to $140 billion by 2013 (MHC 2008, Murray 2008). Developing a sound policy for building practices, especially for green building, must be a priority if the United States is to decrease its environmental burden. In addition, carbon emissions during manufacturing of building materials are expected to play a larger role in consumer selection in the future. A scientific method for analyzing product claims to determine their actual environmental performance is often lacking in the "green" building movement.

Conducting a Life-Cycle Inventory (LCI) for products is part of a science-based approach to addressing environmental claims. LCI data are a major part of Life-Cycle Assessments (LCA). LCA uses rigorous methodology to find the total environmental impact for a particular product referred to as "cradle-to-grave" (raw material extraction to waste disposal) analysis. These analyses include the environmental and energy costs on a per-unit basis using the data from individual LCI studies. These LCI studies are resource extraction, transportation, primary and secondary processing, final product use, maintenance, and final disposal for a particular product. LCI measures all the raw material and energy inputs and outputs to manufacture a particular product on a per-unit basis within carefully defined system boundaries. This is often referred to as a "gate-to-gate" LCI. Results from the LCI are used to assess the environmental impact (ISO 2006a, ISO 2006b). The Consortium for Research on Renewable Industrial Materials (CORRIM) has developed many LCI datasets for structural wood materials (NREL 2011).

CORRIM is a research entity comprised of 15 universities and research institutions (Lippke 2004). CORRIM has set out to evaluate wood as an appropriate environmental choice by researching the impacts of wood materials using the standardized tools of LCI analysis. CORRIM is helping build a multinational database of the environmental and economic impacts associated with using renewable materials (Bowyer et al. 2001). The LCI model, which is well documented in the literature, is a central element of this work (Sundin et al. 2002, Yaros 1997, Kuuluvainen and Salo 1991). This LCI study for prefinished engineered wood flooring will use the methodology and protocols put forth by CORRIM and the International Organization for Standardization (ISO) (CORRIM 2010, ISO 2006a, ISO 2006b).

1.1 Review of Relevant LCI Studies

1.1.1 Previous studies

Previous studies on flooring products include both the United States and Europe. Hubbard and Bowe (2008) evaluated unfinished solid wood flooring in the eastern United States. About 86% of the total energy (including electricity) needed for making the flooring came from biomass (wood residue). This result is consistent with other LCI studies on wood products that show a high percentage of process energy coming from biomass (Puettmann and Wilson 2005a). Additionally, Gustavsson et al. (2010)

found that substituting biomass residue from wood products for fossil fuels significantly lowers net carbon dioxide emissions. Petersen and Solberg (2005) reviewed 14 LCA studies from Norway and Sweden, whereas Werner and Richter (2007) reviewed international research from the past 20 years. The main conclusion is that wood tends to have a favorable environmental profile particularly regarding greenhouse gas emissions (GHGs), compared with competing materials such as steel and concrete.

In Sweden, Jönsson et al. (1997) reported that solid wood flooring showed significant environmental advantages over linoleum and vinyl flooring. Vinyl flooring had the highest environmental burdens. Raw materials play a significant role on the environmental impact for each product because the final product with the highest burdens tended to be the product using synthetics derived from fossil fuels. For example, polyvinyl chloride (PVC) used in vinyl flooring production is synthesized from ethylene made from crude oil. Another reason for the impacts associated with vinyl flooring was that its production consumed the most nonrenewable energy resources. Wood flooring used the least nonrenewable energy resources and its main raw component was from trees, a renewable resource.

A 2006 German study provided data on the environmental impacts of types of prefinished wood flooring including solid wood, solid and multilayer parquets, and wood blocks (Nebel et al. 2006). Nebel et al. found that solvent use and energy consumption had the most effect on the environmental performance of these products. This life-cycle study provided results from the extraction of raw material to the final disposal of material. One important factor is the expected lifetime of a given product and its ability to be refurbished. Wood blocks, wood floor boards, and 22-mm parquet flooring had an expected useful life of 50 years, which was at least twice the useful life of the other wood flooring products such as multilayer parquet flooring. Wood block flooring is made from tongue and grooved wood blocks that are 19 to 38 mm thick, up to 90 mm wide, and 150 to 380 mm long. In this study, wood block flooring was 38 mm thick, nearly twice as thick as the wood floor boards. In addition, the 50 years corresponded to the expected useful life of the house. An environmental advantage was the air drying of wood floor boards to 17% moisture content (MC) that reduced primary energy consumption to 25% of multilayer parquet. The reference flow was 1 m^2 of laid flooring for 50 years. Multilayer parquet had only an expected useful life of 10 years. As other studies have shown, energy consumption during manufacturing was the highest of the individual life-cycle stages. In addition, burning the disposed material for energy lowered the flooring's impact at end-of-life. Solvents used in lay up, prefinishing, and refurbishing played the largest role in photo-oxidant formation, caused mainly by emissions of volatile organic compounds (VOCs).

Coatings play a large role in some wood products, and the choice of coating with the lowest environmental burden is not always obvious. Gustafsson and Börjesson (2007) found through a cradle-to-grave evaluation that a "green" wax produced from rapeseed oil had a greater environmental impact overall than the two ultraviolet light hardening lacquers (UV lacquers), while the "100% UV" lacquer showed the least environmental impact. In addition, Tufvesson and Börjesson (2008) found that wax ester made from rapeseed oil had about a 3.5 times higher Global Warming Potential (GWP) than paraffin wax. Furthermore, cultivation of the rapeseed oil causes soil emissions of ammonia and nitrous oxides, resulting in potential acidification and eutrophication. These results indicate that more work is needed to find coatings with a minimal environmental burden.

1.1.2 Lessons learned

The initial work of CORRIM examined structural wood building products used in residential home construction (Puettmann and Wilson 2005a, Perez-Garcia et al. 2005, Lippke et al. 2004). In each of these studies, wood building materials were found to have smaller environmental impacts than competing non-wood materials such as steel and concrete. Current CORRIM efforts are focusing on nonstructural building products such as interior finish materials. Wood products tend to have lower environmental impact than competing wood products because biomass, considered carbon neutral, is used as a primary energy source in their production.

The useful life of a product plays a large role in its environmental impact. Some flooring products need to be replaced multiple times during the life of a house while others are more durable. Some products are able to be refurbished more easily than others, and refurbishing flooring instead of replacing it reduces its overall environmental impact as shown by Nebel and others (2006).

Caution is needed when addressing coatings to ensure that the whole life-cycle of the material is evaluated for its environmental burdens. A "green" coating does not mean a product contains less environmental burden than a competing product. It is necessary that a product be examined from the raw material stage to its final disposal (i.e., cradle-to-grave life-cycle analysis) to provide the most accurate evaluation of environmental impact.

1.2 Industry Overview

Prefinished engineered wood flooring is a non-structural wood product. Prefinished engineered wood flooring is more dimensionally stable than solid strip wood flooring because it is composed of cross-laminated veneers; this arrangement reduces the shrinking and swelling in width that results from changes in moisture content. Engineered wood flooring as defined by the National Wood Flooring Association (NWFA) consists of several sheets of solid wood (veneer) bonded together with an adhesive under heat and/or pressure. Although plies having 2, 3, 5, 7, or 9 sheets are available, 3 and 5 are most common. Prefinished engineered wood flooring is one of many commercially used flooring products. Competing products include solid wood, laminate, carpet, vinyl, ceramic tile, and laminated bamboo-flooring.

In 2007, wood flooring manufacturers in the United States produced 448.5 million ft^2 solid wood and 391.4 million ft^2 engineered wood flooring for a total of 839.9 million ft^2 (CRI 2008). The market percentage of engineered wood flooring out of the total wood flooring market increased from 42.1% in 2004 to 46.6% in 2007 (CRI 2008). This increase in market share occurred even though its production had actually decreased due to the severe decline in domestic housing construction (USDC 2011a,b,c). However, hard surface flooring demand is expected to increase 2.8% annually from 2008 to 7.6 billion ft^2 by 2013, and the wood flooring market share is expected to increase with vinyl flooring continuing to lose market share. As before the recession, the remodeling market will be the driving force for hard surface flooring consumption, as new residential construction consumes only 20% (Freedonia 2009a). In addition, the market for wood coatings has declined because of the U.S. housing market decline, although is it also expected to rebound.

An increase in wood flooring production results in an increase in wood coatings (protection) production. Total value of the wood protection and preservative market is forecasted to be $3.3 billion by 2013. Although this value does include the treated wood market, the greatest increase in demand is expected to occur in interior wood applications such as flooring. The release of VOCs including formaldehyde during prefinishing and refurbishing will be an issue that is likely to affect the market share. A coating with improved formulation shows better environmental performance and is expected to gather a higher market share (Freedonia 2009b).

1.3 Goal of the Study

The goal of this study is to document the LCI of prefinished engineered wood flooring production from incoming hardwood logs to prefinished engineered wood flooring. This study shows material flow, energy consumption, and air, water, and land emissions for the prefinished engineered wood flooring manufacturing process on a per-unit basis for the eastern United States (Figure 1.1). We collected primary data by surveying veneer mills and flooring plants with a questionnaire, telephone calls, and a site visit; secondary data were collected from peer-reviewed literature per CORRIM guidelines (CORRIM 2010).

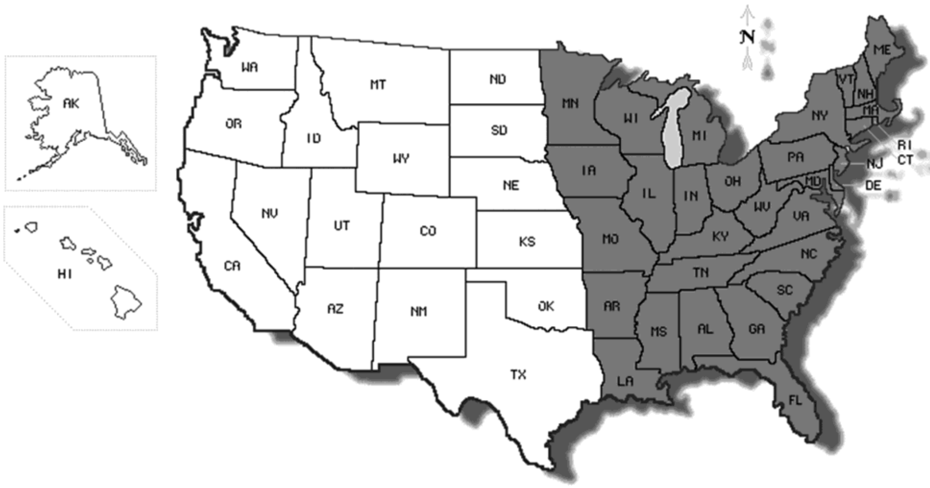

Figure 1.1 The shaded area was selected for life-cycle inventory of engineered wood flooring production in the United States.

We calculated material and energy balances by a spreadsheet algorithm using data from primary and secondary data sources. From these material and energy inputs and reported emissions, environmental impacts were estimated by modeling through SimaPro 7 software (PRé Consultants, Amersfoort, Netherlands) (PRé Consultants 2011). SimaPro has been used in previous CORRIM-initiated LCI projects: hardwood lumber (Bergman and Bowe 2008), softwood lumber (Milota et al. 2005), softwood plywood (Wilson and Sakimoto 2005), I-joist production (Wilson and Dancer 2005a), glue-laminated timbers (Puettmann and Wilson 2005b), and laminated veneer lumber (Wilson and Dancer 2005b). This LCI study conformed to relevant ISO standards (ISO 2006a,b).

Every day, consumers make decisions about whether to purchase and use wood and other non-wood products. In recent years, there has been increasing public interest in the environmental impacts associated with the manufacture, consumption, disposal, and re-use of products that originate from the forest (Bowyer et al. 2001). An assessment of the environmental impact of renewable and nonrenewable raw materials use and the resultant products is needed to enable consumers and policy makers to make informed choices. In addition, climate change policy makers require critically reviewed scientific data to make sound scientific decisions. Furthermore, the market for green building products continues to increase as homeowners and builders desire green products. LCI is a sound scientific method to measure and compare the extent to which products are green. Results from LCI aid in conducting comparative assertions to competing products.

2 Methodology

2.1 Scope of the Study

The scope of this study covers the life-cycle of manufacturing prefinished engineered wood flooring from hardwood logs in the eastern United States. LCI data from this study will help conduct a comparative analysis of prefinished engineered wood flooring to other wood and non-wood flooring options. The life-cycle inventory model provides a gate-to-gate analysis of the cumulative costs of manufacturing and shipping industrial products. Analyses include engineered wood flooring’s contribution to energy consumption, air pollution, water pollution, solid waste pollution, and climate change relative to competing non-wood products.

2.2 Functional Unit

Material flows, energy use, and emission data are standardized to a per-unit volume basis for 1.0 m^3 of prefinished engineered wood flooring, the final product of the engineered wood flooring manufacturing process. Based on U.S. industry measures, 1 m^3 of prefinished engineered wood flooring equals 1,130 ft^2 (3/8 in. basis) or 1.13 thousand ft^2 (3/8-in. basis). Wood flooring is usually sold in square feet at various thicknesses. Rough green veneer and rough dry veneer are assumed to be 2.62 and 2.43 m^3/thousand board feet (bf) after shrinkage and sanding, respectively (Bergman 2010, Koch 1985). Allocating all material and energy on a per-unit basis of 1.0 m^3 prefinished engineered wood flooring standardizes the results to meet ISO standards, and the unit processes can be used to construct a cradle-to-gate LCI and LCA (ISO 2006a,b, CORRIM 2010).

2.3 Reference Flow

The reference flow is defined as the ovendry mass of 1 m^3 or 1,000 ft ^{2} (3/8-in. basis) prefinished engineered wood flooring. In climate-controlled living environments, installed wood flooring typically equilibrates to 8% MC (Bergman 2010).

2.4 Data Quality and Data Gathering

2.4.1 Data collection and treatment

The eastern United States was selected because the majority of wood flooring production occurs in this region because of available resources (Hubbard and Bowe 2008). Primary mill data as required by CORRIM research guidelines were weight-averaged to maintain confidentiality of surveyed facilities and to develop a composite engineered flooring plant (CORRIM 2010).

2.4.2 Validation of data

We conducted the following analyses to ensure validation of raw and LCI data: 1. Comparison of conversion rates from incoming logs to dry veneer to literature values; 2. Performed mass balance to track wood material through the entire process; and, 3. Comparison of LCI data to both a U.S. (CORRIM) hardwood flooring study and to European studies on flooring. Results are shown in Section 10 starting at page 24.

2.4.3 Sensitivity analysis for refining the system boundaries

We performed a sensitivity analysis on burning different types of fuel for process energy. This analysis provided the changes in environmental impacts based on fuel use. Results are shown in Section 9 starting at page 23.

2.4.4 Data quality statement

Data quality was high due to site visits and the extensive and comprehensive questionnaire used to survey the industry (See Section 14 Appendix questionnaire starting at page 36). Primary mill data were collected for the year 2007 from facilities across the eastern United States from average technologies that produced (83,230 thousand ft^2) or nearly 19% of total engineered wood flooring production in the United States. Based on surveyed mill data,[4] total incoming hardwood log volume of 119,400 m^3 (25.6 million bf)[5] produced total dry veneer production of 67,770 m^2 (76.58 million ft^2). Adding 35,600 m^2 (40.28 million ft^2) of purchased dry veneer to dry veneer produced onsite resulted in total dry veneer of 103,400 m^2 (116.86 million ft^2). Total flooring produced was 73,660 m^2 (83.23 million ft^2). We estimated an overall efficiency of 30.1% from logs to prefinished engineered wood flooring. In addition, a log to dried veneer conversion of 40% was calculated. To ensure data completeness, we performed a mass balance and results compared to literature values.

[4] Wood veneer and flooring values provided on a 3/8 in. basis.
[5] Estimated 1,000 board feet of logs equaled 5.32 m^3 (Fonseca 2005).

2.4.5 Aggregation

Method of aggregation for primary data from the mill questionnaire was weight-averaged as in previous CORRIM reports (Milota et al. 2004) using,

$$\bar{P}_{\text{weighted}} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i}$$

where $\bar{P}_{\text{weighted}}$ is the weighted average of the values reported by the mills, P_i is the reported mill value, and x_i is the fraction of the mill's value to total production for that specific value.

2.4.6 Elementary flows

Figure 2.1 shows how wood flows through the system. The manufacturing starts with hardwood logs as the raw material and ends with the final product of prefinished engineered wood flooring. Two unit processes of 1) peeling and clipping, and 2) trimming, sanding, sawing, and moulding generate the most co-products (wood residue). In the eastern region, many commercial hardwood species are peeled into veneers for flooring. Often, several species within one species group are mixed; for example, the red oak group comprises the following species: scarlet (*Quercus coccinea*), southern (*Q. falcata*), cherrybark (*Q. falcata* var. *pagodifolia*), laurel (*Q. laurifolia*), water (*Q. nigra*), pin (*Q. palustris*), willow (*Q. phellos*), northern (*Q. rubra*), and black (*Q. velutina*). Other species groups with multiple species are white oak (6): white (*Quercus alba*), swamp white oak (*Q. bicolor*), bur (*Q. macrocarpa*), swamp chestnut (*Q. michauxii*), chestnut (*Q. prinus*), and post (*Q. stellata*); hard maples (2): sugar (*Acer saccharum*) and black (*A. nigrum*); soft maples (2): red (*Acer rubrum*) and silver (*A. saccharinum*); and ash (3): white (*Fraxinus americana*), black (*F. nigra*), and green (*F. pennsylvanica*).

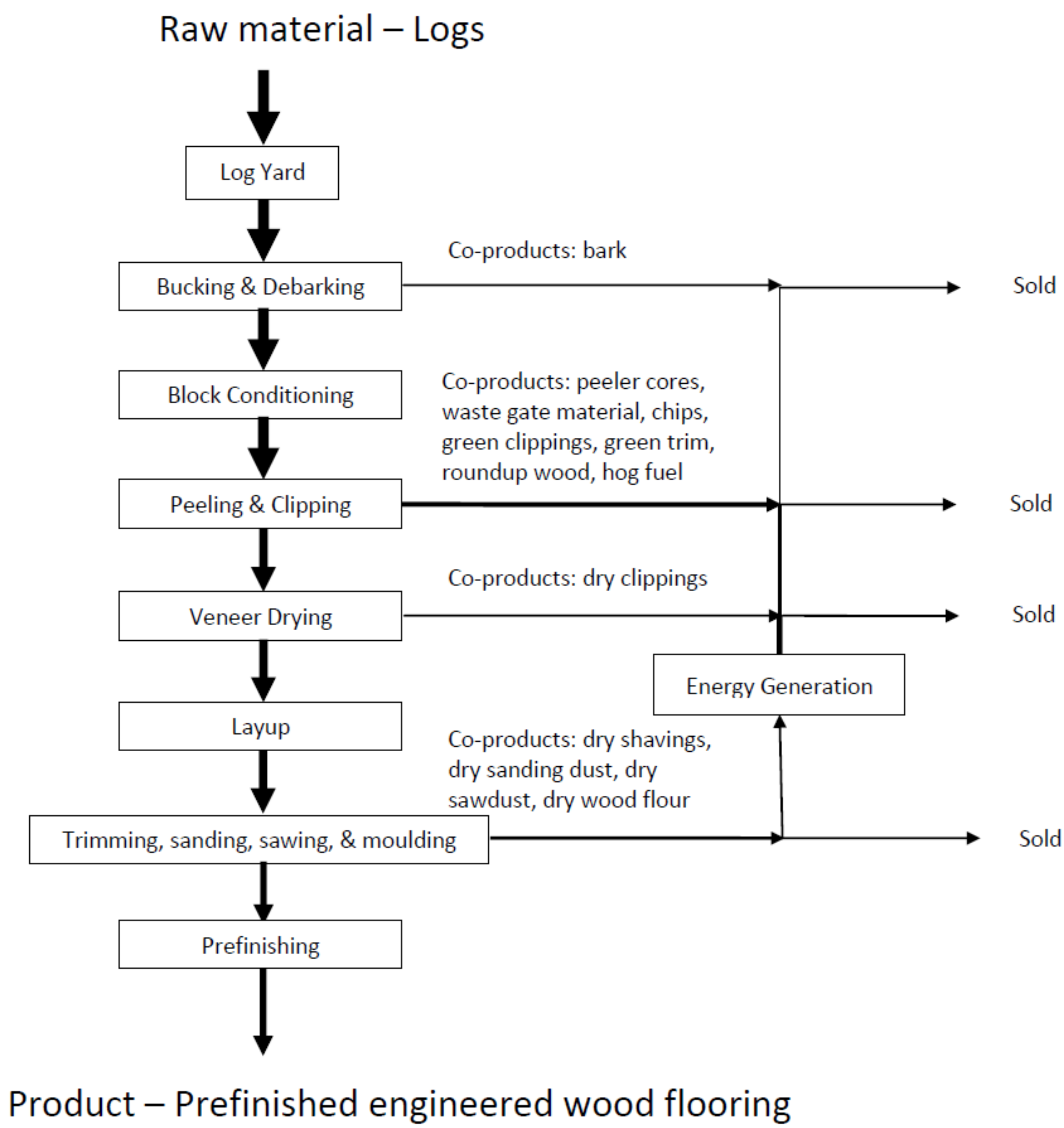

Figure 2.1 Description of product elementary flows.

2.5 Allocation Rules

In the wood products industry, production of a number of co-products including wood residue typically occurs. Residual wood from the process is often burned for process energy. The system boundary was extended to include multiple unit processes; however, co-products that are sold outside the system boundary require an allocation rule. Mass allocation was chosen because the specific gravity of both prefinished engineered wood flooring and the associated co-products are similar (Kodera 2007). This was true for all unit processes. Previous CORRIM studies on wood products also used mass allocation (Puettmann and Wilson 2005a, Jungmeier et al. 2002).

2.6 System Boundary Definition

2.6.1 Definition of product system

Eight unit processes were identified: log yard, bucking and debarking, block conditioning, peeling and clipping, veneer drying, lay up, trimming, sanding, sawing and moulding, and prefinishing (Figure 2.2). Trucks transport logs to the veneer mill. The logs are typically stored wet until needed when temperatures are above 0 °C (32 °F) to prevent staining the wood. Logs are bucked and debarked prior to block conditioning. Block conditioning softens the wood in a hot water bath to allow easier peeling of the logs on the rotating lathes. After trimming the rotary-sliced veneer sheets to 4- by 8-ft (1.2- by 2.4-m) sections, large jet driers dry the thin veneer sheets (plies) to 0–4% MC on an ovendry basis (MC_{DB}). The top, bottom, and core veneer plies are usually from different species. Press-gluing these veneer sheets together forms a veneer panel where 3- and 5-ply panels are common. Before gluing, the sheets are stacked on top of each other with the wood grain facing perpendicular to each subsequent sheet (cross-laminated) for dimensional stability. After trimming, the panels are sanded, sawn, and moulded (profiled) into individual planks that are then pre-finished, resulting in the final product of prefinished engineered wood flooring. The final product is then ready for installation. Final dimensions of the flooring range from 2 1/4 to 7 in. width and 1/4 to 9/16 in. thickness and random lengths.

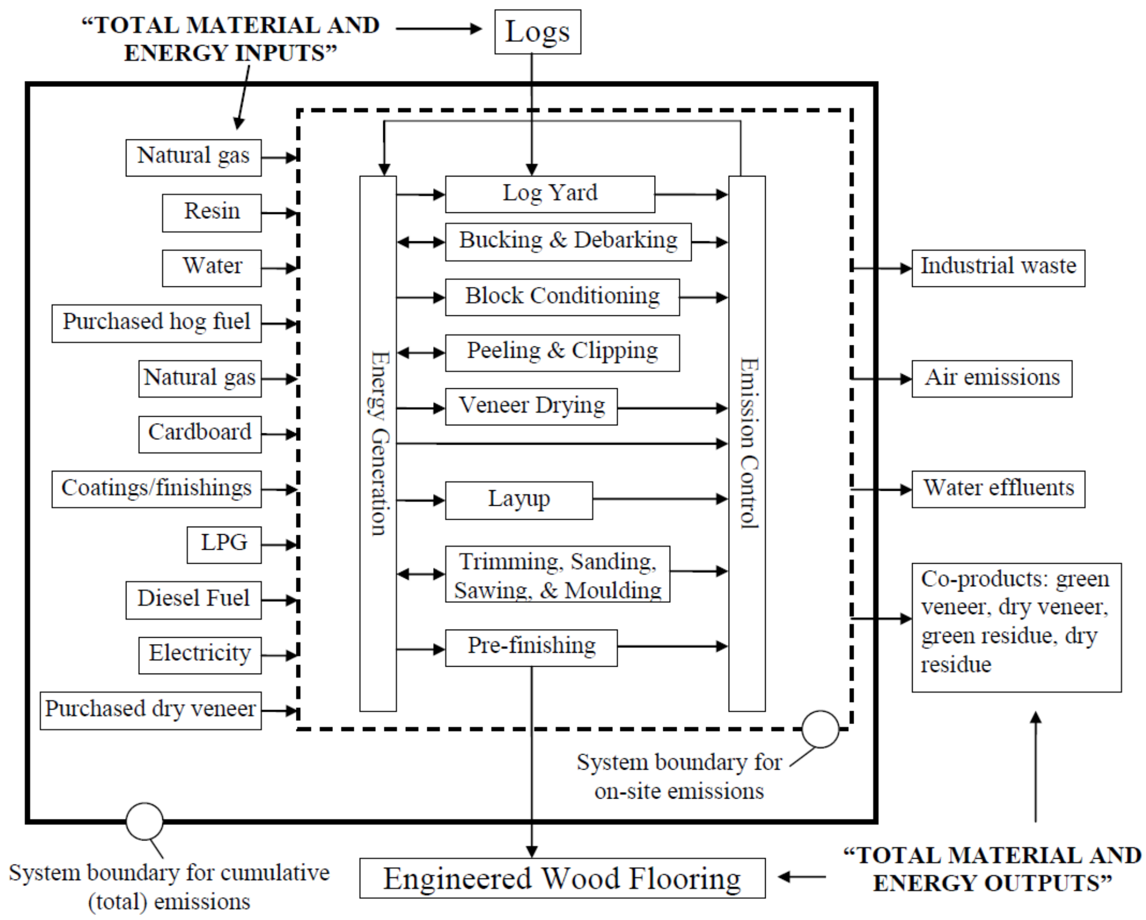

Figure 2.2 System boundaries for engineered wood flooring production.

2.6.2 Decision criteria (cut-off rule, if applicable)

All materials having a significant environmental impact were tracked. We tracked resin and coating materials because it was expected that these materials would have significant environmental burdens relative to their mass. Wood material that contributed less than 0.1% to the total wood output was not modeled in SimaPro.

2.6.3 Omissions of life-cycle stages, processes, input or output flows

All unit processes within the gate-to-gate system boundary were examined. Human labor and production of machinery and infrastructure were outside the system boundaries. In addition, forest growth and management, harvesting, product use and maintenance, recycling options, and final disposal life-cycle stages were not included in the study.

2.7 Assumptions

- We assumed that purchased dry veneer was produced in the same way as non-purchased (onsite) dry veneer was.
- An average log conversion of 5.32 m^3/thousand bf was calculated based on a surveyed weight-averaged log diameter of 15.1 in., with a range from 13 to 18 in., from the four surveyed veneer mills and assuming all lengths (Fonseca 2005). In addition, we calculated a green log volume of 2.46 m^3 based on 1,255 OD kg of incoming wood volume on a per-unit basis and having a green specific gravity of 0.510. Furthermore, we assumed 85% MC_{DB} for the incoming wood to the mill gate; therefore, a green wood log density of 944 kg/m^3 was calculated.
- As part of the CORRIM protocol for ensuring data quality, an overall "wood balance" was required to fall within 5% from material input to material output. Log mass was calculated based on the previous assumption of 5.32 m^3/thousand bf and an average green density of 944 kg/m^3. In this study, we calculated a 3.7% difference for the overall wood mass balance, falling within the CORRIM protocol.
- Higher heating values (HHV) were used to convert volume or mass basis of a fuel to its energy value. HHV represents the (gross) energy content of a fuel with the combustion products such as water vapor brought to liquid at 25 °C (77 °F), whereas lower heating value (net energy) ignores the energy produced by the combustion of hydrogen in fuel. HHV is the preferred method in the United States (EIA 2011).
- Each logging truck hauled about 3,250 bf hardwood logs or 25 tons (7.7 tons logs per thousand bf logs). All four veneer mills reported logging transportation data. Logging trucks were empty when returning to the logging site.
- Purchased wood fuel transportation data came from four veneer mills and three out of the five flooring plants.
- Water used onsite typically was ground water from wells primarily used for sprinkling logs and for make-up boiler water. Two flooring plants did not report water consumption and were not weight-averaged.
- This LCI study covered one full year (2007) and depended on when an operational (fiscal) year started at each company. The geographical area covered the eastern region shown in Figure 1.1.
- Primary mill data were collected through surveying the engineered wood flooring industry in accordance with ISO standards and CORRIM research guidelines. Missing values were not weight-averaged for a particular process per ISO standards.
- Most of the surveyed sites were medium- to large-size facilities with one small veneer mill providing data. Still, some of the larger facilities did not have the primary mill data requested.
- Primary data indicated the species represented were red and white oaks (*Quercus* spp.), hard and soft maples (*Acer* spp.), hackberry (*Celtis* spp.), pecan/hickory (*Carya* spp.), yellow-poplar (*Liriodendron tulipifera*), ash (*Fraxinus* spp.), sweetgum (*Liquidambar styraciflua*), beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), black walnut (*Juglans nigra*), elm (*Ulmus* spp.), and yellow birch (*Betula alleghaniensis*).
- The type of species processed at individual mills alters the density of the final product but not the volume. We noted a range of 0.43 (yellow-poplar) to 0.72 (white oak) ovendry specific gravity

for all the different wood species (Alden 1995). A mixed OD wood specific gravity of 0.578 was calculated.

- U.S. LCI database was the primary database used for materials and energy including electricity (NREL 2011).
- Franklin database provided the necessary boiler emission LCI data (FAL 2003a).
- U.S. EcoInvent (US-EI) database provided material LCI data such as stain and coatings that were not found in either the U.S. LCI or Franklin databases (PRé Consultants 2011).

2.8 Impact Categories

No impact assessment was conducted.

2.9 Critical Review

James Wilson, past vice president of CORRIM, reviewed the questionnaire used to survey the industry. Maureen Puettmann of WoodLife Consulting conducted a review according to ISO standards on both the report and the SimaPro module used to develop this report (ISO 2006 a,b).

3 Inventory Analysis

3.1 Log Yard

This unit process begins with transporting logs from the forest landing to the veneer mill and included the following operations: Transporting veneer logs from forest landing to log yard; sorting veneer logs by grades and size; storing logs either wet or dry, depending on season and species; transporting logs in-yard from point of unloading to log deck storage, and; transporting logs in-yard from log deck storage to the veneer mill infeed (debarker and log bucking saw). Inputs include fossil fuel for the log haulers and water and electricity for the sprinklers. This unit process generates no co-products. The log wetting process releases water emissions.

3.2 Debarking and Bucking

This unit process begins with logs at the debarker and included the following operations: Mechanically removing the bark from the logs and cross-cutting long logs to make wood “blocks” for peeling (cut-off saw). Inputs include electricity to operate the debarker and saw and diesel fuel for the log haulers. Co-products generated include green bark and some green wood waste including material lost as end cuts. The green wood residue are either ground into wood fuel that is burned onsite or sold as mulch. In this study, the surveyed mills listed roughly 50% of the bark as hog fuel.

3.3 Block Conditioning

Wood blocks are heated in vats with either hot water or direct steam to soften the log to improve the quality of the peeled veneer. Inputs include steam or hot water and electricity for the vats and fossil fuel for equipment to load and unload vats. This unit process produces no co-products. Emissions associated with this unit process include air and water emissions from the boilers providing heat for the vats.

3.4 Peeling and Clipping

A rotary lathe slices the hot, softened veneer blocks into thin veneer sheets and a clipper trims the sheets to size. Inputs include electricity to run the lathes, conveyors, clippers, hog fuel grinders, and waste gate equipment and fossil fuel to transport veneer sheets to veneer dryers. Co-products include green roundup wood, green peeler cores, green wood chips, green waste gate material, and green veneer clippings. Roundup wood is the wood material lost from peeling the block to create a cylindrical shape. Green roundup wood and green veneer clippings are ground into wood fuel that is burned onsite. Ground green wood fuel is also listed as hog fuel. Green peeler cores, green chips, and green waste gate material are sold.

3.5 Veneer Drying

Jet dryers dry the green veneer sheets down to 0–4% MC_{DB}. Inputs include electricity to run fans and steam or hot oil for heating the coils inside the dryers and fossil fuel consumed in forklifts transporting veneer from the peeling and clipping operation to the veneer drying process. Veneers are clipped after drying. Co-products include dry clippings. Air emissions occur. This unit process generates air emissions as the wood dries and dryer temperature rises, and resulted in large amounts of volatile organic compounds compared to the other unit processes. Other emissions associated with this unit process include air emissions from the boilers or direct-fired burners providing heat for the dryers.

3.6 Lay up

This unit process involved bonding thin veneer sheets, also called plies, together with resin to form panels. The resins are urea-formaldehyde (UF) and polyvinyl acetate (PVA). The plies are stacked on top of each other with the wood grain oriented perpendicular to each subsequent sheet for dimensional stability. Depending on the resin, pressure and heat are applied to the sheets to cure the resin and bond the sheets to form veneer panels. Three- to 5-ply veneer panels are common for engineered wood flooring. Inputs included heat and electricity to apply the resin and run the presses and fossil fuel for forklifts and for transporting material to the trimming, sanding, sawing, and moulding unit process. Other inputs are water to produce the resin and diesel fuel to transport purchased and non-purchased dry veneer from veneer mills. This unit process generates no co-products. The pressing and heating processes release air emissions as the resin cured. In addition, emissions associated with this unit process include air emissions from the boilers providing heat for the panel presses.

3.7 Trimming, Sanding, Sawing, and Moulding

Veneer panels are trimmed to standard dimensions, 4 by 8 ft (1.22 by 2.44 m). The trimmed panels are sawn into individual boards and sanded. After sanding, the boards are moulded (profiled) into tongue and groove flooring of random lengths. Inputs included electricity for the trim saw, the gang rip saw, sanding, hog fuel grinding, and fossil fuel to transport the unfinished wood flooring to the prefinishing unit process. Co-products include dry trim material, dry sanding dust, dry sawdust, and dry shavings.

3.8 Prefinishing

Prefinishing the unfinished wood flooring protects the surface. This unit process includes the following operations: sanding, priming, staining, filling, curing, sealing, and topcoating. Sanding the wood prepares the surface for priming, staining, filling, sealing, and topcoating. The primer coat promotes adhesion of the other materials and is ultra violet (UV)-cured. Staining material includes a mixture of water-based, solvent-based, and UV-cured types. Rollers typically apply the stain, filler, sealer, and topcoat. Solvents clean the rollers. All the filler, sealer, and topcoats are UV-cured. Aluminum oxide added to the finish increases surface durability. After finishing, the flooring is placed into small cardboard boxes for shipment. Inputs include steam for the stain drying ovens; electricity for UV-curing ovens, conveyors, and wood dust collectors; and cardboard for boxing up flooring for sale. Air emissions released include sanding dust, PM10, hazardous air pollutants (HAPs), and volatile organic compounds (VOCs).

3.9 Auxiliary Processes

3.9.1 Energy generation

This auxiliary process provides heat for use in other parts of the veneer mill and flooring plant. A fuel such as wood, propane, or natural gas is burned; green wood residue from peeling and clipping and dried wood residue from sanding, trimming, sawing, and moulding generates most of the thermal energy produced and used at the plant. This energy is typically in the form of steam used for the presses, jet dryers, and ovens and for facility heating. This process involves the following operations:

- Fuel handling
- Water added to the boiler (i.e., make-up water)
- Chemicals added to either the boiler or the steam lines

- Distribution of steam
- Distribution of electricity
- Treatment of process air, liquids, and solids

Outputs of this auxiliary process are steam and hot water from boilers, combustion gases for drying, solid waste (wood ash), and air emissions (e.g., CO_2, CO) from combustion. In addition, production of grid electricity used onsite releases emissions off-site.

3.9.2 Emission controls
This auxiliary process reduces the amount of air emissions released to the atmosphere. Wood dust collectors collect particulate and PM10 from sanding and finishing operations. Input includes electricity.

4 Limitations of LCI

4.1 Data Quality and Reliability

Franklin database, not primary mill data, provided boiler emission data as part of SimaPro 7 (FAL 2003a,b).

Close proxies were used when available that best matched the material. All resin and finishing materials using close proxies came from the U.S. EcoInvent database (PRé Consultants 2011).

4.2 Function and Functional Unit

For this study, the unit basis was 1 m^3 of prefinished engineered wood flooring. To conduct a comparative assertion on other flooring products, this value needs to be converted to 1 m^2 installed flooring of 9.5 mm thickness for the expected life of the prefinished engineered wood flooring in relation to the life of the building.

4.3 System Boundaries

Not applicable.

4.4 Assumptions

Polyvinyl acetate (PVA) LCI data are not available in the United States, therefore a proxy was developed by using the ethylene acetate polymerization process found in the US-EI database. The one PVA supplier contacted would not provide primary data on its product to develop the needed LCI data.

4.5 Limitations Identified by the Data Collection and Analysis

- Wood flooring production was not available by state.
- U.S. LCI data were not available for polyvinyl acetate resin used in gluing veneers into panels. Staining and coating materials were also not available in SimaPro (U.S. LCI database).

4.6 Conclusions and Recommendations

Not applicable.

5 Results

5.1 Product Yields

Mass and energy values, including emissions for prefinished engineered wood flooring production, were obtained by surveying four veneer mills and five flooring plants in the eastern United States. These facilities provided detailed data on mass flow, energy consumption, and types of fuel. Survey weight-averaged data were modeled in SimaPro 7 to find non-wood raw material use and emission data. Input data collected by survey are provided in Section 14 Appendix LCI inputs on page 33.

Weight-average annual production for the prefinished engineered wood flooring was 19.8 thousand m^3 (0.700 million ft^3) with a range of 6.1 to 31.1 thousand m^3 (0.215 to 1.10 million ft^3). Weight-averaged mill features included a log diameter (small end, inside the bark) of 384 mm (15.1 in.) with a range of 330 to 457 mm (13 to 18 in.). In addition, wood chips were the largest proportion of wood residue produced at 533 OD kg per production unit (Table 5.1). Flooring plants purchased 177 OD kg of dry veneer per production unit. The species veneered were red oak (roughly half), white oak, hard and soft maple, yellow-poplar, yellow birch, black cherry, ash, sweetgum, pecan/hickory, hackberry, elm, and some miscellaneous species.

For the mass balance, the LCI study examined the eight main unit processes and the overall process to track material flows. Using a weight-averaged multi-unit approach, 1,255 OD kg (2,760 OD lb) of incoming hardwood logs with a density of 944 kg/m^3 (58.9 lb/ft^3) and 177 OD kg of purchased rough dry veneer with a density of 613 kg/m^3 produced 1.0 m^3 (1.13 thousand ft^2 (3/8 in. basis)) of prefinished engineered wood flooring. Boilers burned 194 OD kg of both green and dry wood fuel produced onsite (Table 5.1). Overall, a difference of 3.7% was calculated based on the overall mass balance that included intermediate products such as rough green and rough dry veneer.

Table 5-1 Wood mass balance for 1.0 m3 of prefinished engineered wood flooring (weight-averaged values in ovendried kilograms)

	Wood Mass Balance			
Material	In	Out	Boiler Fuel	Sold
Green logs (white wood only)	1255			
Green logs (bark only)[a]	66.9			
Dry veneer (purchased)	177			
Green bark		66.9	6.0	60.9
Green roundup wood		2.8	2.8	0.0
Green peeler cores		0.2	0.0	0.2
Green veneer clipping		0.6	0.6	0.0
Green trim		0.6	0.6	0.0
Green chips		532.8	0.1	532.7
Green hog fuel		175.3	175.3	0.0
Green waste gate material		0.1	0.0	0.1
Dry clipping		7.6	4.6	3.1
Dry Sawdust		106	2.7	103
Dry Shavings		11.1	0.8	10.3
Dry Sanding Dust		17.8	0.2	17.6
Engineered wood flooring		578		
Sum	1499	1499	194	728

[a] About half the bark was included under green hog fuel.

Most veneer mills in the United States track log breakdown to find mill efficiency. The veneer recovery factor (VRF) is one way to track the log breakdown. In this study, VRF quantifies productivity as the weight of veneer (minus resin) produced divided by the total weight of incoming wood in log form. A VRF of 42.6% was calculated. Wilson and Sakimoto (2004) showed a VRF of 51% and 50% for production of softwood plywood in the Pacific Northwest and the Southeast, respectively.

5.2 Non-wood Inputs

5.2.1 Water consumption

Water use was mainly for sprinkling logs, steaming vats, and boiler make-up water. Water consumption was based on responses from four veneer mills and three flooring plants. A surface and ground water consumption of 972 and 2,838 L/m^3 (11.3 and 96.6 gal/thousand ft^2) of prefinished engineered wood flooring was calculated, respectively. Water consumption was broken down into the following unit processes: log yard (30%), block conditioning (40%), lay up (10%), and auxiliary energy generation (20%).

5.2.2 Transportation data

Onsite transportation of wood stock is a major fuel consumer, with off-road diesel having the highest consumption. Onsite transportation includes forklifts, front-end loaders, trucks, and other equipment used within the system boundary of the facility. Total diesel consumption is 11.3 L/m^3 of prefinished engineered wood flooring and is consumed at about three times the rate of propane and gasoline combined, on average. Diesel consumption breaks down into fuel used onsite and fuel used to haul dry veneer to flooring plants. Off-road and on-road diesel use is 7.0 and 4.3 L/m^3, respectively. Gasoline and propane use is 0.57 L/m^3 and 3.10 L/m^3, respectively. Transportation fuel consumption by unit processes is shown in Table 5.2.

Table 5-2 Percentage of fuel use on-site and between facilities broken down by unit processes

Unit Process	Diesel[a,b]	Gasoline[c]	Propane[c]
Logyard	60%	0%	0%
Bucking and debarking	10%	14.3%	14.3%
Block conditioning	5%	14.3%	14.3%
Peeling & clipping	5%	14.3%	14.3%
Veneer drying	5%	14.3%	14.3%
Layup	5%	14.3%	14.3%
Trimming, sanding, sawing, and moulding	5%	14.3%	14.3%
Prefinishing	5%	14.3%	14.3%
Total	100%	100%	100%

[a] Diesel fuel comprised of on-site transport and off-road transport of dry veneer to flooring plants
[b] Divided evenly between the last six unit processes
[c] Divided evenly between the last seven unit processes

5.2.1.1 Logs

Logging transportation data were required to connect the forest resource LCI to the prefinished engineered wood flooring LCI. An average one-way haul distance for hardwood log (including bark) transportation of 201 km (125 mi) with 100% empty backhaul was calculated from primary mill data. Mill average log MC was 85% MC dry basis (45.9% MC wet basis).

5.2.1.2 Purchased wood fuel

All purchased wood fuel was brought for steaming vats, drying veneer, heat pressing panels, heating facilities, and drying stains and coatings. An average one-way haul distance for purchased wood fuel transportation of 165 km (55 mi) with 100% empty backhaul was calculated from primary mill data. Mill average purchased wood fuel MC was 62.6% MC dry basis (35.8% MC wet basis).

5.2.1.3 Dry veneer (purchased)
An average one-way haul distance for purchased dry veneer transportation of 561 km (348 mi) with 100% empty backhaul was calculated from primary mill data. Mill average log MC was 6% MC dry basis (5.7% MC wet basis).

5.2.1.4 Dry veneer (non-purchased)
An average one-way haul distance for non-purchased dry veneer transportation of 1,043 km (648 mi) with 100% empty backhaul was calculated from primary mill data. Mill average log MC was 6% MC dry basis (5.7% MC wet basis). Surveyed mills made this veneer.

5.2.1.5 Resins
An average one-way haul distance for resin (and associated chemicals) transportation of 477 km (296 mi) with 100% empty backhaul was calculated from primary mill data.

5.2.1.6 Stain and coatings
An average one-way haul distance for both stains and coatings (and associated chemicals) transportation of 205 km (127 mi) with 100% empty backhaul was calculated from primary mill data.

6 Manufacturing Energy

6.1 Overall
Prefinished engineered wood flooring production requires both electrical and thermal energy for processing hardwood logs into prefinished engineered wood flooring. All the thermal energy is produced onsite, whereas electricity is produced off-site and delivered through a regional power grid. Electrical energy is required for all unit processes, whereas most of the thermal energy is used for block conditioning, veneer drying, lay up, and prefinishing processes. All veneer mills and flooring plants reported their electrical usage. Total electrical consumption was 1,113 kWh/m^3 (985 kWh/thousand ft^2) prefinished engineered wood flooring. A total process energy (unallocated) of 6,418 MJ was consumed per cubic meter (m^3) prefinished engineered wood flooring, which corresponds to 5.38 million Btu/thousand ft^2 (Table 6.1). Wood fuel at 300 ovendry kg or 6,263 MJ/m^3 (5.26 million Btu/thousand ft^2) contributed 97.6% of process thermal energy required with the remainder from propane (2.2%) and natural gas (0.2%).

6.2 Electrical
For the unit processes and the auxiliary unit processes (energy generation, emission controls (veneer mill), and emission controls (flooring plant)), the distribution of electrical energy consumption is shown in Table 6.2. Total electrical consumption was 1,113 kWh/m^3 (985 kWh/thousand ft^2). Electrical distribution among the unit processes was provided by the surveyed mill and flooring plants. Of all the unit processes, the highest electrical consumption occurred in the emission control (flooring plant) process with a value of 335 kWh/m^3 (296 kWh/thousand ft^2). Total electrical consumption for hardwood plywood production was 462 kWh/m^3 (408 kWh/thousand ft^2)[6]. For hardwood plywood production, lay up consumes roughly 44% of the total. Wilson and Sakimoto (2004) found a softwood plywood electrical consumption of 138 kWh/m^3 (122 kWh/thousand ft^2) for the Pacific Northwest, a significantly lower value. Softwood plywood veneer drying consumed 57.6 kWh/m^3 (51.0 kWh/thousand ft^2), approximately one-third of this total.

[6] Hardwood plywood production includes all unit processes up to lay up.

Table 6-1 Material and energy consumed on-site to produce 1.0 m^3 of prefinished engineered wood flooring (SimaPro input values). Includes fuel used for electricity production and for transportation (unallocated).

Fuel type	Quantity (units/m^3)	(units/thousand ft^2 [f])
Fossil fuel[a]		
Natural gas	0.3 m^3	0.01 thousand ft^3
Propane	5.36 L	1.26 gal
Electricity[b]		
Off-site generation	1,113 kWh	985 kWh
On-site transportation fuel[c]		
Off-road diesel	7.01 L	1.64 gal
On-road diesel[d]	4.26 L	1.00 gal
Gasoline	0.57 L	0.13 gal
Propane	0.04 L	0.73 gal
Renewable fuel[e]		
On-site wood Fuel	194 kg	378 lb
Purchased wood fuel	106 kg	207 lb
Water use		
Surface water	972 L	227 gal
Ground water	2,838 L	664 gal

[a] Energy values were determined using their higher heating values (HHV) in MJ/kg: 54.4 for natural gas and 54.0 for propane.
[b] Conversion unit for electricity is 3.6 MJ/kWh.
[c] Energy values were determined using their higher heating values (HHV) in MJ/kg: 45.5 for off-road and on-road diesel and 54.4 for gasoline.
[d] Transportation of panels and veneer between facilities; not accounted for in other transportation data
[e] Values given in oven-dry weights (20.9 MJ/OD kg)
[f] 0.885 m^3 per thousand ft^2 (3/8” basis)

Table 6-2 Electricity consumption broken down by unit processes

Unit Process	(%)	kWh/m^3	kWh/thousand ft^2 [a]
Bucking and debarking	8.0	89	78
Block conditioning	2.4	26	24
Peeling & clipping	11.9	133	118
Veneer drying	1.2	13	12
Layup	18.1	201	178
Trimming, sanding, sawing, and moulding	6.0	67	59
Prefinishing	6.0	67	59
Energy generation	11.9	133	118
Emissions control (veneer mill)	4.4	49	43
Emission controls (flooring plant)	30.1	335	296
Total	100	1,113	985

[a] 0.885 m^3 per thousand ft^2 (3/8 in. basis); 3.6 MJ per kWh

Off-site generation of electrical power affects the environmental impact from the different fuels used to generate power. Average composition of (off-site) electrical generation for the eastern grid for the United States was taken from SimaPro (i.e., U.S. LCI database) (PRé Consultants 2011). The most significant electric power contributor in the eastern region is coal, with 58.9% of total electrical utility power including both bituminous and lignite coals. Other fuel sources are nuclear, natural gas, petroleum, hydro, biomass, and unspecified fossils, which provide 22.7%, 10.1%, 3.3%, 2.9%, 1.6%, and 0.5%, respectively. Wind power contributes less than 0.05% to the grid.

6.3 Heat

A total process energy (unallocated) of 6,418 MJ are consumed per cubic meter (m^3) prefinished engineered wood flooring, which equals 5.38 million Btu/thousand ft^2. Table 6.3 shows the results by unit processes. The unit processes of block conditioning, veneer drying, and lay up consume 23.7%, 58.8%, 11.3%, and 6.2% of process thermal energy, respectively. Facility heating was divided evenly among these four processes. For an energy check, we estimated a literature value for block conditioning of 1,642 MJ/m^3 assuming frozen oak logs heated to 100 °C, boiler efficiency of 75%, and boiler vat efficiency of 25% due to using live steam (Steinhagen 2005). Previous CORRIM studies on southeast plywood showed a veneer drying value of 1.35 million Btu/thousand ft^2 (3/8 in. basis) (Wilson and Sakimoto 2004). Hardwood plywood may take 4–5 times more energy than softwoods because of the longer times to soften blocks prior to peeling, and hardwood contains more water due to its higher density.[7]

Table 6-3 Thermal process energy consumption broken down by unit processes

Unit Process	MJ/m^3	million BTU/thousand ft^2 [a]
Block conditioning	1,521	1.27
Veneer drying	3,773	3.16
Layup	723	0.61
Stain drying	401	0.34
Total	6,418	5.38

[a] 0.885 m^3 per 1000 ft^2 (3/8 in. basis); 1055 MJ per million BTU

[7] Personal communication with Dr. James Wilson, past vice president of CORRIM on October 10, 2009.

7 Environmental Impacts

SimaPro 7 modeled output factors during the manufacturing process with major consumption of raw materials, other than wood, for electrical generation. Major uses of raw material, other than logs processed into veneer were coal, purchased wood fuel (residue), natural gas, crude oil, and limestone, with allocated values of 358, 105, 76.2, 75.8, and 14.8 kg per unit production, respectively. Wood log volume of 1.43 m^3 was allocated to produce 1.0 m^3 prefinished engineered wood flooring (Table 7.1). Limestone and most of the coal were used to produce off-site electricity, and oil and natural gas was for off-site electricity, resins and finishing materials, and thermal energy used onsite. Veneer mills and flooring plants burned purchased wood fuel for thermal energy use onsite. Limestone helps remove sulfur dioxide emitted from burning coal.

Table 7-1 Raw materials consumed during production of prefinished engineered wood flooring—cumulative, allocated gate-to-gate LCI values (SimaPro output values). Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

	Quantity[b]	
Raw material[a]	*(units/m³)*	(units/thousand ft²)[c]
Logs at mill gate[d]	1.43 m^3	44.7 ft^3
Water, well, in ground[e]	2.51 m^3	78.4 ft^3
Water, process, surface[e]	6.35 m^3	198 ft^3
Purchased wood waste	105 kg	205 lb
Coal, in ground[e]	352 kg	686 lb
Gas, natural, in ground[e]	75.6 kg	147 lb
Oil, crude, in ground[e]	74.8 kg	146 lb
Limestone, in ground[e]	14.8 kg	28.8 lb
Energy, from hydro power	3.74 kWh	3.31 kWh
Energy, unspecified	0.41 kWh	0.36 kWh
Uranium, in ground[e]	0.0106 kg	0.0207 lb

[a] Values are allocated and cumulative.
[b] Energy values were found using HHV in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.
[c] 0.885 m^3 per 1000 ft^2 (3/8 in. basis).
[d] Amount of wood in log form allocated to final product; no shrinkage taken into account from drying process. Value contains no co-products but does include amount of on-site generated wood fuel allocated to the flooring.
[e] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

Table 7.2 shows the allocated cumulative energy of making 1.0 m^3 of prefinished engineered wood flooring. For cumulative energy allocated to prefinished engineered wood flooring, a value of 22,986 MJ/m^3 was found. Coal used to produce electricity provides by far the largest portion of energy needed, and most of this is because of the intensive energy needed for peeling and clipping (11.9%), lay up (18.1%), and for emission controls associated with prefinishing (30.1%).

Table 7-2 Cumulative energy (HHV) consumed during production of prefinished engineered wood flooring—cumulative, allocated gate-to-gate LCI values (SimaPro output values). Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

Fuel[a,b]	*(kg/m³)*	(MJ/m³)	BTU/thousand ft² [c,e]
Purchased wood waste	105 kg	2,195	1,840,000
Coal, in ground[d]	352 kg	9,222	7,740,000
Gas, natural, in ground[d]	75.6 kg	4,113	3,450,000
Oil, crude, in ground[d]	74.8 kg	3,403	2,860,000
Energy, from hydro power	0	13	10,000
Uranium, in ground[d]	0.0106 kg	4,039	3,390,000
Energy, unspecified	0	1	1,000
TOTAL		22,986	19,300,000

[a] Values are allocated and cumulative and based on HHV

[b] Energy values were found using their higher heating values (HHV) in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.

[c] 0.885 m³ per 1000 ft² (3/8 in. basis).

[d] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

[e] Conversion for units of energy is 948.8 BTU/MJ.

Two different life-cycle inventory scenarios for manufacturing prefinished engineered wood flooring were evaluated based on the five veneer mills and four flooring plants surveyed: allocated cumulative and allocated onsite. The method for evaluating the two scenarios followed the ISO 14040 standards and CORRIM guidelines. The allocated accumulative scenarios examined all emissions for electricity and thermal energy generation that are required to produce 1.0 m^3 of prefinished engineered wood flooring starting with hardwood logs at the mill gate. These emissions involve the cradle-to-gate resource requirements (production and delivery) of grid electricity, fossil fuels and purchased wood fuel used in the boiler, and fossil fuels used in yard equipment such as forklifts. In addition, emission data for onsite combustions of the two latter materials and wood fuel generated onsite were included. Transportation of logs (including bark) to the mill gate was included in the cumulative system boundary. The allocated onsite scenario only includes emissions from the combustion of all fuels used at the mills and flooring plants, therefore it did not involve the manufacturing and delivery of materials, fuels, and electricity consumed at the mill.

Table 7.3 shows the lower environmental impact of onsite compared to cumulative emissions for the facilities surveyed. Carbon dioxide and particulates are typically measured, although other emissions are frequently monitored from boilers to ensure regulatory compliance. Carbon dioxide (CO_2) emissions are separated by two fuel sources, biogenic (biomass-derived) and anthropogenic (fossil-fuel-derived). Accumulative total emission values of 623 and 1,049 kg were reported from SimaPro for CO_2 (biogenic) and CO_2 (fossil), respectively (Table 7.3). The percentage of biogenic CO_2 to total CO_2 increased from 37.3% to 64.8% from the total (cumulative) to onsite scenarios. Emissions of volatile organic compound (VOC) gases was roughly the same at approximately 1 kg, regardless of scenario, thus indicating wood drying was a significant contributor to the overall amount of VOCs.

Table 7-3 Life-cycle inventory results for total cumulative and on-site emissions on a per unit basis of prefinished engineered wood flooring (allocated)

Substance	Total cumulative		On-site	
	(kg/m^3)	($lb/thousand\ ft^2$)[a]	(kg/m^3)	($lb/thousand\ ft^2$)[a]
Water emissions				
Biological oxygen demand (BOD)	1.09	2.13	1.06	2.06
Cl^-	14.9	29.1	7.9	15.38
Suspended solids, unspecified	0.933	1.82	0.591	1.15
Oils, unspecified	0.0911	0.178	0.0865	0.169
Dissolved solids	12.6	24.6	3.94	7.68
Chemical oxygen demand (COD)	1.52	2.96	1.45	2.84
Other solid materials[b]				
Waste in inert landfill	28.4	55.4	28.4	55.4
Recycled material	9.34	18.2	9.34	18.2
Solid waste[c]	41.0	81.0	41.0	81.0
Air emissions				
Acetaldehyde	2.17E-01	4.24E-01	2.17E-01	4.24E-01
Acrolein	4.90E-05	9.57E-05	1.10E-05	2.15E-05
Benzene	2.32E-03	4.53E-03	2.14E-03	4.18E-03
Carbon dioxide (biomass)	6.23E+02	1.22E+03	6.10E+02	1.19E+03
Carbon dioxide (fossil)	1.05E+03	2.05E+03	3.31E+02	6.46E+02
Carbon monoxide	5.57E+00	1.09E+01	5.02E+00	9.80E+00
Methane	2.65E+00	5.17E+00	1.21E+00	2.36E+00
Formaldehyde	4.00E-02	7.80E-02	3.98E-02	7.77E-02
Mercury	4.84E-04	9.45E-04	3.36E-02	6.55E-02
Naphthalene	6.99E-04	1.36E-03	6.96E-04	1.36E-03
Nitrous oxides	3.76E+00	7.34E+00	1.61E+00	3.14E+00
Non-methane, volatile organic compounds (NMVOC)	5.79E-01	1.13E+00	5.02E-01	9.79E-01
Organic substances, unspecified	8.05E-02	1.57E-01	7.97E-02	1.55E-01
Particulate (PM10)	1.38E-01	2.70E-01	1.38E-01	2.70E-01
Particulate (unspecified)	6.10E-01	1.19E+00	1.71E-01	3.34E-01
Phenol	1.92E-02	3.74E-02	1.92E-02	3.74E-02
Sulfur dioxide	5.05E+00	9.85E+00	5.58E-01	1.09E+00
VOC	1.04E+00	2.03E+00	9.99E-01	1.95E+00

[a] 0.885 m^3 per 1000 ft^2 (3/8 in. basis).
[b] Includes solid materials not incorporated into the product or co-products and leave the system boundary
[c] Solid waste is mostly boiler ash from burning wood. Boiler ash is either spread as a soil amendment or landfilled depending on the facility.

Material and energy resources consumed to manufacture 1 m^3 of prefinished engineered wood flooring are shown in Table 6.1. These input values are unallocated and were entered into SimaPro 7 to find the environmental burdens of manufacturing 1 m^3 of prefinished engineered wood flooring. Table 7.4 lists the onsite energy values unallocated and allocated to the planed dry lumber. Unallocated values were calculated from material and energy resources found in Table 6.1 and were the sum of all fuel and electricity inputs to the process. Allocated onsite energy use is roughly 57% of the total unallocated onsite use. Material and energy consumed at the mill for SimaPro 7 gave LCI outputs allocated to manufacturing prefinished engineered wood flooring, not to associated wood co-products. Using the total difference between the unallocated and allocated values, we calculated 4,700 MJ of energy used at the mill was allocated to the co-products. Some LCI outputs listed raw materials used.

Table 7-4 Fuel and electrical energy used on-site to produce a 1 m^3 of prefinished engineered wood flooring.

	Energy use at mill Unallocated (MJ/m3)	Allocated (MJ/m3)
Fossil fuel[1]		
Natural gas	11.4	6.62
Propane	143	82.9
Electricity[2]		
Off-site generation	4,006	2,326
On-site transportation fuel[3]		
Off-road diesel	271	110
On-road diesel	165	66.9
Gasoline	19.9	8.09
Propane	167	67.9
Renewable fuel[4]		
On-site wood fuel	4,050	2,350
Purchased wood fuel	2,220	1,290
Total	11,000	6,300

[1] Energy values were determined using their higher heating values in MJ/kg: 43.3 for fuel oil #1 and #2.
[2] Conversion unit for electricity is 3.6 MJ/kWh.
[3] Energy values were determined using their higher heating values in MJ/l: 38.7 for off-road diesel, 26.6 for propane, and 34.8 for gasoline.
[4] Values given in oven-dried weights (20.9 MJ/OD kg).

8 Carbon Balance

Carbon emissions are playing an increasingly important role in policy decision making in the United States and throughout the world. The impact of carbon was determined by estimating values of carbon found in wood and bark as described from previous studies, such as Skog and Nicholson (1998), using a mixture of hardwood roundwood values for the eastern United States. We used a mixed hardwood factor of 305.1 kg/m^3 of wood material and a carbon content of 51.7% with an incoming log wood mass of 1,255 OD kg/m^3 prefinished engineered wood flooring to calculate the carbon balance. Resins and coating processes are not included. Total carbon input and output of 831 and 872 kg/m^3 prefinished engineered wood flooring are found (Table 8.1) resulting in a difference of 4.4 %. Contribution to the carbon balance from air emissions are shown in Table 8.2. A cubic meter of prefinished engineered wood flooring stores 1,096 kg CO_2-equivalents[8] as a final product.

Table 8-1 Tracking of wood-based carbon inputs and outputs for prefinished engineered wood flooring

	Elemental carbon	
Substance[a]	(kg/m^3)	(lb/thousand ft^2)[b]
Input		
Logs	649	1,265
Bark[c]	35	67.4
Purchased dry veneers	92	179
Purchased wood fuel	55	107
Sum carbon in	831	1,618
Output		
Prefinished engineered wood flooring	299	582
Co-products[c]	376	733
Solid emissions	21	42
Air emissions	176	343
Sum carbon out	872	1,700

[a] Wood-related carbon and its emissions.
[b] 0.885 m^3 per 1000 ft^2 (3/8 in. basis).
[c] Bark leaves system both as wood fuel and as a co-product (mulch).

Table 8-2 Composition of wood-based air emissions related to carbon contribution

	Total[a]		Carbon[a]		
Substance	(kg/m^3)	(lb/thousand ft^2)[b]	(%)[c]	(kg/m^3)	(lb/thousand ft^2)[b]
Benzene	2.32E-03	4.53E-03	92.3%	2.14E-03	4.18E-03
Carbon dioxide, biogenic	6.23E+02	1.22E+03	27.3%	1.70E+02	3.32E+02
Carbon monoxide	5.57E+00	1.09E+01	42.9%	2.39E+00	4.66E+00
Formaldehyde	4.00E-02	7.80E-02	40.0%	1.60E-02	3.12E-02
Methane	2.65E+00	5.17E+00	75.0%	1.99E+00	3.88E+00
Naphthalene	6.99E-04	1.36E-03	93.7%	6.55E-04	1.28E-03
NMVOC, non-methane volatile organic compounds, unspecified origin	5.79E-01	1.13E+00	88.2%	5.11E-01	9.96E-01
Organic substances, unspecified	8.05E-02	1.57E-01	50.0%	4.02E-02	7.85E-02
Phenol	1.92E-02	3.74E-02	76.6%	1.47E-02	2.87E-02
VOC, volatile organic compounds	1.04E+00	2.03E+00	88.2%	9.20E-01	1.79E+00
Total	633	1236	27.7	176	343

[a] All values per unit of prefinished engineered wood flooring.
[b] 0.885 m^3 per 1000 ft^2 (3/8 in. basis).
[3] Percentage from Softwood Lumber LCI (Milota et al. 2004) and Softwood Plywood LCI (Wilson and Sakimoto 2004).

[8] Multiplying (mass of wood flooring) × (carbon content) × (carbon to carbon dioxide conversion) = 578 kg × 51.7% × 44/12 = 1,096 kg CO_2-equivalents.

9 Sensitivity Analysis

A sensitivity analysis was completed per ISO 14040 standards in SimaPro to model the effects of using different quantities of fuel sources for thermal energy generation. Sensitivity analysis can be useful to understand how various process parameters contribute to environmental output factors. For instance, in prefinished engineered wood flooring manufacturing, heat is used in several sub-processes, consuming a combination of wood, natural gas, and propane as fuel to generate the heat. Changing fuel sources, also referred to as fuel switching, can have a significant effect on the type and quantity of emissions. This sensitivity analysis compared the effects of the “base” fuel mix to using (1) all onsite generated wood fuel (mostly green hog fuel from the peeling and clipping process) and (2) using all propane as a fuel input. Propane is chosen because it burns cleaner than fuel oil and is abundantly available domestically.

9.1 Alternative Fuel Sources

The “base” fuel mix in this study included three fuel sources, with wood fuel and propane supplying the majority of the energy. Natural gas contributed less than 1%. Based on survey data, the original model assumed that 97.6% of the fuel used was in the form of wood fuel (63.1% produced onsite and the remainder purchased) and 2.2% as propane. Most mills use only one or two types of fuel, whereas the base case resulted in a weight-averaged composite model incorporating different fuel sources taken from primary mill data for the five veneer mills and four flooring plants. In this sensitivity analysis, two alternative fuel-use scenarios were created for comparison to the “composite mill” or “base” scenario. One alternative assumed consumption of only onsite (generated) wood fuel used for all thermal energy by increasing the initial base value of 194 to 307 OD kg for this “100% onsite wood fuel” case to generate 6,418 MJ/m^3 (5.38 million Btu/thousand ft^2) of prefinished engineered wood flooring. The second alternative fuel-use scenarios, “100% propane,” had propane use increase from the base value of 5.4 to 241 L to provide all necessary heat for the facility.

9.2 Three Fuel Source Scenarios

This sensitivity analysis examined three scenarios for heat generation using the base fuel mix, 100% propane, and 100% onsite (generated) wood fuel cases. All three scenarios include emissions from the cradle-to-gate resource requirements (production and delivery) of grid electricity. The following three scenarios were modeled using SimaPro to find the differences in emissions: (1) comparing 100% propane case to the “base” hardwood lumber fuel mix that used both propane and wood fuel, (2) comparing 100% onsite (generated) wood fuel to the “base” hardwood lumber fuel mix that again had no fuel changes, and (3) comparing 100% propane to 100% onsite (generated) wood fuel cases.

9.3 Sensitivity Analysis Results

Table 9.1 presents the summary of the three fuel use scenarios, with a partial list of air emissions for the eastern region. In scenarios 1 and 2, a negative percentage difference number indicated that the alternative fuel source released fewer emissions than did the base model. A positive percentage difference means that the base or original model released fewer emissions. Scenario 1 indicated that less particulate (PM10), solid waste, acetaldehyde, and biogenic CO_2, but more fossil CO_2, non-methane VOC, and NOx, were produced when burning 100% propane than in the base fuel mix (original). Scenario 2 showed more biogenic CO_2, both types of particulate, acetaldehyde, benzene, naphthalene, and phenol, but less fossil CO_2 and NOx were produced when burning 100% wood fuel than in the base fuel mix (original). In scenario 3, a negative number indicates that the all-propane case released fewer emissions than the all-onsite produced wood fuel case, and a positive percentage number means that all onsite produced wood fuel models released fewer emissions. Scenario 3 highlighted the increase of fossil CO_2, non-methane VOC, and NOx produced along with less particulate (PM10) and biogenic CO_2 produced compared with scenario 1. For all three scenarios, the amount of VOC produced was similar regardless of the fuel used because most VOC originated in the actual drying of the veneer and during panel making and prefinishing.

Table 9-1 Sensitivity analysis for manufacturing prefinished engineered wood flooring

	Fuel Distribution (kg per cubic meter planed dry lumber)			Difference (%)		
Substance	100% propane	100% wood fuel[a]	Original (base)	Scenario 1—100% propane to original	Scenario 2—100% wood fuel to original	Scenario 3—100% propane to 100% wood fuel
Acetaldehyde	2.15E-01	2.18E-01	2.17E-01	-1.2%	0.5%	-1.7%
Benzene	1.41E-03	2.44E-03	2.40E-03	-51.9%	1.7%	-53.5%
CO_2 (biogenic)	5.59E+01	6.41E+02	6.24E+02	-167.1%	2.7%	-167.9%
CO_2 (fossil)	1.45E+03	1.06E+03	1.06E+03	30.6%	0.1%	30.4%
CO	3.61E+00	5.73E+00	4.39E+00	-19.4%	26.6%	-45.4%
Formaldehyde	3.80E-02	4.02E-02	4.00E-02	-5.1%	0.5%	-5.6%
Methane	2.20E+00	1.72E+00	2.67E+00	-19.5%	-43.4%	24.3%
Naphthalene	5.00E-05	7.18E-04	6.99E-04	-173.3%	2.7%	-174.0%
Nitrogen oxides	4.10E+00	3.79E+00	3.80E+00	7.5%	-0.5%	7.9%
Non-methane, VOC	8.22E-01	5.85E-01	5.87E-01	33.3%	-0.3%	33.6%
Organic substances, unspecified	3.55E-02	8.18E-02	8.05E-02	-77.5%	1.7%	-78.9%
Particulate (PM10)	9.19E-02	1.40E-01	1.38E-01	-40.3%	1.1%	-41.4%
Particulate (unspecified)	6.31E-01	6.19E-01	6.10E-01	3.3%	1.4%	2.0%
Phenol	8.31E-03	1.95E-02	1.92E-02	-79.1%	1.8%	-80.6%
Sulfur dioxide	2.16E+00	5.15E+00	5.11E+00	-81.2%	0.8%	-81.9%
VOC	1.06E+00	1.05E+00	1.04E+00	1.3%	0.4%	0.9%
Solid waste	1.67E+01	4.18E+01	4.14E+01	-84.8%	1.1%	-85.7%

[a] All wood fuel used was generated on-site.

10 Study Summary

A rigorous material and energy balance was completed on five veneer mills and four flooring plants located in the eastern United States. A weight-averaged process energy (unallocated) of 6,418 MJ/m^3 of prefinished engineered wood flooring (5.38 million Btu/thousand ft^2) was found with 1,521 MJ for block conditioning, 3,773 MJ for veneer drying, 723 MJ for lay up, and 401 MJ for stain drying. Total electrical energy consumption of 1,113 kWh/m^3 of prefinished engineered wood flooring (985 kWh/thousand ft^2) was also determined. Results showed a cumulative allocated value for manufacturing prefinished engineered wood flooring from the forest road to the final product leaving the flooring plant of 22,990 MJ/m^3 (19.3 million Btu/thousand ft^2)[9]. Unfinished engineered wood flooring showed a cumulative allocated value of 13,600 MJ/m^3 (11.4 million Btu/thousand ft^2).

Table 10.1 showed the difference by type of wood flooring for cumulative energy (allocated). Prefinished consumes more energy compared to unfinished engineered wood flooring, roughly 60%. Much of this increase in energy resulted from electrical consumption in the emission control devices to prevent the release of VOCs. These devices consumed approximately 30% of total electricity (335 kWh/m^3 (296 kWh/thousand ft^2)) needed for the entire manufacturing process. Resin usage also increased the environmental impact as noted when comparing unfinished engineered to unfinished solid strip wood flooring. Unfinished solid strip flooring cumulative energy showed a consumption rate of only 6,498 MJ/m^3, roughly half of unfinished engineered wood flooring.

[9] Cumulative allocated value considers electrical efficiency of grid power provided.

Table 10-1 Cumulative energy (HHV) consumed during production of prefinished engineered wood flooring compared to unfinished engineered and solid strip wood flooring—cumulative, allocated gate-to-gate LCI values (SimaPro output values). Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

		Engineered wood flooring	
Fuel[1] (MJ/m^3)	Unfinished Solid Strip Flooring[2]	Unfinished	Prefinished
Biomass	4,195	1,724	2,195
Coal	748	4,992	9,222
Natural Gas	934	2,930	4,113
Crude Oil	557	2,580	3,403
Hydro	9	4	13
Uranium	48	1,363	4,039
Energy, unspecified	7	1	1
Total	6,498	13,595	22,986

[1] based on HHV; Energy values were found using their higher heating values (HHV) in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.
[2] Puettmann et al. (2010)

From a Swedish perspective, Potting and Blok (1995) conducted a life-cycle assessment on different flooring materials including linoleum and cushioned vinyl. Linoleum is comprised of linseed oil (27%), limestone (10%), ground wood (10%), ground cork (10%), colophonium (8%), and pigment (5%). Cushioned vinyl is comprised of polyvinyl chloride (50%, plasticizer (30%), limestone (15%), stabilizers (3%), and pigments (0.3%), and a few other additives. Each compound contributes to the overall amount of process energy required to produce the final product. Total percentage of components does not equal 100% for unknown reasons.

From Potting and Blok's study, we calculated the cumulative energy per kilogram of flooring for linoleum and cushioned vinyl. For linoleum with a density of 600 $kg/m^3$and ignoring material transportation, a value of 35.5 MJ/kg linoleum was calculated (Table 10.2). For cushioned vinyl with a density of 590 kg/m^3 and ignoring material transportation, a value of 70.0 MJ/kg was calculated. Caution is necessary because no allocation method was selected and no statement on whether higher or lower heating values was used.

Table 10.3 shows how wood and non-wood flooring material compare based on cumulative energy values. Unfinished solid strip flooring in the United States has the lowest cumulative energy value with 9.89 MJ/kg, about 14% of cushioned vinyl. Prefinished engineered wood flooring is similar in energy values to linoleum. Converting to MJ/m^2 (functional unit) indicates that wood material has higher cumulative energy values than the non-wood alternatives. However, no biomass energy was consumed during production of linoleum and cushioned vinyl. Furthermore, significant amounts of biomass energy were consumed during production of the different types of wood flooring. For example, nearly 98% of the process (thermal) energy for prefinished engineered wood flooring in the United States came from biomass. Contrarily, natural gas was the primary fuel for production of linoleum and cushioned vinyl (Potting and Blok 1995). In addition, Potting and Blok (1995) indicated that wood flooring products would typically last 50 years, about three and six times longer than linoleum and cushioned vinyl flooring would, respectively.

Table 10-2 Cumulative energy consumed during production of linoleum and cushioned vinyl—cumulative values. Transportation fuel data not included.

Linoleum			Cushioned vinyl		
Substance	(%)	(MJ/kg)	Substance	(%)	(MJ/kg)
Fertilizer		2.64	Polyvinyl chloride	50	77.9
Linseed oil[a] (27%)	27	0.54	Plasticizer	30	75.3
Limestone (10%)	10	0.08	Limestone	15	0.08
Ground wood (10%)	10	3.24	Stabilizers	3	-----
Ground cork (10%)	10	1.62	Pigments	0.3	70
Colophonium[b] (8%)	8	---------	Glass Fibre	3.2	5.9
Pigment (5%)	5	70.0	Process energy		8
Jute	11	0.96			
Acrylate dispersion layer	0.35	----			
Process energy		10.6			
Electricity		18.0			
Total		35.5	Total		70.0

[a] Fertilizing (Reaping (0.65MJ/kg); Extracting linseed oil (0.54MJ/kg)

[a] No data available

[b] Conversion for units of electricity is 3.6 MJ/kWh; assume 30% overall electrical efficiency; 1.5kWh/m^2

Table 10-3 Cumulative energy consumed production of wood and non-wood flooring.

Type	Density[a] (kg/m^3)	Energy (MJ/kg)	Weight (kg/m^2)	Energy (MJ/m^2)
Prefinished engineered wood[b]	656	35.0	6.56	230
Unfinished engineered wood[b]	643	21.1	6.43	136
Unfinished solid strip (US)[c]	657	9.89	12.5	123
Linoleum[d]	600	35.5	2.0	71
Cushioned vinyl[d]	590	70.0	1.7	119
Wood floor boards (Germany)[e]	---	19.8	10.71	212

[a] Oven dried

[b] Wood material had 9.5 mm thickness

[c] Hubbard and Bowe (2010); 19 mm thickness

[d] Transportation fuel data not included in the total

[e] Nebel et al. (2006); 212 MJ/m^2; 8kg/m^2; air dried to 17%MC; mass allocation

11 Discussion

Our data show that engineered wood flooring has two significant advantages over non-wood substitutes: biomass fuel is used instead of fossil fuel during manufacturing and and carbon can be sequestered (captured and stored) in the wood product. Burning biomass for energy does not contribute to increasing atmospheric CO_2, provided forests are regrowing and reabsorbing the emitted CO_2 on a sustainable basis. Other non-wood products typically do not have the benefits of a renewable product to use both as a fuel and a finished product. The carbon stored in the final product equates to the fossil CO_2 released during manufacturing. In addition, decreasing energy consumption would be of great benefit to the mills in terms of its both financial benefits (cost reduction) and environmental burden benefits, especially in veneer drying, lay up and prefinishing.

A trade-off occurs for prefinishing the engineered wood floor onsite. Additional electricity for emission controls of the VOCs emitted during prefinishing has a large environmental impact up-front. However, the environmental impact of prefinishing onsite compared to finishing engineered wood flooring once installed would likely show a positive environmental influence overall. This is due to controlling emissions at the flooring plants instead of finishing the installed engineered wood floor at a residential or commercial building that would likely allow uncontrolled release of VOCs.

12 Conclusions and Recommendations

The following main conclusions are based on the life-cycle inventory:

- The amount of carbon stored in prefinished engineered wood flooring exceeds the fossil carbon emissions by about 4%. Therefore, as long as prefinished engineered wood flooring and its carbon stay in products held in end uses, the carbon stored will exceed the fossil carbon emitted in manufacturing.

- A trade-off exists between prefinished and unfinished engineered wood flooring. A large amount of electricity is consumed during the prefinishing unit process to control emissions from staining and coating the wood flooring. As a result, the environmental impact is significantly higher for prefinished engineered wood flooring than for unfinished engineered wood flooring. However, finishing the wood floor after installation in a residential or commercial building (an uncontrolled environment) would result in greater harm to the environment. This harm is caused by uncontrolled emissions released from the staining and coating process that are now captured or destroyed onsite at the flooring plant.

- Burning fuel for energy generates CO_2. Nearly all energy burned onsite for manufacturing prefinished engineered wood flooring comes from woody biomass. Burning biomass for energy does not contribute to increasing atmospheric CO_2 provided forests are regrowing and reabsorbing the emitted CO_2 on a sustainable basis.

- Increasing onsite wood fuel consumption would reduce fossil greenhouse gases but increase other gases, especially particulate emissions. Particulate matter can be captured prior to release to the atmosphere using commercially available technology but not without increased costs.

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14 Appendix

14.1 LCI inputs

Logyard										
Products										
Roundwood, hardwood, green, at mill, US E	1255	kg			94.9%					
Bark, hardwood, green, at mill, US E	66.9	kg			5.1%					
Resources										
Water, well, in ground	851	l			30.0%	of total	2,838	l		
Water, process and cooling, surface	292	l			30.0%	of total	972	l		
Materials/fuels										
Roundwood, hardwood, at forest road, US NE-NC	1255	kg								
Bark, hardwood, at forest road, US NE-NC	66.9	kg								
Transport, combination truck, diesel powered	467	tkm	tkm=	1255	kg*	201	km*(1+		85.0%	MC)/1000
Transport, combination truck, diesel powered	25	tkm	tkm=	66.9	kg*	201	km*(1+		85.0%	MC)/1000
Diesel, combusted in industrial equipment	6.76	l			60%	of total	11.3	l		
Gasoline equipment (gal)	0.0	l			0%	of total	0.6	l		
Natural gas equipment (gal) - surrogate for propane	0.0	l			0%	of total	3.1	l		
Debarking and bucking										
Products										
Bucked log, hardwood, green, at veneer mill, US E	1255	kg			94.9%					
Bark, hardwood, green, at veneer mill, US E	60.9	kg			4.6%					
Fuel wood, hardwood, green, at veneer mill, US E	6.0	kg			0.5%					
Materials/fuels										
Roundwood, hardwood, at forest road, US E	1255	kg								
Bark, hardwood, at forest road, US E	66.9	kg								
Diesel, combusted in industrial equipment/US	1.13	l			10.0%	of total	11.3	l		
Gasoline, combusted in equipment/US	0.08	l			14.3%	of total	0.6	l		
Natural gas, combusted in industrial equipment/RNA	0.44	l			14.3%	of total	3.1	l		
Electricity/heat										
Electricity, at grid, Eastern US/US	319	MJ			8.0%	of total	4,006	MJ		
Final waste flows										
Dummy_Disposal, solid waste, unspecified, to inert material landfill	0.837	kg			9.44%	allocated to this stage				8.87
Dummy_Recycling, waste, unspecified	2.15	kg			7.21%	allocated to this stage				29.8
Block conditioning										
Products										
Conditioned log, hardwood, green, at veneer mill, US E	1255	kg								
Materials/fuels										
Bucked log, hardwood, green, at veneer mill, US E	1255	kg								
Diesel, combusted in industrial equipment/US	0.56	l			5.0%	of total	11.3	l		
Gasoline, combusted in equipment/US	0.08	l			14.3%	of total	0.6	l		
Natural gas, combusted in industrial equipment/RNA	0.44	l			14.3%	of total	3.1	l		
Electricity/heat										
Block conditiong, at veneer mill, US E	1,522	MJ			23.7%	of total	6,418	MJ		
Electricity, at grid, Eastern US/US	27	kWh			2.4%	of total	1,113	MJ		
Resources										
Water, well, in ground	1135	l			40.0%	of total	2,838	l		
Water, process and cooling, surface	389	l			40.0%	of total	972	l		
Peeling and clipping										
Products										
Veneer, hardwood, green, at veneer mill, US E	1	kg	43.26%							
Wood fuel, hardwood, green, at veneer mill, US E	0.330	kg	14.29%							
Wood chips, hardwood, green, at veneer mill, US E	0.981	kg	42.43%							
Peeler cores, hardwood, green, E, USA, U	0.00031	kg	0.01%							
Waste gate material, hardwood, green, E, USA, U	0.00027	kg	0.01%	2						
Materials/fuels										
Conditioned log, hardwood, green, at veneer mill, US E	2.31	kg	100%							
Diesel, combusted in industrial equipment/US	0.00104	l			5.0%	of total	11.3	l		
Gasoline, combusted in equipment/US	0.00015	l			14.3%	of total	0.6	l		
Natural gas, combusted in industrial equipment/RNA	0.00081	l			14.3%	of total	3.1	l		
Electricity/heat										
Electricity, at grid, Eastern US/US	0.245	kWh			11.95%	of total	1,113	kWh		
Veneer drying										
Products										
Veneer, hardwood, dry, at veneer mill, US E	1	kg	98.6%							
Wood fuel, hardwood, dry, at veneer mill, US E	0.009	kg	0.9%							
Clippings, hardwood, dry, at veneer mill, US E	0.006	kg	0.6%							
Materials/fuels										
Veneer, hardwood, green, at veneer mill, US E	1.015	kg								
Diesel, combusted in industrial equipment/US	0.00105	l			5.0%	of total	11.3	l		
Gasoline, combusted in equipment/US	0.00015	l			14.3%	of total	0.6	l		
Natural gas, combusted in industrial equipment/RNA	0.00083	l			14.3%	of total	3.1	l		
Electricity/heat										
Drying veneer, hardwood, , at veneer mill, US E	7.05	MJ			58.8%	of total	6,418	MJ		

Electricity, at grid, Eastern US/US	0.0248	kWh			1.2%	of total	1,113	kWh	
Emissions control, at veneer mill, US E	0.0911	kWh			4.4%	of total	1,113	kWh	
Air emissions									
Acetaldehyde	0.0001869	kg			2 of 5 mills reporting				
Acetone	0.0000477	kg							
Carbon monoxide	0.0001007	kg							
Formaldehyde	0.0000071	kg							
Methanol	0.0000579	kg							
Particulates	0.0003271	kg							
Phenol	0.0000028	kg							
VOC, volatile organic compounds	0.0005607	kg							
Hydrocarbons, unspecified	0.0007944	kg							

Layup

Products									
Pressed raw panels, hardwood, at engineered wood flooring plant, US E	1	kg							
Resources									
Water, well, in ground	0.4761	l			10.0%	of total	2,838	l	
Water, process and cooling, surface	0.1630	l			10.0%	of total	972	l	
Materials/fuels			1						
Dry hardwood veneer, at veneer mill, US E	0.8984	kg							
Polyvinyl acetate, hardwood, panel making, US	0.1113	kg			65%	NVS			
Urea formaldehyde resin, liquid,65% non-volatile solids, USA, U	0.0583	kg			52.40%	NVS			
Diesel, combusted in industrial equipment/US	0.000945	l			5.0%	of total	11.3	l	
Gasoline, combusted in equipment/US	0.000137	l			14.3%	of total	0.6	l	
Natural gas, combusted in industrial equipment/RNA	0.000742	l			14.3%	of total	3.1	l	
Transport, combination truck, diesel powered	0.0810	tkm		Resin	tkm=	0.1697	kg*		477 km/1000
Transport, combination truck, diesel powered	0.9368	tkm		Dry veneer	tkm=	0.8984	kg*		1,043 km/1000
Electricity/heat									
Pressing panels, hardwood, at engineered wood flooring plant, US E	1.21	MJ			11.26%	of total	6,418	MJ	
Electricity, at grid, Eastern US/US	0.337	kWh			18.05%	of total	1,113	kWh	
Air emissions									
VOC, volatile organic compounds	0.0005537	kg							
Acetaldehyde	0.0001678	kg							
Methanol	0.0000839	kg							
Formaldehyde	0.0000503	kg							
Acetone	0.0000210	kg							
4-Methyl-2-pentanone	0.0000048	kg							
Hydrocarbons, unspecified	0.0000461	kg							
Phenol	0.0000092	kg							

Layup

Products									
Pressed raw panels **(purchased veneer)**, hardwood, at engineered wood flooring plant, US E	1	kg							
Resources									
Water, well, in ground	0.476	l			10.0%	of total	2,838	l	
Water, process and cooling, surface	0.163	l			10.0%	of total	972	l	
Materials/fuels			1						
Veneer, hardwood, dry, at veneer mill, US E	0.8984	kg							
Polyvinyl acetate, hardwood, panel making, US	0.1113	kg			65.0%	NVS			
Urea formaldehyde resin, liquid,65% non-volatile solids, USA, U	0.0583	kg			52.4%	NVS			
Diesel, combusted in industrial equipment/US	0.00095	l			5.0%	of total	0.0	l	
Gasoline, combusted in equipment/US	0.00014	l			14.3%	of total	0.6	l	
Natural gas, combusted in industrial equipment/RNA	0.00074	l			14.3%	of total	3.1	l	
Transport, combination truck, diesel powered	0.08099	tkm				0.170	kg*		477 km/1000
Transport, combination truck, diesel powered	0.50355	tkm				0.90	kg*		561 km/1000
Electricity/heat									
Pressing panels, hardwood, at engineered wood flooring plant, US E	1.21	MJ			11.26%	of total	6,418	MJ	
Electricity, at grid, Eastern US/US	0.337	kWh			18.1%	of total	1,113	kWh	
Air emissions									
VOC, volatile organic compounds	0.0005537	kg							
Acetaldehyde	0.0001678	kg							
Methanol	0.0000839	kg							
Formaldehyde	0.0000503	kg							
Acetone	0.0000210	kg							
4-Methyl-2-pentanone	0.0000048	kg							
Hydrocarbons, unspecified	0.0000461	kg							
Phenol	0.0000092	kg							

Trimming, sanding, sawing, and moulding

Products		
Engineered flooring, hardwood, unfinished, US E	1.00	kg
Wood fuel, hardwood, dry, at engineered wood flooring plant, US E	0.0065	kg
Sawdust, hardwood, dry, at engineered wood flooring plant, US E	0.1781	kg
Shavings, hardwood, dry, at engineered wood flooring plant, US E	0.0178	kg
Sanding dust, hardwood, dry, at engineered wood flooring plant, US E	0.0003	kg
Materials/fuels		
Pressed raw panels, hardwood, at engineered wood flooring plant, US E	0.927	kg

Pressed raw panels (purchased veneer), hardwood, at engineered wood flooring plant, US E	0.276	kg							
Diesel, combusted in industrial equipment/US	0.000876	l	5.0%	of total	11.3	l			
Gasoline, combusted in equipment/US	0.000127	l	14.3%	of total	0.57	l			
Natural gas, combusted in industrial equipment/RNA	0.000688	l	14.3%	of total	3.1	l			
Electricity/heat									
Electricity, at grid, Eastern US/US	0.104	kWh	6.0%	of total	1,113	kWh			
Air emissions									
Particulates, < 10 um	0.000109	kg							
Prefinishing									
Products									
Prefinished engineered wood flooring, at engineered wood flooring plant, US E	1	kg							
Materials/fuels									
Engineered flooring, hardwood, unfinished, US E	0.980	kg							
Diesel, combusted in industrial equipment/US	0.000859	l	5.0%	of total	11.3	l			
Gasoline, combusted in equipment/US	0.000125	l	14.3%	of total	0.6	l			
Natural gas, combusted in industrial equipment/RNA	0.000674	l	14.3%	of total	3.1	l			
Alkyd resin, long oil, 70% in white spirit, at plant/RER with US electricity U	0.000369	kg	30%	%solids					
Epoxy resin, liquid, at plant/RER with US electricity U	0.002114	kg	100%	%solids		expoxy acrylic			
Acrylic varnish, 87.5% in H2O, at plant/RER U US	0.000660	kg	20%	%solids		urethane acrylic			
Acetone, liquid, at plant/RER with US electricity U	0.000796	kg	0%	%solids	40%				
Butyl acetate, at plant/RER with US electricity U	0.000199	kg	0%	%solids	10%				
Isopropanol, at plant/RER with US electricity U	0.000498	kg	0%	%solids	25%				
Isopropyl acetate, at plant/RER with US electricity U	0.000498	kg	0%	%solids	25%				
Transport, combination truck, diesel powered	0.00105	tkm	Stains	0.0051	kg*	205	km/1000		
			0.00						
Polyurethane, rigid foam, at plant/RER with US electricity U	0.002779	kg	100%	%solids					
Alumina, at plant/US	0.000695	kg	100%	%solids					
Acrylic filler, at plant/RER U US	0.005101	kg	100%	%solids					
Polyurethane, rigid foam, at plant/RER with US electricity U	0.005080	kg	100%	%solids					
Acrylic filler, at plant/RER U US	0.003984	kg	100%	%solids					
Acetone, liquid, at plant/RER with US electricity U	0.000408	kg	0%	%solids		80%			
Isobutyl acetate, at plant/RER with US electricity U	0.000102	kg	0%	%solids		20%			
Transport, combination truck, diesel powered	0.00372	tkm	tkm=	0.0181	kg*	205	km/1000		
Corrugated cardboard FAL	0.0615	kg	used to protect final product for shipping, not counted toward final weight of product						
Electricity/heat									
Electricity, at grid, Eastern US/US	0.102	kWh	6.0%	of total	1,113	kWh			
Emission control, at engineered wood flooring plant, US E	0.510	kWh	30.1%	of total	1,113	kWh			
Drying stain, at engineered wood flooring mill, US E	0.611	MJ	6.25%	of total	6,418	MJ			
Air emissions									
HAPs	0.019	kg							
VOCs	0.301	kg							
Final waste flows									
Material for recycling	0.0122	kg	90.56%	allocated to this stage		8.87			
Waste in inert lanfilled	0.0422	kg	92.79%	allocated to this stage		29.8			
Energy Generation (Franklin Boiler)									
Products									
Block conditioning, at veneer mill, E, USA, U	1,522	MJ	23.7%	of total	6,418	MJ			
Veneer drying, at veneer mill, Franklin Boiler, E, USA, U	3,773	MJ	58.8%	of total	6,418	MJ			
Pressing panels, hardwood, at engineered wood flooring plant, US E	723	MJ	11.3%	of total	6,418	MJ			
Drying stain, at engineered wood flooring mill, US E	401	MJ	6.2%	of total	6,418	MJ			
		MJ	100.0%						
	6,418								
Resources									
Water, well, in ground	568	l	20.0%	of total	2,838	l			
Water, process and cooling, surface	194	l	20.0%	of total	972	l			
Materials/fuels									
Wood into industrial boilers (generated on-site), engineered wood flooring, green and dry, E, USA, U	194	kg							
Wood into industrial boilers (purchased), engineered wood flooring, green and dry, E, USA, U	106	kg							
Transport, combination truck, diesel powered	23.7	tkm	tkm=	106	kg*	165	km*(1+	35.8%	MC)/1000
Natural gas, combusted in industrial boiler/US	0.30	m3							
Liquefied petroleum gas, combusted in industrial boiler/US	5.36	l							
Emission Controls									
Electricity/heat									
Grid Electricity, Veneer Mill Emission Control, Engineered Wood Flooring Region	49	kWh	4.4%	of total	1,113	kWh			
Grid Electricity, Flooring Plant Emission Control, Engineered Wood Flooring Region	335	kWh	30.1%	of total	1,113	kWh			

14.2 Questionnaire

CONFIDENTIAL

Engineered Wood Flooring Analysis Project

Thank you for giving me the opportunity to work with you on a project involving the long-term viability and profitability of the U.S. wood products industry. Results from this project will be a good marketing tool for the U.S. engineered wood flooring industry particularly the green building industry. A growing demand for building projects that use environmentally friendly and energy-efficient materials has spurred a green movement in the construction industry. For 2006, an estimated $10 billion of "green buildings" were in the process of construction in the United States and the residential green building market share may increase to over $38 billion by 2010.

As a member of the U.S. forest products industry you know that using wood is a sensible choice because wood is renewable and often poses fewer burdens to the environment than substitute materials. Many consumers do not understand this. With your input we can test the theory that engineered wood flooring poses less negative impacts to the environment than substitute materials do. Completed projects of this type have shown other wood products to be a sustainable and sound environmental choice over non-wood product alternatives.

This questionnaire focuses on annual production, annual energy use and generation, annual material inputs and outputs, and annual environmental emissions for engineered wood flooring manufactured in the United States. Regarding the questionnaire, our primary focus is on overall mill information because this data is vital for precise and accurate results. Details harder to report may be requested later. We realize that you may not have all the information requested, but the data you are able to provide will be appreciated. My final report will describe a gate-to-gate life cycle analysis of manufactured engineered wood flooring. **Strict confidentiality will be maintained for all companies that supply data for this project.** Please complete the following questionnaire by **August 8, 2008.**

Company Name: ______________________________

Facility Address: ______________________________

____

Contact Person: ______________________________

Telephone: (   ) ______________ **Fax:** (   ) ________

Contact email: ______________________________

Please direct questions and send complete questionnaires to:

Rick Bergman
University of Wisconsin-Wood Products Program
1630 Linden Drive
Madison, WI 53706
Phone (608) 231-9477 / Fax (608) 231-9200
Email: rbergman@wisc.edu

CONFIDENTIAL

ENGINEERED WOOD FLOORING ANALYSIS

Manufacturing engineered wood flooring is designed to be more dimensionally stable than solid strip wood flooring because it is less susceptible to changes in moisture. Engineered wood flooring as defined by the National Wood Flooring Association (NWFA) is composed of several sheets of solid wood (veneer) bonded together with an adhesive under heat and pressure. Although plies having 2, 3, 5, 7, or 9 sheets are available, 3 and 5 are most common. Also, the veneer plies may be produced from different species for the face, bottom, and core sections. Sheets are stacked on top of each other with the wood grain facing perpendicular to each subsequent sheet for dimensional stability. The flooring consists of random lengths with the final dimensions of width ranging from 2 ¼ to 7" and from ¼ to 9/16" in thickness. For this project, we need information on the total inputs and outputs from your company as a whole and then for some individual processes. Answer the questions as best you can. The questionnaire is organized as follows:

Part I: Basic description of facility operations

Part II: Information about facility total inputs and outputs

A. Veneer mill

B. Flooring plant

All responses you provide should be for the reporting year (annual basis). Add comments or clarifications directly on the questionnaire if needed. Thank you for your valuable time and careful effort to fill in all the blanks. It should be easier than it looks to complete. **Please contact Rick Bergman at (608) 231-9477 or rbergman@wisc.edu with any questions.**

PART I: OPERATION OVERVIEW

GENERAL INFORMATION **(Please provide responses for all requested information)**

1. **Reporting Year: ________ Starting Month: ________ Ending Month: ________**

2. **Type of operation (questionnaire split into main sections: veneer mill and flooring plant)**

   a. **Veneer mill (please check one):**

      i. ☐ Rotary veneer ______% production ________ thousand ft^2 3/8" basis/year
      ii. ☐ Sliced veneer ______% production ________ thousand ft^2 3/8" basis/year
      iii. ☐ Dry solid-sawn ______% production _______ thousand ft^2 3/8" basis/year (or bf)
      iv. Average log diameter if logs are processed _________ inches
      v. Average log length _________ inches
      vi. Average final core size if logs are rotary peeled _________ inches
      vii. Initial green veneer MC ________%MC
      viii. Final dry veneer MC ________%MC

   b. **Flooring Production (please write in amount for reporting year indicated above):**

      i. Volume of incoming veneer _____________ thousand ft^2 3/8" basis/year
      ii. Volume of incoming lumber _____________ thousand bf
      iii. Annual production of engineered wood flooring produced: ____________ sq. ft.
      iv. Percent of engineered wood flooring that is pre-finished: _________ %

PART II: TOTAL MILL MATERIAL & ENERGY INPUTS & OUTPUTS

A. VENEER MILL (annual production for reporting year; if no veneer mill go to page 7)

1. **Log scale: Dolye, International, Scribner, Weight base (circle one)**
2. **Type of veneer dryer: Jet, Rotary (circle one)**

- Incoming hardwood logs ______________ thousand BF/year
- Incoming softwood logs (if any) ______________ thousand BF/year
- Incoming hardwood lumber (if any) ______________ thousand BF/year
- Incoming green veneer (if any) ______________ thousand ft^2 3/8" basis/year
- Veneer produced on-site ______________ thousand ft^2 3/8" basis/year
- Hardwood lumber produced on-site (if any) ______________ thousand BF/year
- Hardwood lumber kiln-dried on-site (if any) ______________ thousand BF/year
- Average moisture content into dryer _________%MC
- Average moisture content out of dryer _________%MC
- Percent of redry _________%

Please complete the following table showing the breakdown of the ***individual tree species*** and approximate ***sizes*** processed by your mill by species and the average log diameter. If less than 2% of total, use category labeled "Other".

Species	% of total log input into veneer mill	Log Diameter* (in)
Total	100%	

*Please provide individual log diameters if known otherwise please state the average or range of logs processed at your facility in bottom row under Log Diameter

TOTAL WATER USE

- Ground (municipal/well) water __________ gallons or ft^3 _______percent recycled
- Surface water __________ gallons or ft^3 _______percent recycled

TOTAL TRANSPORTATION FUEL USE ON-SITE (includes all fuels for yard equipment, forklifts, and carriers)

Type	Units
On-road diesel (between facilities)	Gallons
Off-road diesel	Gallons
Fuel Oil #6	Gallons
Propane	Gallons
Gasoline	Gallons
Other	

TOTAL MILEAGE: (Raw materials delivered to your manufacturing facility)

By Truck _______% By Rail_______%

- Average one-way distance to deliver logs: _______________miles
- Average one-way distance to deliver lumber if any: _______________miles
- Average one-way distance to deliver green veneer if any: _______________miles

What is the percentage that travel one-way (sole destination is your mill) _____________ %

What is the percentage that leave your mill empty (no backhaul) _____________%

TOTAL (NON-TRANSPORTATION) FUEL USE (boilers, cogeneration units, etc.)

Circle all types of boiler used: wood fuel, natural gas, oil, or propane

- Wood
  - On-site wood boiler fuel _______________@_________%MC tons
  - Purchased wood boiler fuel _______________@_________%MC tons
- Fossil Fuel
  - Natural Gas ____________________ thousand cubic feet (ft^3)
  - Fuel oil #1(kerosene) ____________________ gallons
  - Fuel oil #2 (heating oil) ____________________ gallons
  - Fuel oil #6 ____________________ gallons
  - Propane ____________________ gallons
  - Other ____________________
  - Electricity for entire facility ____________________ kilowatt-hours (kWh)
  - Electricity for the following processes **(Estimation is ok)**

Process	kWh	% of total
1. Bucking & Debarking		
2.Block Conditioning		
3. Peeling & Clipping		

Process	kWh	% of total
4. Veneer Drying		
5. Energy Generation		
6. Emissions control		

TOTAL PRODUCT OUTPUT (DRIED VENEER)

Total volume of outgoing dried veneer ____________________ thousand ft^2 3/8" basis/year

- Wood species ____________________ / ____________________ thousand ft^2 3/8" basis/year
- Wood species ____________________ / ____________________ thousand ft^2 3/8" basis/year
- Wood species ____________________ / ____________________ thousand ft^2 3/8" basis/year
- Wood species ____________________ / ____________________ thousand ft^2 3/8" basis/year
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- Wood species ____________________ / ____________________ thousand ft^2 3/8" basis/year
- Wood species ____________________ / ____________________ thousand ft^2 3/8" basis/year
- Wood species ____________________ / ____________________ thousand ft^2 3/8" basis/year

TOTAL WOOD CO-PRODUCT/BY-PRODUCT OUTPUT

For each material, please record the amount of wood residue for the reporting period that are sold (shipped) to other users, used internally (such as fuel), landfill, or inventoried for future use. Select whatever category best fits your mill's situation. Please state units if other than tons such as cubic yards. **Please indicate whether the wood residue is listed as wet or dry weights.**

Co-products and By-Products	MC	Wet or dry weights	Sold (Shipped)	Boiler Fuel	Other uses	Landfilled	Inventory	Total
	(%)		tons	tons	tons	tons	tons	tons
Bark, green								
Roundup wood, green								
Peeler cores, green								
Veneer clippings, green								
Trim, green								
Chips, green								
Hogged material								
Waste gate material								
Clippings, dry								
Other								

TOTAL INDUSTRIAL (SOLID) WASTE **(material requiring disposal outside of mill)**

Type	Tons/Pounds	Percent Landfilled
Pallets (not re-used)		
General refuse (do not include above materials)		
Recycled material		

VENEER DRYER OR/AND ENTIRE MILL EMISSIONS: (Provide stack test if available)

	SOURCE	
Emission	**Veneer dryer**	**Entire veneer mill**
Dust	pounds	pounds
Particulate	pounds	pounds
PM10	pounds	pounds
Hazardous Air Pollutants (HAPS)	pounds	pounds
Volatile organic compounds (VOCs)	pounds	pounds
Nitrous oxide (N_20)	pounds	pounds
Nitrogen oxide (NO)	pounds	pounds
Sulfur oxides (SOx)	pounds	pounds
Carbon monoxide (CO)	pounds	pounds
Carbon dioxide (CO_2)	pounds	pounds
Others (please list all known):	units	units

EMISSIONS CONTROL EQUIPMENT

If your facility has emission control devices, please complete the table below. For air emissions include devices such as cyclones, bag houses, and electric static precipitators (ESPs). For water emissions, explain how runoff or other water discharges from the boiler and mill are controlled (i.e. settling pond, city sewer, septic; annual basis). Please list ALL devices. If your facility has more than one of the same device please indicate the total number for that type of device.

Type of Emission Control Device (cyclone, bag house, esp, etc.)	How Many?	Equipment Controlled	Type of Emissions (gas, liquid, solid)	Electrical Usage For Device kWh (annual basis)

B. ENGINEERED WOOD FLOORING PLANT

WOOD AND OTHER MATERIAL INPUTS

Total volume of incoming dry veneer ________________ thousand ft^2 3/8" basis/year

- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year
- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year
- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year
- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year
- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year
- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year
- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year
- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year
- Wood species ________________ / ________________ thousand ft^2 3/8" basis/year

- Total volume of cardboard ____________ cartons/year
- Total volume of sandpaper ____________ rolls/year

TOTAL WATER USE

- Ground (municipal/well) water __________ gallons or ft^3 ______percent recycled
- Surface water __________ gallons or ft^3 ______percent recycled

TOTAL TRANSPORTATION FUEL USE ON-SITE **(includes all fuels for yard equipment, forklifts, and carriers)**

Type	Units
On-road diesel (between facilities)	Gallons
Off-road diesel	Gallons
Fuel Oil #6	Gallons
Propane	Gallons
Gasoline	Gallons
Other	

ADHESIVE INPUTS (glues used for lay-up (hot pressing) veneer plies)

Spread rate (gross plywood) ______________ grams per squ. ft. or lbs per squ. ft. (circle one)

Mark type of glue/adhesive used in lay-up and give percent solids:

☐ Urea Formaldehyde (UF) _______________lbs or gallons /year / __________% solid

☐ Polyvinyl acetates (PVA) _______________lbs or gallons /year / __________% solid

☐ Phenol formaldehyde (PF) _______________lbs or gallons /year / __________% solid

☐ Melamine-urea-formaldehyde (MUF) _______lbs or gallons /year __________% solid

☐ Phenol resorcinol (PR) _______________lbs or gallons /year / __________% solid

☐ Phenol resorcinol formaldehyde (PFR) ______lbs or gallons /year / __________% solid

List name and amount of other materials used in adhesives (such as extenders/ fillers, water and other solvents, catalysts, hardener, stabilizers, etc.) : Composition of material used to prepare glue by percent or by weight

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

Name of material _________________/ Percent or weight ________________ / _______% solid

FINISHING INPUTS (used for staining and coating)

List weights and percent solids of all stains used:

Spread rate _____________ grams per squ. ft. or lbs per squ. ft. (circle one)

- Solvent-based ___________________lbs or gallons /year / _____% solid
  - Type of solvent ____________________/ __________lbs or gallons /year
  - Type of solvent ____________________/ __________lbs or gallons /year
  - Type of solvent ____________________/ __________lbs or gallons /year
  - Type of solvent ____________________/ __________lbs or gallons /year
  - Type of solvent ____________________/ __________lbs or gallons /year
- Water-based ___________________lbs or gallons /year / _____% solid
- UV-cured ___________________lbs or gallons /year / _____% solid
- Other material (please specify) ___________________lbs or gallons /year / _____% solid
- Other material (please specify) ___________________lbs or gallons /year / _____% solid
- Other material (please specify) ___________________lbs or gallons /year / _____% solid
- Other material (please specify) ___________________lbs or gallons /year / _____% solid
- Other material (please specify) ___________________lbs or gallons /year / _____% solid

List weights and percent solids of materials used in coating

Spread rate (gross plywood) ____________ grams per squ. ft. or lbs per squ. ft. (circle one)

- Polyurethane lacquer ________________________lbs or gallons /year / _____% solid
- Acid-curing lacquer ________________________lbs or gallons /year / _____% solid
- UV-curing lacquer ________________________lbs or gallons /year / _____% solid
- Oil treatment ________________________lbs or gallons /year / _____% solid
- Melamine ________________________lbs or gallons /year / _____% solid
- Water-borne lacquer ________________________lbs or gallons /year / _____% solid
- Aluminum oxide ________________________lbs or gallons /year
- Name of filler ______________ / __________lbs or gallons /year / _____% solid
- Name of filler ______________ / __________lbs or gallons /year / _____% solid
- Other (please specify) __________________ / ___________lbs or gallons /year / _____% solid
- Other (please specify) ________________________________lbs or gallons /year / _____% solid
- Other (please specify) ________________________________lbs or gallons /year / _____% solid
- Other (please specify) ________________________________lbs or gallons /year / _____% solid
- Other (please specify) ________________________________lbs or gallons /year / _____% solid

TOTAL (NON-TRANSPORTATION) FUEL USE

- Wood
  - On-site wood boiler fuel ________ @ ________ %MC tons
  - Purchased wood boiler fuel ________ @ ________ %MC tons
- Fossil Fuel
  - Natural Gas ________ thousand cubic feet (ft^3)
  - Fuel oil #1(kerosene) ________ gallons
  - Fuel oil #2 (heating oil) ________ gallons
  - Fuel oil #6 ________ gallons
  - Propane ________ gallons
  - Other ________
  - Electricity for entire facility ________ kilowatt-hours (kWh)
  - Electricity for the following processes **(Estimation is ok)**

Process	kWh	% of total
6. Hot Pressing		
7. Trimming		
8. Pre-finishing		

Process	kWh	% of total
9. Sawing & Moulding		
10. Packaging		
11. Emissions control		

TOTAL MILEAGE: (Raw materials delivered to your manufacturing facility)

By Truck _______% By Rail_______%

Average one-way distance to deliver dry veneer: ____________miles

Average one-way distance to deliver lumber: ____________miles

Average one-way distance to deliver resin and associated products: ____________miles

Average one-way distance to deliver stains, coatings, and such: ____________miles

What is the percentage that travel one-way (sole destination is your mill)_____________ %

What is the percentage that leave your mill empty (no backhaul) _____________%

TOTAL WOOD CO-PRODUCT/BY-PRODUCT OUTPUT

For each material, please record the amount of wood residue for the reporting period that are sold (shipped) to other users, used internally (such as fuel), landfill, or inventoried for future use. Select whatever category best fits your mill's situation. Please state units if other than tons such as cubic yards.
Please indicate whether the wood residue is listed as wet or dry weights.

Co-products and By-Products	MC	Wet or dry weights	Sold (Shipped)	Boiler Fuel	Other uses	Landfilled	Inventory	Total
	(%)		tons	tons	tons	tons	tons	tons
Clippings, dry								
Sawdust, dry								
Shavings, dry								
Sanding dust, dry								
Wood flour, dry								
Other								

TOTAL PRODUCT OUTPUT (for reporting year)

Please complete the table for the different species used to produce *engineered wood flooring* including surface, bottom, and core plies. Do *not* include parquet, cork, bamboo or hardwood flooring data in this table. *See example on first line. Please copy and fill out multiple sheets as needed*

Engineered Wood Flooring Annual Production	
Species[1]	**For Each Species Please Write In:** **Square Feet Produced / Width (inches) / Thickness (inches)**
Example: White Oak	3,000,000 ft^2 / $3\frac{1}{8}$"/ 3/8", 1,500,000 ft^2/$2\frac{1}{4}$"/ $\frac{1}{2}$ ", 5,000,000 ft^2 / $3\frac{1}{8}$"/ $\frac{1}{2}$", & 500,000 ft^2/3"/ $\frac{1}{2}$", etc.
Red oak	
Hard maple	
Hickory/pecan	
White oak	
Cherry	
Birch	
Yellow poplar	
Walnut	
Beech	
Ash	
Soft maple	
Other (specify)	
Other (specify)	
Other (specify)	
Other (specify)	
TOTAL SQUARE FEET PRODUCED FOR ALL SPECIES ABOVE (do not worry about totals by widths and thickness)	___________**Square feet**

INDUSTRIAL (SOLID) WASTE (material requiring disposal outside of mill)

Type	Tons/Pounds	Percent Landfilled
Pallets (not re-used)		
Adhesive mixed with wood waste		
General refuse (do not include above materials)		
Recycled material		

FINISHING LINE OR/AND ENTIRE MILL EMISSIONS: (Provide stack test if available)

	SOURCE	
Emission	**Finishing line**	**Flooring Plant**
Dust	pounds	pounds
Particulate	pounds	pounds
PM10	pounds	pounds
Hazardous Air Pollutants (HAPS)	pounds	pounds
Volatile organic compounds (VOCs)	pounds	pounds
Nitrous oxide (N_20)	pounds	pounds
Methane	pounds	pounds
Nitrogen oxide (NO)	pounds	pounds
Sulfur oxides (SOx)	pounds	pounds
Carbon monoxide (CO)	pounds	pounds
Carbon dioxide (CO_2)	pounds	pounds
Others (please list all known):	units	units

EMISSIONS CONTROL EQUIPMENT

If your facility has emission control devices, please complete the table below. For air emissions include devices such as cyclones, bag houses, and electric static precipitators (ESPs). For water emissions, explain how runoff or other water discharges from the boiler are controlled (i.e. settling pond, city sewer, septic). Please list ALL devices. If your facility has more than one of the same device please indicate the total number for that type of device.

Type of Emission Control Device (cyclone, bag house, esp, etc.)	How Many?	Equipment Controlled	Type of Emissions (gas, liquid, solid)	Electrical Usage For Device kWh (annual basis)

Glossary

Baghouse: Air pollution device which forces gases through a filter thereby capturing gas born particles.
By-product: Material produced during manufacturing that is recycled or used "within system boundaries."
Bottom ash: Residual by-product of burning coal. Porous, grainy, roughly sand sized particles.
Co-product: A material produced from manufacturing and "sold outside of the system boundary."
Cyclone: A device that uses centrifugal forces to collect waste material.
Dust: Dispersion particles formed in grinding a solid; particles may be small enough to temporarily suspend in the air.
Edgings: Pieces of board produced after lumber passes through an edger to achieve desired width.
Electrostatic Precipitator (esp): A type of precipitator which changes the electrical charge on a particle so that it can be captured by electrostatic forces.
Emissions: Expulsion of pollutants to air from a source.
Fly ash: Particulate impurities that come from burning coal and other materials.
General refuse: Waste collected from the facility that is mixed with dirt and cannot be sent to the boiler.
HAPs: Hazardous Air Pollutants (carbon oxides, nitrogen oxides, sulfur oxides).
Inorganic material: Material such as sand and other non-solubles.
Industrial waste: Material produced during manufacture requiring disposal out of the "system boundary."
Packaging material: Steel strapping, plastic lumber covers, cardboard corners, plastic or paper wrap.
Particulates: By-products of combustion or milling; can be solid or liquid state.
PM10: Standard for measuring solid and liquid particulates in suspension in the atmosphere; particulates are defined here as less than 10 micrometers in diameter.
Product: The primary material produced from manufacturing and "sold outside of the system boundary."
Recycled material: Material collected from the manufacturing facility operation that is re-used.
VOCs: Volatile Organic Compounds- produced in incomplete combustion of carbon based compounds; does not include methane; examples are oil based paints and gasoline fumes.

Paper 2: Wood and Fiber Science article -- “Life-cycle inventory of manufacturing prefinished engineered wood flooring in the eastern United States with a comparison to solid strip wood flooring”

Paper #2 covers dissertation pages 102-122.

LIFE CYCLE INVENTORY OF MANUFACTURING PREFINISHED ENGINEERED WOOD FLOORING IN EASTERN US WITH COMPARSION TO SOLID STRIP WOOD FLOORING

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Abstract. Building products have come under increased scrutiny because of environmental impacts from their manufacture. Our study followed the life cycle inventory approach for prefinished engineered wood flooring in the eastern US and compared the results with those of solid strip wood flooring. Our study surveyed five engineered wood flooring manufacturers in the eastern US. These production facilities represented 18.7% of total annual production in 2007. Primary data collected for 2007 included annual production, energy consumption and type, material inputs, emission data, product outputs, and other coproducts. Modeling data estimated biogenic and fossil CO_2 emissions at 623 and 1050 kg/m^3, respectively, and volatile organic compounds at 1.04 kg/m^3. Cumulative allocated energy consumption for prefinished engineered wood flooring was 23.0 GJ/m^3 with 40% coming from coal. Unfinished solid strip flooring cumulative energy consumption was only 6.50 GJ/m^3 with 65% from biomass, roughly half that of unfinished engineered wood flooring. However, after converting to an area (in-use) basis, unfinished engineered wood flooring consumed 136 MJ/m^2 compared with 123 MJ/m^2 for unfinished solid strip flooring. After changing to an in-use parameter, the two wood flooring products were similar in energy consumption during manufacturing, but engineered wood flooring still consumed significantly more fossil fuel.

Keywords: Life cycle inventory, prefinished engineered wood, wood flooring, environmental impact, carbon.

INTRODUCTION

Components of residential or commercial buildings are evaluated because of concerns about their environmental impact, especially in relation to climate change. Some research claims that the main cause of climate change is fossil fuel burning (IPCC 2007). Therefore, carbon emissions are playing an increasingly important role in policy decision-making in the US and throughout the world. Some building products consume large amounts of fossil fuels during processing (Khatib 2009). However, wood building products typically consume more biomass than fossil fuels during manufacturing, a significant environmental advantage (Puettmann and Wilson 2005). Biomass carbon dioxide (CO_2) accumulates less in the atmosphere because biomass is rapidly recoverable by plant growth and carbon is fixed in the final product (EPA 2003; UNFCCC 2003; Lippke et al 2010).

The practice of improving construction, operation, and energy efficiency of buildings while decreasing overall environmental impact is called green building. The US market for green building materials is expected to increase from

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an estimated $9.6 billion in 2009 to nearly $31.4 billion in 2014, for a 5-yr compound annual growth rate of 26.7%. The value of interior materials such as flooring is predicted to increase from $2 billion in 2009 to $5.8 billion in 2014 (McWilliams 2010). Having a sound green building policy for building practices in the US would significantly decrease the environmental impact on the world's resources. However, to evaluate building materials and practices regarding their environmental impact for creating such a policy and addressing environmental claims, life cycle information is necessary.

Conducting a life cycle inventory (LCI) for products is part of a science-based approach to addressing environmental claims. LCI data are a major part of life cycle assessments (LCA). LCA use rigorous methodology to find the total environmental profile for a particular product referred to as cradle-to-grave (raw material extraction to waste disposal) analysis. These analyses include environmental and energy costs on a per-unit basis using data from individual LCI studies. LCI studies include resource extraction, raw material and product transportation, primary and secondary processing, final product use, maintenance, and final disposal. For the manufacturing stage, LCI measures all raw material and energy inputs and outputs including emissions to manufacture a particular product on a per-unit basis within carefully defined system boundaries, eg a gate-to-gate LCI. The LCI results are used to assess environmental impact (ISO 2006b, 2006c). In the US, the Consortium for Research on Renewable Industrial Materials (CORRIM) has developed many LCI data sets for wood materials (NREL 2004).

CORRIM has examined wood as a suitable environmental choice by developing LCI data of wood materials using the standardized tools of LCI analysis. CORRIM is helping build a multinational database of environmental and economic impacts associated with using renewable materials (Bowyer et al 2001). This LCI study for prefinished engineered wood flooring uses methodology and protocols put forth by CORRIM and the International Organization of Standardization (ISO) (ISO 2006b, 2006c; CORRIM 2010). Results from this project may aid LCA practitioners conducting studies that document use of wood products in building construction for their entire life cycle (cradle-to-grave).

REVIEW OF RELEVANT LCI STUDIES

Previous Studies

Previous studies on flooring products included both the US and Europe. Hubbard and Bowe (2008) evaluated unfinished solid wood flooring in the eastern US. About 86% of the total energy (including electricity) needed for making the flooring came from biomass (wood residue). This result is consistent with other LCI studies on wood products that show a high percentage of process energy coming from biomass (Puettmann and Wilson 2005). Also, Gustavsson et al (2010) found that substituting biomass residue from wood products for fossil fuels significantly lowered net CO_2 emissions. Petersen and Solberg (2005) reviewed 14 LCA studies from Norway and Sweden, whereas Werner and Richter (2007) reviewed international research from the past 20 yr. The main conclusion is that wood tends to have a favorable environmental profile particularly regarding greenhouse gas emissions (GHGs) compared with competing materials such as steel and concrete.

In Sweden, Jönsson et al (1997) reported that solid wood flooring showed significant environmental advantages compared with linoleum and vinyl flooring. Vinyl flooring had the greatest environmental impact. Raw materials play a significant role in environmental impact for each product because the final product with the greatest impact tended to be the product using synthetics derived from fossil fuels. For example, polyvinyl chloride used in vinyl flooring production is synthesized from ethylene made from crude oil. Another reason for the greater impact associated with vinyl flooring was that its production consumed the most nonrenewable energy resources. Wood flooring used the least nonrenewable energy resources, and its main raw component was trees, a renewable resource.

A 2006 German study provided data on environmental impacts of types of prefinished wood flooring including solid wood, solid and multilayer parquets, and wood blocks (Nebel et al 2006). Nebel et al (2006) found that solvent use and energy consumption had the most effect on environmental performance of these products. This life cycle study provided results from extraction of raw material to final disposal of material. One important factor was the expected lifetime of a given product and its ability to be refurbished. Wood blocks, wood floor boards, and 22-mm parquet flooring had an expected useful life of 50 yr, which was at least twice the useful life of other wood flooring products such as multilayer parquet flooring. Wood block flooring is made from tongue and groove wood blocks that are 19-38 mm thick, up to 90 mm wide, and 150-380 mm long. In this study, wood block flooring was 38 mm thick, nearly twice as thick as the wood floor boards. In addition, the 50 yr corresponded to the expected useful life of the house. An environmental advantage was the air drying of wood floor boards to 17% MC that decreased primary energy consumption to 25% of multilayer parquet. The reference flow was 1 m^2 of laid flooring for 50 yr. Multilayer parquet had only an expected useful life of 10 yr. As other studies have shown, energy consumption during manufacturing was the highest of the individual life cycle stages. In addition, burning the disposed material for energy lowered the flooring's impact at end of life. Solvents used in lay up, prefinishing, and refurbishing played the largest role in photo-oxidant formation, caused mainly by emissions of volatile organic compounds (VOCs).

Coatings play a large role in some wood products, and the coating with the lowest environmental impact is not always obvious. Gustafsson and Börjesson (2007) found through a cradle-to-grave evaluation that a "green" wax produced from rapeseed oil had a greater overall environmental impact than the two ultraviolet (UV) light hardening lacquers, whereas the 100% UV lacquer showed the least environmental impact. In addition, Tufvesson and Börjesson (2008) found that wax ester made from rapeseed oil had about 3.5 times higher global warming potential than paraffin wax. Furthermore, cultivation of rapeseed oil causes soil emissions of ammonia and nitrous oxides, resulting in potential acidification and eutrophication. These results indicate that more work is needed to find coatings with minimal environmental impact.

Lessons Learned

The initial work of CORRIM examined structural wood building products used in residential home construction (Lippke et al 2004; Perez-Garcia et al 2005; Puettmann and Wilson 2005). In each of these studies, wood building materials were found to have smaller environmental impacts than competing nonwood materials such as steel and concrete. Current CORRIM efforts are focusing on nonstructural building products such as interior finish materials. Wood products tend to have lower environmental impact than competing wood products because biomass, considered carbon-neutral, is used as a primary energy source in their production.

The useful life of a product plays a large role in its environmental impact. Some flooring products need to be replaced multiple times during the life of a house, whereas others are more durable. Some products are able to be refurbished more easily than others, and refurbishing flooring instead of replacing it decreases its overall environmental impact (Nebel et al 2006).

Caution is needed when addressing coatings to ensure that the whole life cycle of the material is evaluated for its environmental burdens. A "green" coating does not necessarily have less environmental impact than a competing product. A product must be examined from the raw material stage to its final disposal (ie cradle-to-grave

LCA) to provide the most accurate evaluation of environmental impact.

INDUSTRY OVERVIEW

Prefinished engineered wood flooring is a nonstructural wood product. Prefinished engineered wood flooring is more dimensionally stable than solid strip wood flooring because it is made up of cross-laminated veneers; this arrangement decreases shrinking and swelling in width that result from changes in moisture content. Engineered wood flooring as defined by the National Wood Flooring Association (NWFA) comprises several sheets of solid wood (veneer) bonded together with an adhesive under heat, pressure, or both. Although plies with two, three, five, seven, or nine sheets are available, three and five are most common. Prefinished engineered wood flooring is one of many commercially available flooring products. Competing products include solid strip wood, laminated wood, carpet, vinyl, ceramic tile, and laminated bamboo flooring.

In 2007, wood flooring manufacturers in the US produced 41.67 million m^2 solid wood and 36.36 million m^2 engineered wood flooring for a total of 78.03 million m^2 (CRI 2008). Market percentage of engineered wood flooring out of the total wood flooring market increased from 42.1% in 2004 to 46.6% in 2007 (CRI 2008). This increase in market share occurred although its production had actually decreased because of the severe decline in domestic housing construction (USDC 2011). However, hard surface flooring demand is expected to increase 2.8% annually from 2008 to 710 million m^2 by 2013, and the wood flooring market share is expected to increase, whereas vinyl flooring continues to lose market share. As before the recession, the remodeling market will be the driving force for hard surface flooring consumption because new residential construction consumes only 20% (Freedonia 2009a). In addition, the market for wood coatings has also declined because of the downturn in the US housing market, although is it also expected to rebound.

An increase in wood flooring production results in an increase in wood coatings (protection) production. Total value of the wood protection and preservative market is forecast to be $3.3 billion by 2013. Although this value does include the treated wood market, the greatest increase in demand is expected to occur in interior wood applications such as flooring. The release of VOCs, including formaldehyde, during prefinishing and refurbishing will be an issue that is likely to affect market share. Coatings with an improved formulation that show better environmental performance are expected to gather a higher market share (Freedonia 2009b).

GOAL OF THE STUDY

The goal of this study was to document the LCI of prefinished engineered wood flooring production from incoming hardwood logs to prefinished engineered wood flooring in the eastern US (Fig 1). Our study showed material flow, energy consumption, air pollution, water effluent, and solid waste for the prefinished engineered wood flooring manufacturing process on a per-unit basis. We collected primary data by surveying veneer mills and flooring plants with a questionnaire, telephone calls, and a site visit. We obtained secondary data from peer-reviewed literature per CORRIM guidelines (CORRIM 2010). We calculated material and energy balances by a spreadsheet algorithm using data from primary and secondary sources. From these material and energy inputs and reported emission, environmental outputs were estimated by modeling with SimaPro 7 software (PRé Consultants, Amersfoort, Netherlands) (PRé Consultants 2011). SimaPro has been used in previous CORRIM-initiated LCI projects: hardwood lumber (Bergman and Bowe 2008), softwood lumber (Milota et al 2005), softwood lumber (Bergman and Bowe 2010), and softwood plywood (Wilson and Sakimoto 2005). This LCI study conformed to relevant ISO standards (ISO 2006b, 2006c). Results from LCIs can aid in developing environmental product declarations (ISO 2006a, 2007).

Figure 1. Shaded area was selected for life cycle inventory of prefinished engineered wood flooring production in the US.

METHODOLOGY

Scope of the Study

This study covered the life cycle of manufacturing prefinished engineered wood flooring from hardwood logs in the eastern US. LCI data from this study may help conduct an analysis comparing prefinished engineered wood flooring with other wood and nonwood flooring options. The LCI model provided a gate-to-gate analysis of cumulative costs of manufacturing including transportation of raw materials. Analyses included engineered wood flooring's contribution to energy consumption, air pollution, water pollution, solid waste, and climate change. We compared energy consumption of unfinished and prefinished engineered to unfinished solid strip wood flooring.

Functional Unit

Material flows, energy use, and emission data were standardized to a per-unit volume basis for 1.0 m^3 of prefinished engineered wood flooring, the final product of the engineered wood flooring manufacturing process. On the basis of US industry measures, 1 m^3 of prefinished engineered wood flooring equals 100 m^2 (10-mm basis), 1130 ft^2 (3/8-inch basis), or 1.13 thousand ft^2 (3/8-inch basis). In this study, the reference unit was also referred to as the production unit. Wood flooring is usually sold in square feet (ft^2) at various thicknesses. Rough green veneer and rough dry veneer were assumed to be 2.62 and 2.43 m^3/thousand board feet after shrinkage and sanding, respectively (Koch 1985; Bergman 2010). Allocating all material and energy on a per-unit basis of 1.0 m^3 prefinished engineered wood flooring standardized the results to meet ISO standards, thus the unit processes could be used to construct a cradle-to-gate LCI and LCA (ISO 2006b, 2006c; CORRIM 2010).

Reference Flow

Reference flow was defined as oven-dry (OD) mass of 1 m^3 or 100 m^2 (10-mm basis) ready-to-install prefinished engineered wood flooring. In climate-controlled living environments, installed wood flooring typically equilibrates to 8% MC (Bergman 2010).

Data Quality and Data Gathering

Data collection and treatment. We selected the eastern US because the majority of wood flooring production occurs in this region (Hubbard and Bowe 2010). Primary mill data as required by CORRIM Research Guidelines were aggregated to maintain confidentiality of surveyed facilities and to develop a composite engineered wood flooring plant (CORRIM 2010).

Validation of data. We conducted the following analyses to ensure validation of raw and LCI data: 1) comparison of conversion rates from incoming logs to dry veneer to literature values; 2) performed mass balance to track wood material through the entire process; and 3) comparison of gate-to-gate LCI data to a US solid-strip wood flooring gate-to-gate LCI study.

Sensitivity analysis for refining system boundaries. We performed a sensitivity analysis on burning different types of fuel for process energy. This analysis provided changes in environmental impacts based on fuel use.

Data quality statement. Data quality was high because of the extensive and comprehensive questionnaire used to survey the industry (Bergman and Bowe 2011). We collected primary mill data for 2007 from facilities across the eastern US from average technologies ranging from the 1940s to the 2000s that produced 7.366 million m^2 or nearly 19% of total engineered wood flooring production in the US. Approximately 30 engineered wood flooring plants were in the study area (NWFA 2011). We surveyed 5 of the 30 available, about 17%. Most flooring plants produce their own veneer, although one flooring plant used veneer from another vendor. Surveyed facilities provided wood veneer and flooring values on a 3/8-in basis. Based on surveyed mill data, total incoming hardwood log volume of 119,400 m^3 produced total dry veneer production of 67,770 m^3. Adding 35,600 m^3 of purchased dry veneer to that produced on-site resulted in total dry veneer of 103,400 m^3 (10.34 million m^2). Total flooring produced was 73,660 m^3 (7.366 million m^2). We estimated an overall efficiency of 30.1% from logs to prefinished engineered wood flooring. In addition, a log to dried veneer conversion of 40% was calculated. To ensure data completeness, we performed a mass balance and compared results with literature values.

Aggregation. Weighted average was the method of aggregation for primary data from the mill questionnaire. This was also done in previous CORRIM studies with the following equation:

$$\overline{P}_{\text{weighted}} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i}$$

where $\overline{P}_{\text{weighted}}$ was weighted average of values reported by mills, P_i was reported mill value, and x_i was fraction of the mill's value to total production for that specific value.

Elementary flows. Figure 2 shows wood flow through the system. Manufacturing started with hardwood logs as the raw material and ended with the final product of prefinished engineered wood flooring. Two unit processes of peeling and clipping and trimming, sanding, sawing, and moulding generated the most coproducts (wood residues). In the east, many commercial hardwood species are peeled into veneers for flooring. Often, several species within one species group are mixed; eg the red oak group comprises the following species: scarlet (*Quercus coccinea*), southern (*Q. falcate*), cherrybark (*Q. falcate var. pagodifolia*), laurel (*Q. laurifolia*), water (*Q. nigra*), pin (*Q. palustris*), willow (*Q. phellos*), northern (*Q. rubra*), and black (*Q. velutina*). Other species groups with multiple species are white oak (six): white (*Quercus alba*), swamp white oak (*Q. bicolor*), bur (*Q. macrocarpa*), swamp chestnut (*Q. michauxii*), chestnut (*Q. prinus*), and post (*Q. stellata*); hard maples (two): sugar (*Acer saccharum*) and black (*A. nigrum*); soft maples (two): red (*Acer rubrum*) and silver (*A. saccharinum*); and ash (three): white (*Fraxinus Americana*), black (*F. nigra*), and green (*F. pennsylvanica*).

Allocation Rules

In the wood products industry, a number of coproducts including wood residues are typically produced. In this study, residual wood from manufacturing prefinished engineered wood flooring was often burned on-site for process energy. We expanded the system boundary to include multiple unit processes, however,

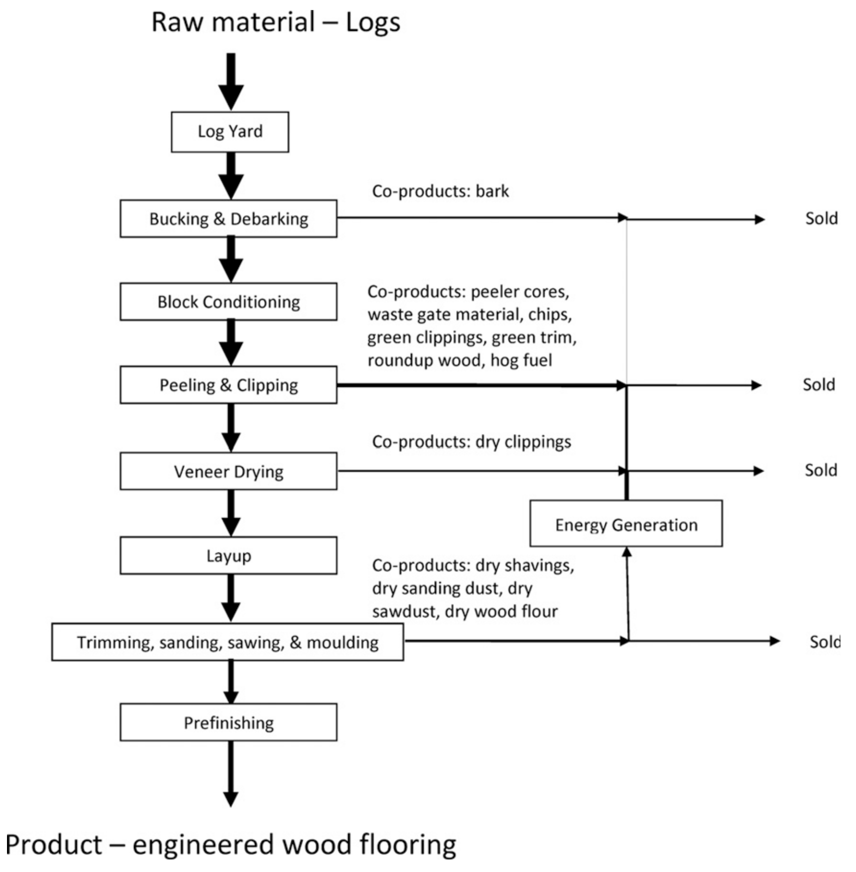

Figure 2. Description of product elementary flows.

coproducts that were sold outside the system boundary required an allocation rule. Mass allocation was chosen because specific gravity of both prefinished engineered wood flooring and associated coproducts was similar (Kodera 2007). This was true for all unit processes. Previous studies on wood products also used mass allocation (Jungmeier et al 2002; Puettmann and Wilson 2005; Werner and Richter 2007; Puettmann et al 2010).

System Boundary Definition

Definition of product system. Eight unit processes were identified—1) logyard; 2) bucking and debarking; 3) block conditioning; 4) peeling and clipping; 5) veneer drying; 6) layup; 7) trimming, sanding, sawing, and moulding; and 8) prefinishing (Fig 3). Trucks transported logs to the veneer mill. Logs were typically stored wet until needed when temperatures were greater than 0°C to prevent staining. Logs were bucked and debarked prior to block conditioning. Block conditioning softened the wood in a hot water bath to allow easier peeling of logs on rotating lathes. After trimming the rotary-sliced veneer sheets to 1.2- × 2.4-m sections, large jet driers dried the thin veneer sheets (plies) to 0-4% MC. The top, bottom, and core veneer plies were usually from different wood species. Press-gluing these veneer sheets together formed a veneer panel, and three- and five-ply panels were common. Before gluing, the sheets were stacked on top of each other with the wood grain running perpendicular to each subsequent sheet (cross-laminated) for dimensional

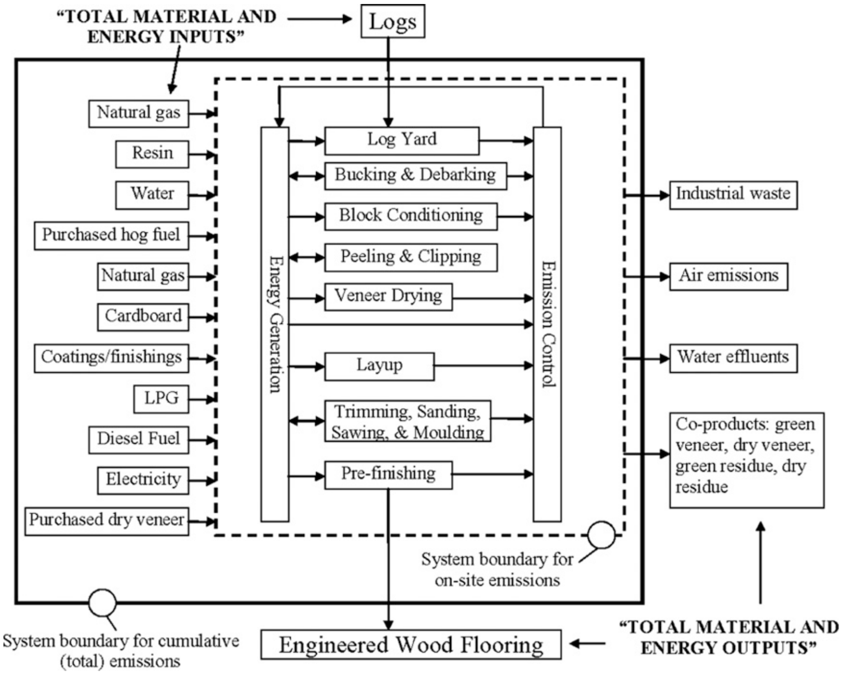

Figure 3. System boundaries for prefinished engineered wood flooring production.

stability. After trimming, machines sanded, sawed, and moulded (profiled) the panels into individual floorboards. These unfinished floorboards were then sanded, stained, and coated, resulting in the final product of prefinished engineered wood flooring. The final product was ready for installation. Final dimensions of flooring ranged from 60-180 mm wide and 6.4-14 mm thick with random lengths.

Decision criteria (cutoff rule, if applicable). All materials expecting to have a significant environmental impact were tracked. We tracked resin and coating materials because we expected that these materials would have a significant environmental impact relative to their mass. Wood material that contributed less than 0.1% by mass to total wood output was not modeled in SimaPro.

Omissions of life cycle stages, processes, and input or output flows. All unit processes within the gate-to-gate system boundary were examined. Human labor and production of machinery and infrastructure were outside system boundaries. Also, forest growth and management, harvesting, product use and maintenance, recycling options, and final disposal life cycle stages were not included in the study.

Project Assumptions and Limitations

Bergman and Bowe (2011) provided detailed assumptions and limitations for determining results of this LCI study (ISO 2006b).

Impact Categories

No impact assessment was conducted because it was beyond the scope of this study.

Critical Review

James Wilson, past vice-president of CORRIM, reviewed the questionnaire used to survey the industry. Maureen Puettmann of WoodLife Consulting, who conducts critical reviews for CORRIM, conducted a review according to ISO standards on the SimaPro module used to develop this report (ISO 2006b, 2006c).

INVENTORY ANALYSIS

Log Yard

This unit process began with transporting logs from the forest landing to the veneer mill and included the following operations: transporting veneer logs from forest landing to the log yard, sorting veneer logs by grades and size, storing logs either wet or dry depending on the season and species, transporting logs in-yard from the point of unloading to log deck storage, and transporting logs in-yard from log deck storage to the veneer mill infeed (debarker and log bucking saw). Inputs included fossil fuel for log haulers and water and electricity for sprinklers. This unit process generated no coproducts. The log wetting process released water emissions. Logging transportation data were required to connect forest resource LCI to prefinished engineered wood flooring LCI.

Debarking and Bucking

This unit process began with logs at the debarker and included mechanically removing the bark from the logs and cross-cutting long logs to make wood "blocks" for peeling (cutoff saw). Inputs included electricity to operate the debarker and saw and diesel fuel for the log haulers. Coproducts generated included green bark and some green wood waste including material lost as end cuts. Green wood residues were either ground into wood fuel that was burned on-site or sold as mulch. In this study, surveyed mills listed roughly 50% of the bark as hog fuel.

Block Conditioning

Wood blocks were heated in vats with either hot water or direct steam to soften the log to improve quality of the peeled veneer. Inputs included steam or hot water and electricity for the vats and fossil fuel for equipment to load and unload vats. This unit process produced no coproducts. Emissions associated with this unit process included air and water emissions from boilers providing heat for vats.

Peeling and Clipping

A rotary lathe sliced the hot, softened veneer blocks into thin veneer sheets, and a clipper trimmed the sheets to size. Inputs included electricity to run lathes, conveyors, clippers, hog fuel grinders, and waste gate equipment and fossil fuel to transport veneer sheets to veneer dryers. Coproducts included green roundup wood, green peeler cores, green wood chips, green waste gate material, and green veneer clippings. Roundup wood was the wood material lost from peeling the block to create a cylindrical shape. Green roundup wood and green veneer clippings were ground into wood fuel that was burned on-site. Ground green wood fuel was also listed as hog fuel. Green peeler cores, green chips, and green waste gate material were sold.

Veneer Drying

Jet dryers dried the green veneer sheets to 0-4% MC. Inputs included electricity to run fans, steam or hot oil for heating the coils inside the dryers, and fossil fuel consumed in forklifts transporting veneer from the peeling and clipping operation to the veneer drying process. Veneers were clipped after drying. Coproducts included dry clippings. Air emissions occurred. This unit process generated air emissions as wood dried and dryer temperature rose and resulted in large amounts of VOCs compared with other unit processes. Other emissions associated with this unit process included air emissions from boilers or direct-fired burners providing heat for dryers.

Layup

This unit process involved bonding thin veneer sheets, also called plies, together with resin to form panels. The resins were urea–formaldehyde and polyvinyl acetate. Plies were stacked on top of each other with the wood grain oriented perpendicular to the previous sheet for dimensional stability. Depending on the resin, pressure and heat were applied to the sheets to cure the resin and bond the sheets to form veneer panels. Three- to five-ply veneer panels are common for engineered wood flooring. Inputs included heat and electricity to apply resin and run presses and fossil fuel for forklifts and for transporting material to the trimming, sanding, sawing, and moulding unit process. Other inputs were water to produce the resin and diesel fuel to transport dry veneer from veneer mills. This unit process generated no coproducts. The pressing and heating processes released air emissions as the resin cured. In addition, emissions associated with this unit process included air emissions from boilers providing heat for panel presses.

Trimming, Sanding, Sawing, and Moulding

Veneer panels were trimmed to standard dimensions, 1.2 × 2.4 m. Trimmed panels were sawn into individual boards and sanded. After sanding, the boards were moulded (profiled) into tongue and groove flooring of random lengths. Inputs included electricity for the trim saw, the gang rip saw, sanding, and hog fuel grinding and fossil fuel to transport the unfinished wood flooring to the prefinishing unit process. Coproducts included dry trim material, dry sanding dust, dry sawdust, and dry shavings.

Prefinishing

Prefinishing unfinished wood flooring protected the surface. This unit process included the following operations: sanding, priming, staining, filling, curing, sealing, and topcoating. Sanding the wood prepared the surface for priming, staining, filling, sealing, and topcoating. The primer coat promoted adhesion of other materials and was UV-cured. Staining material included water-based, solvent-based, and UV-cured types. Rollers typically applied the stain, filler, sealer, and topcoat. Solvents cleaned the rollers. All filler, sealer, and topcoats were UV-cured. Aluminum oxide added to the finish increased surface durability. After prefinishing, facilities shipped ready-to-install flooring in small cardboard boxes. Inputs included steam for the stain-drying ovens; electricity for UV-curing ovens, conveyors, and wood dust collectors; and cardboard for boxing. Air emissions released included sanding dust, PM10, hazardous air pollutants, and VOCs.

Auxiliary Processes

Energy generation. Wood, propane, and natural gas were burned for thermal process energy. Green wood residue from peeling and clipping and dried wood residue from trimming, sanding, sawing, and moulding generated almost all the thermal energy produced and used at the plant. This energy was typically in the form of steam used for presses, jet dryers, ovens, and facility heating. Also, this auxiliary process provided heat for use in other parts of the veneer mill and flooring plant. This process involved the following operations: fuel handling; adding water to the boiler (ie make-up water); adding chemicals to either the boiler or the steam lines; distributing steam and electricity; and treating process air, liquids, and solids.

Outputs of this auxiliary process were steam and hot water from boilers, combustion gases for drying, solid waste (wood ash), and air emissions (eg CO_2, CO) from combustion. Also, production of grid electricity used on-site released emissions off-site. An environmental profile for grid electricity was included in this analysis.

Emission controls. This auxiliary process decreased the amount of air emissions released. Wood dust collectors collected particulate and PM10 from sanding and prefinishing operations. Air handlers prevented release of VOCs from prefinishing and veneer drying. Input included electricity.

RESULTS

Product Yields

Mass and energy values and the environmental profile for making prefinished engineered wood flooring were obtained by surveying four veneer mills and five flooring plants in the eastern US. These facilities provided detailed survey production data on mass flow, energy consumption, types of fuel, and emission data. The survey-weighted average data were modeled in SimaPro 7 to find nonwood raw material use and emission data. Bergman and Bowe (2011) provided the SimaPro input data.

Weighted average annual production for the prefinished engineered wood flooring facilities was 19.8 thousand m^3 with a range of 6.1-31.1 thousand m^3. Other weighted average mill features included log diameter (small end, inside bark) of 380 mm with a range of 330-460 mm. Also, wood chips were the largest proportion of wood residue produced at 533 OD kg per production unit (Table 1). Flooring plants purchased 177 OD kg of dry veneer per production unit. Species veneered were red oak (roughly half), white oak, hard and soft maple, yellow poplar, yellow birch, black cherry, ash, sweetgum, pecan, hickory, hackberry, elm, and some miscellaneous species.

Table 1. Wood mass balance for 1.0 m^3 of prefinished engineered wood flooring (weighted average values in oven-dried kilograms).

	Wood mass balance			
Material	In	Out	Boiler fuel	Sold
Green logs (white wood only)	1255			
Green logs (bark only)[a]	66.9			
Dry veneer (purchased)	177			
Green bark		66.9	6.0	60.9
Green roundup wood		2.8	2.8	0.0
Green peeler cores		0.2	0.0	0.2
Green veneer clipping		0.6	0.6	0.0
Green trim		0.6	0.6	0.0
Green chips		532.8	0.1	532.7
Green hog fuel		175.3	175.3	0.0
Green waste gate material		0.1	0.0	0.1
Dry clipping		7.6	4.6	3.1
Dry sawdust		106	2.7	103
Dry shavings		11.1	0.8	10.3
Dry sanding dust		17.8	0.2	17.6
Engineered wood flooring		578		
Sum	1500	1500	194	728

[a] About half the bark was included under green hog fuel.

For the mass balance, the LCI study examined eight main unit processes and the overall process to track material flows. Using a weighted average multiunit approach, 1255 OD kg of incoming hardwood logs with a green density of 944 kg/m^3 and 177 OD kg of purchased rough dry veneer with a density of 613 kg/m^3 produced 1.0 m^3 of prefinished engineered wood flooring. Boilers burned 194 OD kg of both green and dry wood fuel produced on-site (Table 1). Overall, a difference of 3.7% was calculated based on overall mass balance that included intermediate products such as rough green and rough dry veneer.

Most veneer mills in the US track log breakdown to find mill efficiency. The veneer recovery factor (VRF) is one way to track log breakdown. In this study, VRF quantified productivity as weight of veneer (minus resin) produced divided by total weight of incoming wood in log form. A VRF of 42.6% was calculated. Wilson and Sakimoto (2004) showed a VRF of 51 and 50% for production of softwood plywood in the Pacific Northwest and the Southeast, respectively.

NONWOOD INPUTS

Water Consumption

Water use was mainly for sprinkling logs, steaming vats, and boiler make-up water. Surface and ground water consumption of 972 and 2840 L/m^3 of prefinished engineered wood flooring were calculated, respectively. Water consumption was broken down into the following unit processes: logyard (30%), block conditioning (40%), layup (10%), and auxiliary energy generation (20%).

Transportation Data

On-site transportation of wood stock was a major fuel consumer with off-road diesel having the greatest consumption. On-site transportation included forklifts, front-end loaders, trucks, and other equipment used within the system boundary of the facility. Total diesel consumption was 11.3 L/m^3 of prefinished engineered wood flooring. Diesel consumption was about three times the rate of propane and gasoline combined. Gasoline and propane use was 0.57 and 3.10 L/m^3, respectively. Diesel consumption was comprised of off-road fuel used on-site and on-road fuel used to haul dry veneer to flooring plants. Off-road and on-road diesel use was 7.0 and 4.3 L/m^3, respectively.

Resource Transportation

Resource transportation data considered many resources (Table 2). Distance traveled had a large effect on results, especially for dry veneer material. In this study, nonpurchased and purchased dry veneers traveled about three to five times farther than logs did. Therefore, log transportation data of 467 t-km were close to the average value of 558 and 300 t-km for nonpurchased and purchased dry veneer, respectively. Logs were heavier, however, at 85% MC, whereas dry veneer was lighter at 6% MC. Surveyed mills produced the nonpurchased dry veneer. Stains and coatings had minimal effect on transportation because of the small volume consumed in the manufacturing process.

MANUFACTURING ENERGY

Overall

Prefinished engineered wood flooring production required both electrical and thermal energy for processing logs into flooring. All the thermal energy was produced directly on-site, whereas electricity was produced indirectly (ie off-site) and delivered through a regional power grid. Electrical energy was required for all unit processes, whereas most thermal energy was required for block conditioning, veneer drying, layup, and prefinishing processes. Total electrical consumption was 1110 kWh/m^3 prefinished engineered wood flooring (Table 3). Total process energy (unallocated) of 6.42 GJ was consumed per cubic meter of prefinished engineered wood flooring. Wood fuel at 300 OD kg or 6.26 GJ/m^3 contributed 97.6% of process thermal energy required with the remainder from propane (2.2%) and natural gas (0.2%).

Table 2. Resource transportation.

Resource	Distance (km)	Transportation (t-km)
Logs (white wood only)	201	467
Bark	201	25
Purchased wood fuel	165	24
Dry veneer (nonpurchased)	1040	558
Dry veneer (purchased)	535	300
Resin	477	48
Stain	205	1
Coatings	205	2

Electrical

For unit processes and auxiliary unit processes (energy generation, emission controls [veneer mill], and emission controls [flooring plant]), distribution of electrical energy consumption is

Table 3. Material and energy consumed on site to produce 1.0 m^3 of prefinished engineered wood flooring (SimaPro input values).[a]

Fuel type	Quantity (units/m^3)
Fossil fuel[b]	
Natural gas	0.30 m^3
Propane	5.36 L
Electricity[c]	
Off-site generation	1110 kWh
On-site transportation fuel[d]	
Off-road diesel	7.01 L
On-road diesel[e]	4.26 L
Gasoline	0.57 L
Propane	0.04 L
Renewable fuel[f]	
On-site wood fuel	194 kg
Purchased wood fuel	106 kg
Water use	
Surface water	972 L
Ground water	2840 L

[a] Includes fuel used for electricity production and for transportation (unallocated).
[b] Energy values were determined using their higher heating values in MJ/kg: 54.4 for natural gas and 54.0 for propane.
[c] Conversion unit for electricity is 3.6 MJ/kWh.
[d] Energy values were determined using their higher heating values in MJ/kg: 45.5 for off-road and on-road diesel and 54.4 for gasoline.
[e] Transportation of panels and veneer between facilities; not accounted for in other transportation data.
[f] Values given in oven-dry weights (20.9 MJ/OD kg).

shown in Table 4. Total electrical consumption was 1110 kWh/m^3. For auxiliary unit processes, the greatest electrical consumption occurred in the emission control (flooring plant) process with 335 kWh/m^3, about 30% of the total. Total electrical consumption for hardwood plywood production was 462 kWh/m^3. Hardwood plywood production included all unit processes from incoming hardwood logs to layup. For hardwood plywood production, layup consumed roughly 44% of the total at 201 kWh/m^3. Wilson and Sakimoto (2004) reported electrical consumption of 138 kWh/m^3 for Pacific Northwest softwood plywood, approximately 30% of hardwood plywood production.

Off-site generation of electrical power affected environmental impact because of all the different fuels used to generate power. Average composition of (off-site) electrical generation for the eastern US grid was taken from SimaPro (ie US LCI Database) (PRé Consultants 2011). The most significant electric power contributor in the Eastern region was coal with 58.9% of total electrical utility power including both bituminous and lignite coals. Other fuel sources were nuclear, natural gas, petroleum, hydro, biomass, and unspecified fossils, which provided 22.7, 10.1, 3.3, 2.9, 1.6, and 0.5%, respectively. Wind power contributed less than 0.05% to the grid.

Heat

A total process energy (unallocated) of 6.42 GJ was consumed per cubic meter prefinished engineered wood flooring. Unit processes of block conditioning, veneer drying, layup, and stain drying consumed 1.521 GJ (23.7%), 3.773 GJ (58.8%), 0.723 GJ (11.3%), and 0.401 GJ (6.2%) of process thermal energy, respectively. Facility heating was divided evenly among these four processes. For an energy check, we estimated a literature value for block conditioning of 1.64 GJ/m^3 assuming frozen oak logs heated to 100°C, boiler efficiency of 75%, and boiler vat efficiency of 25% caused by using live steam (Steinhagen 2005). In addition, a previous CORRIM study on southeast plywood showed a veneer drying value of 1.61 GJ/m^3 (Wilson and Sakimoto 2004). Hardwood plywood may take two to three times more energy for drying than softwoods because hardwood contains more water because of its higher density.

Table 4. Electricity consumption broken down by unit processes.

Unit process	%	kWh/m^3
Bucking and debarking	8.0	89
Block conditioning	2.4	26
Peeling and clipping	11.9	133
Veneer drying	1.2	13
Layup	18.1	201
Trimming, sanding, sawing, and moulding	6.0	67
Prefinishing	6.0	67
Energy generation	11.9	133
Emissions control (veneer mill)	4.4	49
Emission controls (flooring plant)	30.1	335
Total	100	1110

ENVIRONMENTAL IMPACTS

SimaPro 7 modeled output factors during the manufacturing process with major consumption of raw materials, other than wood, for electrical generation. Other major raw materials used, other than logs processed into veneer, were coal, purchased wood fuel (residue), natural gas, crude oil, and limestone with allocated values of 352, 105, 75.6, 74.8, and 14.8 kg per production unit, respectively. A wood log volume of 1.43 m^3 was allocated to produce 1.0 m^3 prefinished engineered wood flooring (Table 5). Limestone (which helps remove sulfur dioxide emitted from burning coal) and most of the coal were used to produce off-site electricity; oil and natural gas were for off-site electricity, resins, and finishing materials; and thermal energy used on-site. Veneer mills and flooring plants burned purchased wood fuel for thermal energy use on-site.

Table 6 shows allocated cumulative energy of making 1.0 m^3 of prefinished engineered wood flooring. For cumulative energy allocated to prefinished engineered wood flooring, a value of 23.0 GJ/m^3 was found. Coal used to produce electricity provided by far the largest portion of energy needed, mostly because of the intensive

Table 5. Raw materials consumed during production of prefinished engineered wood flooring—cumulative, allocated gate-to-gate life cycle inventory values (SimaPro output values).[a]

Raw material[b]	Quantity[c] (units/m^3)
Logs at mill gate[d]	1.43 m^3
Water, well, in ground[e]	2.51 m^3
Water, process, surface[e]	6.35 m^3
Wood fuel	105 kg
Coal, in ground[e]	352 kg
Gas, natural, in ground[e]	75.6 kg
Oil, crude, in ground[e]	74.8 kg
Limestone, in ground[e]	14.8 kg
Energy, from hydro power	3.74 kWh
Energy, unspecified	0.41 kWh
Uranium, in ground[e]	0.0106 kg

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).
[b] Values are allocated and cumulative.
[c] Energy values were found using higher heating values in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.
[d] Amount of wood in log form allocated to final product; no shrinkage was taken into account from the drying process. Value contains no coproducts but does include amount of on-site-generated wood fuel allocated to the flooring.
[e] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

Table 6. Cumulative energy (higher heating values) consumed during production of prefinished engineered wood flooring—cumulative, allocated gate-to-gate life cycle inventory values (SimaPro output values).[a]

Fuel[b,c]	kg/m^3	MJ/m^3
Wood fuel	105	2,200
Coal, in ground[d]	352	9,220
Gas, natural, in ground[d]	75.6	4,110
Oil, crude, in ground[d]	74.8	3,400
Energy, from hydro power[e]	—	13
Uranium, in ground[d]	0.0106	4,040
Energy, unspecified[e]	—	1
Total		23,000

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).
[b] Values are allocated, cumulative, and based on higher heating values.
[c] Energy values were found using their higher heating values in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.
[d] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.
[e] No mass units are assigned to hydro and unspecified energy.

electrical energy needed for peeling and clipping (11.9%), layup (18.1%), and emission controls associated with prefinishing (30.1%).

Two different LCI scenarios for manufacturing prefinished engineered wood flooring were evaluated based on five veneer mills and four flooring plants surveyed—allocated cumulatively and allocated on-site. The method for evaluating the two scenarios followed ISO 14040 standards and CORRIM guidelines. Allocated accumulative scenarios examined all emissions for electricity and thermal energy generation that were required to produce 1.0 m^3 of prefinished engineered wood flooring starting with hardwood logs at the mill gate. These emissions involved the cradle-to-gate resource requirements (production and delivery) of grid electricity, fossil fuels, and purchased wood fuel used in the boiler and fossil fuels used in yard equipment such as forklifts. Also, emission data for on-site combustion of the two latter materials and wood fuel generated on-site were included. Transportation of logs (including bark) to the mill gate was included in the cumulative system boundary. The allocated on-site scenario only includes emissions from combustion of all fuels used at the mills and flooring plants, therefore it did not involve manufacturing and delivery of materials, fuels, and electricity consumed at the mill.

Table 7 shows the lower environmental impact of on-site compared with cumulative emissions for facilities surveyed. CO_2 and particulates are typically measured, although other emissions are frequently monitored from boilers to ensure regulatory compliance. CO_2 emissions are separated by two fuel sources, biogenic (biomass-derived) and anthropogenic (fossil fuel-derived). Accumulative total emission values of 623 and 1050 kg were reported from SimaPro for CO_2 (biogenic) and CO_2 (fossil), respectively (Table 7). The percentage of biogenic CO_2 to total CO_2 increased from 37.3 to 64.8% from the total (cumulative) to on-site scenarios. Emissions of VOC gases were roughly the same at approximately 1 kg regardless of scenario, indicating that veneer (wood) drying was a significant contributor to the overall amount of VOCs.

Material and energy resources consumed to manufacture 1 m^3 of prefinished engineered wood flooring are shown in Table 3. These LCI

Table 7. Life cycle inventory results for total cumulative and on-site emissions on a per-unit basis of prefinished engineered wood flooring (allocated).

Substance	Total cumulative (kg/m^3)	On-site (kg/m^3)
Water emissions		
Biological oxygen demand (BOD)	1.09	1.06
Cl^-	14.9	7.9
Suspended solids, unspecified	0.933	0.591
Oils, unspecified	0.0911	0.0865
Dissolved solids	12.6	3.94
Chemical oxygen demand (COD)	1.52	1.45
Other solid materials[a]		
Waste in inert landfill	28.4	28.4
Recycled material	9.34	9.34
Solid waste[b]	41.0	41.0
Air emissions		
Acetaldehyde	0.217	0.217
Acrolein	4.90×10^{-5}	1.10×10^{-5}
Benzene	0.00232	0.00214
Carbon dioxide (biomass)	623	610
Carbon dioxide (fossil)	1050	331
Carbon monoxide	5.57	5.02
Methane	2.65	1.211
Formaldehyde	0.0400	0.0398
Mercury	4.84×10^{-4}	1.39×10^{-5}
Naphthalene	6.99×10^{-4}	9.96×10^{-4}
Nitrous oxides	3.76	1.61
Nonmethane, volatile organic compounds (NMVOC)	0.579	0.502
Organic substances, unspecified	0.0805	0.0797
Particulate (PM10)	0.138	0.138
Particulate (unspecified)	0.610	0.171
Phenol	0.0192	0.0192
Sulfur dioxide	5.05	0.558
VOC	1.04	0.999

[a] Includes solid materials not incorporated into the product or coproducts and leaving the system boundary.
[b] Solid waste is mostly boiler ash from burning wood. Boiler ash is either spread as a soil amendment or landfilled depending on the facility.

input values were unallocated and were entered into SimaPro 7 to find the environmental impact of manufacturing 1 m^3 of prefinished engineered wood flooring. Table 8 lists on-site energy values unallocated and allocated to planed dry lumber. Unallocated values were calculated from material and energy resources found in Table 3 and were the sum of all fuel and electricity inputs to the process. Allocated on-site energy use is roughly 57% of the total unallocated on-site use. Material and energy consumed at the mill for SimaPro 7 gave LCI outputs allocated to manufacturing prefinished engineered wood flooring, not to associated wood coproducts. Using the total difference between unallocated and allocated values, we calculated 4.70 GJ of energy used at the mill allocated to coproducts.

Table 8. Fuel and electrical energy used on site to produce a 1 m^3 of prefinished engineered wood flooring.

	Energy use at mill	
	Unallocated (MJ/m^3)	Allocated (MJ/m^3)
Fossil fuel[a]		
Natural gas	11.4	6.62
Propane	143	82.9
Electricity[b]		
Off-site generation	4010	2330
On-site transportation fuel[c]		
Off-road diesel	271	110
On-road diesel	165	66.9
Gasoline	19.9	8.09
Propane	167	67.9
Renewable fuel[d]		
On-site wood fuel	4050	2350
Purchased wood fuel	2220	1290
Total	11,000	6300

[a] Energy values were determined using their higher heating values in MJ/kg: 43.3 for fuel oil #1 and #2.
[b] Conversion unit for electricity is 3.6 MJ/kWh.
[c] Energy values were determined using their higher heating values in MJ/l: 38.7 for off-road diesel, 26.6 for propane, and 34.8 for gasoline.
[d] Values given in oven-dried weights (20.9 MJ/OD kg).

Table 9 shows the difference by type of wood flooring for cumulative energy (allocated). Results showed a cumulative allocated value for manufacturing prefinished engineered wood flooring from the forest road to the final product leaving the flooring plant of 23.0 GJ/m^3. Cumulative allocated value considers electrical efficiency of grid power provided. Unfinished engineered wood flooring showed a cumulative allocated value of 13.6 GJ/m^3. Prefinished

Table 9. Cumulative energy (higher heating values) consumed during production of prefinished engineered wood flooring compared with unfinished engineered and solid strip wood flooring—cumulative, allocated gate-to-gate life cycle inventory values (SimaPro output values).[a]

	Unfinished solid strip flooring[c]	Engineered wood flooring	
		Unfinished	Prefinished
Fuel[b] (MJ/m^3)			
Biomass	4,200	1,720	2,200
Coal	748	4,990	9,220
Natural gas	934	2,930	4,110
Crude oil	557	2,580	3,400
Hydro	9	4	13
Uranium	48	1,360	4,040
Energy, unspecified	7	1	1
Total	6,500	13,600	23,000

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).
[b] Based on higher heating values. Energy values were found using their higher heating values in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.
[c] Puettmann et al (2010).

consumed more energy than unfinished engineered wood flooring, roughly 60% more. Much of this increase in energy resulted from electrical consumption in emission control devices used to prevent release of VOCs. These devices consumed approximately 30% (335 kWh/m^3) of total electricity needed for the entire manufacturing process, whereas unfinished solid strip flooring consumed 182 kWh/m^3 allocated from gate to gate (Hubbard and Bowe 2010). Resin usage also increased environmental loading as shown when comparing unfinished engineered with unfinished solid strip wood flooring. Unfinished solid strip flooring cumulative energy consumption of only 6.50 GJ/m^3 was roughly half that of unfinished engineered wood flooring. Also, most of that energy was derived from biomass, not fossil fuels.

Allocated cumulative energy values comparing various wood flooring materials in different units are shown in Table 10. Unfinished solid strip flooring in the US had the lowest cumulative energy value with 9.89 MJ/kg, about 50% that of unfinished engineered wood flooring on a mass (ie volume) basis. Converting to MJ/m^2 (production unit) indicated that the two unfinished wood flooring materials have similar values. However,

Table 10. Cumulative energy consumed during production of various wood floorings (allocated).

Type	Density[a] (kg/m^3)	Energy (MJ/kg)	Weight (kg/m^2)	Energy (MJ/m^2)
Prefinished engineered wood[b]	656	35.0	6.56	230
Unfinished engineered wood[b]	643	21.1	6.43	136
Unfinished solid strip (US)[c]	657	9.89	12.5	123

[a] Oven-dried.
[b] Wood material had 9.5-mm thickness.
[c] Hubbard and Bowe (2010); 19-mm thickness.

prefinishing the final product resulted in a 60% increase in energy consumption, exactly the same result as previously mentioned.

CARBON BALANCE

Carbon impact was determined by estimating values of carbon found in wood and bark as described in previous studies (Birdsey 1992; Skog and Nicholson 1998) using a mixture of hardwood roundwood values for the Eastern US. We used a mixed hardwood factor of 305.1 kg/m^3 of wood material and a carbon content of 51.7% with an incoming log wood mass of 1255 OD kg/m^3 prefinished engineered wood floor ing to calculate carbon balance. Resins and coating processes were not included. Total carbon input and output of 831 and 872 kg/m^3 prefinished engineered wood flooring were found (Table 11), resulting in a difference of 4.4%. One meter cubed of prefinished engineered wood flooring stored 1100 kg CO_2 equivalents as a final product.

SENSITIVITY ANALYSIS

A sensitivity analysis was completed per ISO 14040 standards in SimaPro to model the effects of using different quantities of fuel sources for thermal energy generation. Sensitivity analysis can be useful to understand how various process parameters contribute to environmental output factors. For instance, in prefinished engineered wood flooring manufacturing, heat is used in several subprocesses. A combination of wood, natural gas, and propane is used to generate the

Table 11. Tracking of wood-based carbon inputs and outputs for prefinished engineered wood flooring.

Substance[a]	Wood (kg/m^3)	Elemental carbon (kg/m^3)
Input		
Logs	1260	649
Bark[b]	67	35
Purchased dry veneers	177	92
Purchased wood fuel	106	55
Sum carbon in	1610	831
Output		
Prefinished engineered wood flooring	578	299
Coproducts[c]	728	376
Solid emissions	41	21
Air emissions	633	176
Sum carbon out	1980	872

[a] Wood-related carbon and its emissions.
[b] Multiplying (mass of wood flooring) × (carbon content) × (carbon to CO_2 conversion) = 578 kg × 51.7% × 44/12 = 1100 kg CO_2 equivalents.
[c] Bark leaves system both as wood fuel and a coproduct (mulch).

heat. Changing fuel sources, also referred to as fuel switching, can have a significant effect on emission type and amount. This sensitivity analysis compared effects of using the "base" fuel mix to using 1) all on-site-generated wood fuel (mostly green hog fuel from the peeling and clipping process); and 2) all propane as the fuel input. Propane is chosen because it burns cleaner than fuel oil and is abundantly available domestically.

Alternative Fuel Sources

The base fuel mix in this study included three fuel sources with wood fuel and propane supplying the majority of the energy. Natural gas contributed less than 1%. Based on survey data, the original model assumed that 97.6% of the fuel used was wood fuel (63.1% produced on-site [194 kg] and the remainder purchased [106 kg]) and 2.2% was propane. Most mills use only one or two types of fuel, whereas the base mix resulted in a weight-averaged composite model incorporating different fuel sources taken from primary mill data for the five veneer mills and four flooring plants. In this sensitivity analysis, two alternative fuel-use scenarios were created for comparison with the composite mill or base scenario. One alternative assumed consumption of only on-site (generated) wood fuel for all thermal energy by increasing the initial base value of 194 to 307 OD kg to generate 6.42 GJ/m^3 of prefinished engineered wood flooring. In the second alternative fuel-use scenario, 100% propane, propane use increased from base value of 5.4 to 241 L to provide all necessary heat for the facility.

Three Fuel-Source Scenarios

This sensitivity analysis examined three scenarios for heat generation: base fuel mix, 100% propane, and 100% on-site (generated) wood. All three scenarios included emissions from cradle-to-gate resource requirements (production and delivery) of grid electricity. The following three scenarios were modeled using SimaPro to find differences in emissions: 1) 100% propane compared with base hardwood lumber fuel mix that used both propane and wood fuel; 2) 100% on-site (generated) wood fuel compared with base hardwood lumber fuel mix that again had no fuel changes; and 3) 100% propane compared with 100% on-site (generated) wood fuel.

Sensitivity Analysis Results

Table 12 presents the summary of the three fuel-use scenarios with a partial list of air emissions for the Eastern US. In scenarios 1 and 2, a negative percentage difference number indicated that the alternative fuel source released fewer emissions than did the base model. A positive percentage difference means that the base or original model released fewer emissions. Scenario 1 indicated that less particulate (PM10), solid waste, acetaldehyde, and biogenic CO_2 but more fossil CO_2, nonmethane VOC, and NOx were produced when burning 100% propane compared with the base fuel mix (original). Scenario 2 showed slightly more biogenic CO_2, both types of particulate, acetaldehyde, benzene, naphthalene, and phenol but less fossil CO_2 and NOx were produced when burning 100% wood fuel compared with the base fuel mix (original). In scenario 3, a negative number indicates that the all propane case released fewer emissions

Table 12. Sensitivity analysis for manufacturing prefinished engineered wood flooring.

Substance	Fuel distribution (kg/m^3 planed dry lumber)			Difference (%)		
	100% propane	100% wood fuel[a]	Original (base)	Scenario 1—100% propane to original	Scenario 2—100% wood fuel to original	Scenario 3—100% propane to 100% wood fuel
Acetaldehyde	2.15E-01	2.18E-01	2.17E-01	−1.2%	0.5%	−1.7%
Benzene	1.41E-03	2.44E-03	2.40E-03	−51.9%	1.7%	−53.5%
CO_2 (biogenic)	5.59E+01	6.41E+02	6.24E+02	−167.1%	2.7%	−167.9%
CO_2 (fossil)	1.45E+03	1.06E+03	1.06E+03	30.6%	0.1%	30.4%
CO	3.61E+00	5.73E+00	4.39E+00	−19.4%	26.6%	−45.4%
Formaldehyde	3.80E-02	4.02E-02	4.00E-02	−5.1%	0.5%	−5.6%
Methane	2.20E+00	1.72E+00	2.67E+00	−19.5%	−43.4%	24.3%
Naphthalene	5.00E-05	7.18E-04	6.99E-04	−173.3%	2.7%	−174.0%
Nitrogen oxides	4.10E+00	3.79E+00	3.80E+00	7.5%	−0.5%	7.9%
Nonmethane, VOC	8.22E-01	5.85E-01	5.87E-01	33.3%	−0.3%	33.6%
Organic substances, unspecified	3.55E-02	8.18E-02	8.05E-02	−77.5%	1.7%	−78.9%
Particulate (PM10)	9.19E-02	1.40E-01	1.38E-01	−40.3%	1.1%	−41.4%
Particulate (unspecified)	6.31E-01	6.19E-01	6.10E-01	3.3%	1.4%	2.0%
Phenol	8.31E-03	1.95E-02	1.92E-02	−79.1%	1.8%	−80.6%
Sulfur dioxide	2.16E+00	5.15E+00	5.11E+00	−81.2%	0.8%	−81.9%
VOC	1.06E+00	1.05E+00	1.04E+00	1.3%	0.4%	0.9%
Solid waste	1.67E+01	4.18E+01	4.14E+01	−84.8%	1.1%	−85.7%

[a] All wood fuel used was generated on-site.
VOC = volatile organic compounds.

than the all on-site-produced wood fuel case, and a positive percentage number means that all on-site-produced wood fuel models released fewer emissions. Scenario 3 highlighted the increase of fossil CO_2, nonmethane VOC, and NOx along with less particulate (PM10) and biogenic CO_2 produced compared with scenario 1. For all three scenarios, amount of VOC produced was similar regardless of fuel used because most VOC originated in the actual drying of the veneer and during panel-making and prefinishing.

DISCUSSION

Results showed that two of the eight unit processes had the greatest impact regarding process thermal energy consumption. Veneer drying and block conditioning consumed more than 80% of process energy produced on-site. Therefore, these two unit processes had the greatest potential for energy decrease and should be the area of process improvements for the wood flooring and veneer industry. Wood drying processes such as veneer drying consume considerable energy to produce a reasonably dry dimensionally stable product for installation. Decreasing energy consumption also would be of great benefit to mills in terms of financial benefits (decreased costs).

This study indicated that processing hardwood species into plywood consumed two to three times more process energy than softwood plywood production. Other studies on drying hardwoods in conjunction with manufacturing wood products also showed that hardwoods consumed significantly more process energy than softwoods on a per-unit production basis (Puettmann et al 2010; Bergman and Bowe 2010; Hubbard and Bowe 2010).

A tradeoff occurred for prefinishing engineered wood flooring on-site. Additional electricity for emission controls of VOCs emitted during prefinishing had a large environmental impact up front. Prefinishing emission controls consumed more than 30% of total electricity consumed during the manufacturing phase. However, environmental impact of prefinishing on-site would probably be less than that of finishing engineered wood flooring after installation when other factors are included besides energy consumption.

This is because of controlling emissions at flooring plants instead of allowing uncontrolled release of VOCs when finishing the installed engineered wood floor at a residential or commercial building.

In this LCI study, different physical units give different results, therefore, selecting the proper unit for comparison is critical for an accurate assessment. Unfinished engineered wood flooring consumes roughly the same allocated cumulative energy as unfinished solid strip flooring on an area basis, whereas energy consumption for unfinished engineered is about 200% of unfinished solid strip on a volume basis. Regardless, most of the allocated cumulative energy for unfinished engineered wood flooring is derived from fossil fuels because of the large amount of electricity consumed during manufacturing, unlike solid strip.

For a LCI to be consistent within the region studied and adequately represent industry data, both the surveyed facilities and all of the industry facilities with the surveyed facilities included should be of similar size. The average surveyed flooring facility was 19.8 thousand m^3, whereas the industry average was 20.3 thousand m^3 (CRI 2009). Average production for surveyed facilities and for the industry was roughly the same, indicating high data quality representation from the surveyed facilities.

The sensitivity analysis showed how the emission profile changes because of fuel switching. Fuel switching occurs frequently in industry based on fuel costs. Burning only propane adds significant fossil GHGs to the atmosphere. Fossil GHGs are a significant source of the current climate change phenomenon. Burning additional wood fuel, a typically cheaper fuel, lowers fossil GHG emissions, however it potentially adds more particulate matter if emission control devices are not effective.

CONCLUSIONS AND RECOMMENDATIONS

The following main conclusions are based on the LCI.

Converting flooring to an area basis provides a more accurate in-use comparison on energy consumption. Making engineered instead of solid strip flooring requires twice the energy on a volume basis. However, converting to an area basis results in similar energy usage. Area basis uses an industry standard in-use parameter, whereas volume basis can link other life cycle stages to the manufacturing stage to construct a cradle-to-gate LCI or a LCA. The selection of unit in reference to the final product may change the results and needs to be considered when reporting LCI results and making comparisons.

Carbon stored in the flooring—1100 kg CO_2 equivalents—exceeds by 4% the amount required to offset fossil CO_2 emitted and offsets 66% of total CO_2 emissions during manufacturing.

A tradeoff exists between prefinished and unfinished engineered wood flooring. A large amount of electricity is consumed during the prefinishing unit process to control emissions during staining and coating of wood flooring. As a result, the environmental impact is significantly greater for prefinished engineered wood flooring than for unfinished engineered wood flooring. However, finishing the wood floor after installation in a residential or commercial building (an uncontrolled environment) may result in increased emissions released from the staining and coating process that would have been captured or destroyed on-site at the flooring plant.

Burning fuel for energy generates CO_2. Nearly all energy burned on-site for manufacturing prefinished engineered wood flooring comes from woody biomass. Burning biomass for energy does not contribute to increasing atmospheric CO_2 provided forests are regrowing and reabsorbing the emitted CO_2 on a sustainable basis. Increasing on-site wood fuel consumption would decrease fossil greenhouse gases but increase other gases, especially particulate emissions. Particulate matter can be captured prior to release with commercially available technology but not without increased costs.

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Paper 3: Traditional life-cycle assessment of solid strip hardwood flooring and engineered wood flooring in the United States

Paper #3 covers dissertation pages 124-185

Traditional Life-Cycle Assessments of Solid Strip Hardwood Flooring and Engineered Wood Flooring in the United States

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June 13, 2012

EXECUTIVE SUMMARY

Study Goals

The goal of the study was to identify the critical environmental impacts of solid strip hardwood flooring (SSHF) and engineered wood flooring (EWF) made in the United States especially greenhouse gas (GHG) and biogenic CO_2 emissions. Categorizing the GHG emissions for the various life-cycle stages provided the background data for a new dynamic life-cycle assessment (LCA) methodology. The new methodology will show the climate change impacts on the timing of GHG emissions for building products using wood flooring as an example.

Methodology

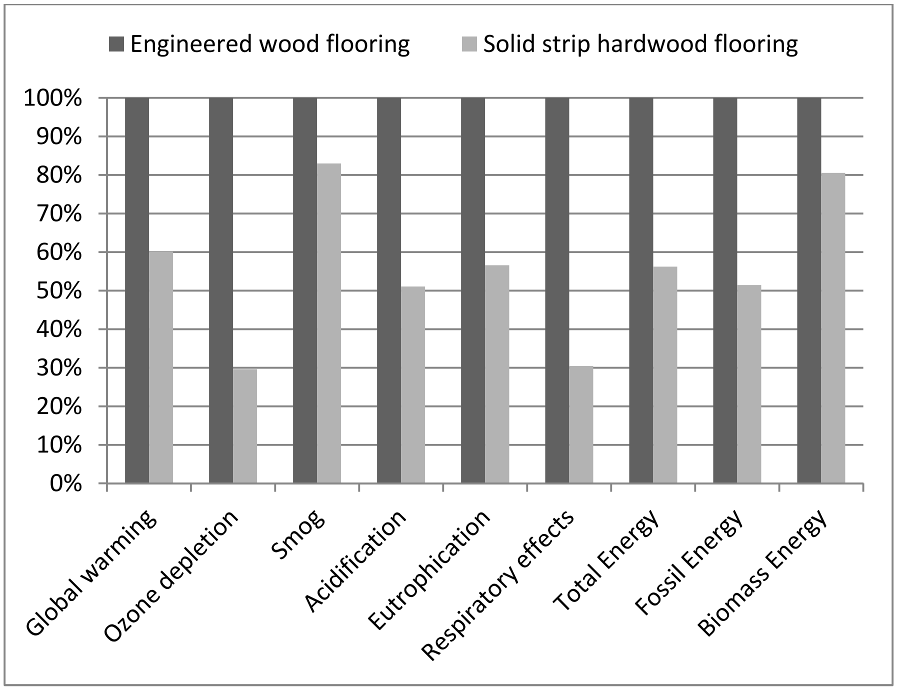
The environmental impacts were determined using LCA techniques conducted to ISO 14040 and 14044 standards. System boundaries delineated the life cycle covered from extraction through product production and maintenance to disposal of old flooring into a landfill with standard methane capture equipment with energy recovery. The present study chose the functional unit as one square meter of installed flooring in service for 80 years. Eighty years is the expected service life of a US residential housing structure. The two wood flooring products evaluated require refinishing every 20 years. SSHF lasts 80 years in service thus requires three refinishes whereas EWF lasts 40 years and requires one refinishing per service life before needing replacement. Both flooring products come prefinished from the flooring plant. TRACI 2.0 V4.00 method found in SimaPro 7 modeled the life-cycle impact assessment (LCIA) per functional unit.

Key Findings

The following table shows the LCIA per functional unit for SSHF (13.4 oven-dried kg) and EWF (13.1 oven-dried kg). Global warming potential (GWP) for EWF (34.7 kg CO_2-eq) was about 166% of SSHF (20.9 kg CO_2-eq). In addition, all impacts were higher in value for the EWF than for the SSHF. Smog was the closest impact, 3.2 and 3.8 kg O_3-eq per functional unit of SSHF and EWF, respectively.

Impact Category	Unit (per functional unit)	Solid strip hardwood	Engineered wood
Global warming	kg CO_2 eq	20.9	34.7
Ozone depletion	kg CFC-11 eq	4.47E-07	1.51E-06
Smog	kg O_3 eq	3.2	3.8
Acidification	mole H+ eq	6.4	12.5
Eutrophication	kg N eq	8.76E-03	1.55E-02
Respiratory effects	kg PM10 eq	5.28E-07	1.74E-06
Total energy	MJ	321	570
Fossil energy	MJ	205	398
Biomass energy	MJ	91	113

The following figure illustrates the considerable differences between the environmental impacts associated with SSHF to EWF. All environmental impacts for SSHF were less than for EWF based on a functional unit. For GWP, SSHF was roughly 60% of EWF.



Interpretation

Functional units mattered when examining environmental impacts. If the LCA study only examined the flooring products based on a square meter basis, the impacts for EWF would be about half of what they would be for a functional unit. Additionally, the replacement for EWF occurs 40 years after the initial installation, a considerable difference in time. Cradle-to-gate wood product manufacturing typically consumes the most energy during these stages. Therefore, delaying emissions could change their climate change impact if emissions timing were included instead of using the standard LCA static practice of GWP. Furthermore, wood products typically use wood residues for energy during product production thus generating biogenic CO_2 emissions. Standard LCA practice does not include biogenic CO_2 when calculating GWP unless the impacts of carbon sequestration and carbon storage are considered. The present study did not consider these impacts by assuming that the forest regenerates over an indefinite time period. Therefore, any life-cycle stage that avoids fossil energy usage by using wood (i.e. biomass) energy would have a lower GWP if following standard LCA practices.

Sensitivity Analysis

The final disposition of the flooring product did make a large difference in the overall environmental profile. For the baseline case, landfilling the old flooring was the preferred process whereas the alternative disposal option was burning the wood for power. Wood power avoids coal power production. Landfilling wood results in partial decomposition of about 23% of the original product and generates landfill gases (LFG) primarily made of methane and biogenic CO_2. For this study, landfill technology captured 75% of LFG. The remaining LFG escaped to the atmosphere and had a significant effect on GWP. Burning wood for power used the entire product and the primary gas emitted was biogenic CO_2. In addition, not burning coal for power avoided the release of fossil CO_2, therefore a significant reduction in GWP occurred. For SSHF, GWP was essentially zero. Additionally, these emissions did occur after the building has reached its end-of-life, about 80 years after initial production and installation of the flooring.

Recommendations

The static LCA approach aggregates individual emissions such as methane and fossil CO_2 regardless of when or how much was released at any given time. Aggregate emissions were used to calculate the environmental impacts. Conducting a dynamic LCA with respect to GHG emissions will show how well GWP accounts for large emissions that often happen decades after making a product. The future study (paper #4) will focus on whether or not GWP is sufficient for long-lived products.

Table of Contents

Table of Figures

Table of Tables

1 INTRODUCTION

In recent years, there has been increasing public interest in an ongoing debate about the environmental impacts associated with the manufacture, consumption, disposal and re-use of products that originate from the forest (Bowyer et al. 2001). Therefore, a scientifically sound and defensible assessment of the environmental impacts of wood-based materials is needed. This assessment can be used to develop marketing strategies aimed at correcting misperceptions about the environmental impact of wood as a building material. This project primarily identified the environmental impact of solid strip hardwood flooring (SSHF) and engineered wood flooring (EWF). The environmental impact was determined using life-cycle assessment (LCA) techniques conducted to ISO 14040 standards.

1.1 Background

Life-cycle inventory (LCI) data are a major component of a life-cycle assessment (LCA). LCA uses rigorous methodology to find the critical environmental impact for a particular product referred to as “cradle-to-grave” (raw material extraction to final product disposal) analysis. LCI measures all the raw material and energy inputs and outputs required to manufacture a particular product on a per unit basis within carefully defined system boundaries. The current LCI study includes forest resources, resource transportation, manufacturing, product transportation, final product use, maintenance, and final disposal for wood flooring (**Figure 1-1**) (ISO 2006a; 2006b). Forest resources include three levels of forest management intensity found in US hardwood stands. The analysis includes the environmental costs on a per unit basis using data from individual LCI studies.

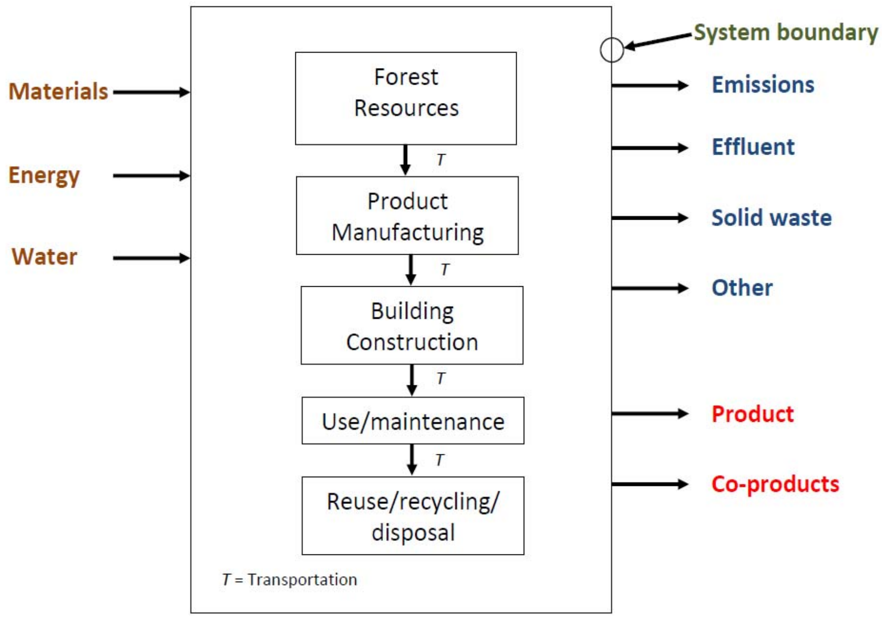


Figure 1-1: Complete life cycle from regeneration of trees to disposal of wood materials

(Source: Based on Fava et al. 1994)

A LCA is comprised of four stages (phases) as defined by the ISO. These are 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (**Figure 1-2**). A LCA study includes all stages but a LCI study does not include stage 3, the impact assessment (SAIC 2006, ISO 2006a; ISO 2006b).

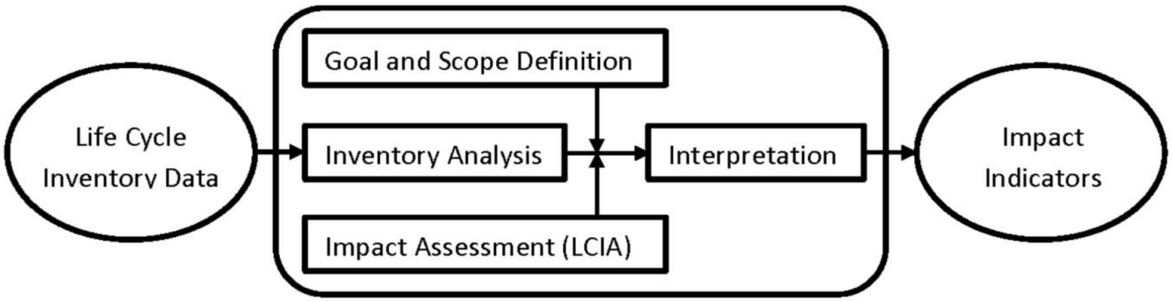


Figure 1-2: Life-cycle assessment phases

The full life-cycle study can provide information about the potential environmental impacts associated with a product or service, or the impacts implied by any product selection decision. It represents a holistic yardstick of environmental performance that helps us understand and avoid possible “burden shifting;” such as from the manufacturing to the use phase of the product’s life cycle or resolving environmental problems while simultaneously creating economic or social problems.

The work by the Consortium for Research on Renewable Industrial Materials (CORRIM) has examined structural wood building products used in residential home construction (Puettmann and Wilson 2005; Puettmann et al. 2010). In a 2004 study conducted by Lippke and others, wood building materials were found to consume significantly less fossil fuel when compared to their non-wood alternatives. Given current concerns about climate change, reducing the use of fossil fuels is seen as a critical element of any marketing claims made about the relative environmental performance of competing materials.

1.2 Significance

In 2007, wood flooring manufacturers in the US produced 41.67 million m^2 solid wood and 36.36 million m^2 engineered wood flooring for a total of 78.03 million m^2 (CRI 2008). Therefore, flooring LCAs for the United States can be important to both manufacturing and consumer groups. This LCA information would be useful to flooring manufacturers, policy makers and consumers concerned with the physical environment, the sustainability of natural resources and sustainability of local businesses.

For consumers, choices to buy or use products made from metal, wood, plastic, or concrete are done daily. Product selection is based on a broad range of attributes including price, quality and intended service application. In recent decades, the burdens that a particular product may place on human health and the physical environment have begun receiving increased consideration. To help make informed product choices consumers need transparent, scientifically verified, non-biased life-cycle information. The statistically sound LCA methodology used by CORRIM can provide this information for an array of wood products across multiple geographic regions using life-cycle inventories (CORRIM 2010). However, to date no such LCA has been completed for prefinished solid strip hardwood flooring (SSHF) and prefinished engineered wood flooring (EWF) in the United States. Given the popularity of wood flooring for residential flooring, an evaluation of the collective material and energy inputs and outputs required to manufacture this product is needed. Products with low environmental impacts have a competitive advantage and are in greater demand than products with high environmental impacts (Lober and Eisen 1995).

2 GOAL OF THE STUDY

The goal of the study was to identify the environmental impacts of SSHF and EWF made in the United States especially greenhouse gas (GHG) emissions. The environmental impacts were determined using life-cycle assessment (LCA) techniques conducted to ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) standards. Categorizing the greenhouse gas emissions for the various life-cycle stages provided the background data for a new dynamic life-cycle assessment (LCA) methodology. The new methodology will show the climate change impacts on the timing of GHG emissions for building products using wood flooring as an example.

Other intended audiences included manufacturers and buyers of flooring material. For flooring manufacturers, the continuous improvement of manufacturing processes is essential to remaining competitive. This study identified improvement opportunities for the wood flooring industry in the areas of energy efficiency and product refurbishment and replacement. ***Only data in an aggregated form will be released publicly to protect proprietary information.***

3 SCOPE OF THE STUDY

The scope of the study covered the full life cycle of the wood flooring types. **Figure 3-1** shows the region of the United States where the raw material for wood flooring is primarily harvested and made into the final product (Bergman and Bowe 2011a). The following thicknesses for SSHF (20 mm) and EWF (10 mm) were used to evaluate environmental burdens for the two products (Hubbard and Bowe 2010; Bergman and Bowe 2011a). Primary data from product manufacturers and secondary data from peer-reviewed literature were used to construct the full LCAs. In addition, tertiary sources used to complete the LCA included primarily the US LCI Database, previously hosted by the National Renewable Energy Laboratory (USDA 2012). The two wood flooring products were evaluated on a functionally-equivalent basis with respect to service life. The service life for SSHF is 80 years versus 40 years for EWF. Results included life-cycle impact assessment (LCIA) measures formulated through the tool for the reduction and assessment of chemical and other environmental impacts (TRACI) method (Bare 2002; Bare 2011).

Figure 3-1: Shaded regions show area of wood flooring production

Source: Bergman and Bowe 2011a

3.1 Functional unit

Setting system boundaries selects the unit processes to include in the life-cycle study and standardizes material flows, energy use, and emission data to a production unit. The present study selected the functional unit of one m^2 of installed flooring material in service for 80 years. Product thickness depended on material selection. Service life varies between 40 years for engineered wood flooring (EWF) and 80 years for solid strip hardwood flooring (SSHF). Based on U.S. industry measures, 1 thousand board feet (bf) of wood flooring equals 2.36 m^3 (Bergman 2010). For 20-mm thick SSHF, one m^2 equals 0.02 m^3 (8.47 bf). For 10-mm thick EWF, one m^2 equals 0.01 m^3 (4.24 bf). Therefore, half the volume of EWF is needed per square meter of flooring compared to SSHF because of the differences in thickness. The oven-dried weight of SSHF and EWF minus resins and coatings are 657 and 579 kg/m^3, respectively. EWF is about 10% resin (Bergman and Bowe 2011a). **Table 3-1** shows reference flows and thicknesses for the two wood flooring products. Thicknesses provided are derived from weighted averages of the individual product.

Table 3-1: Reference flows for the two wood flooring products

Flooring Material	Mass (ODkg/m^3)	Reference Flow (OD kg/m^2)	Conversion (m^2/m^3)	Functional unit (OD kg/FU[d])	Thickness (mm)
SSHF, unfinished[a]	657	-	-	-	20
EWF, unfinished[b]	643	-	-	-	10
SSHF, prefinished[c]	670	12.8	50	12.8	20
EWF, prefinished[b]	656	6.56	100	13.12	10

[a] Hubbard and Bowe 2010
[b] Bergman and Bowe 2011a
[c] Unfinished wood flooring weighs 98% of prefinished wood flooring (Bergman and Bowe 2011a)
[d] FU=functional unit

3.2 System boundary

This project considered the full life-cycle of the wood flooring products, starting from raw material extraction to final disposal in a municipal solid waste (MSW) landfill with methane capture (**Figure 3-2**). Raw material extraction includes forest resources with hardwood resources naturally regenerating. Maintenance requires a refinishing process every 20 years of service life. The end-of-life approach is similar to Mahalle (2011). Joists used to support the floor were omitted from this analysis since these materials are common for both systems.

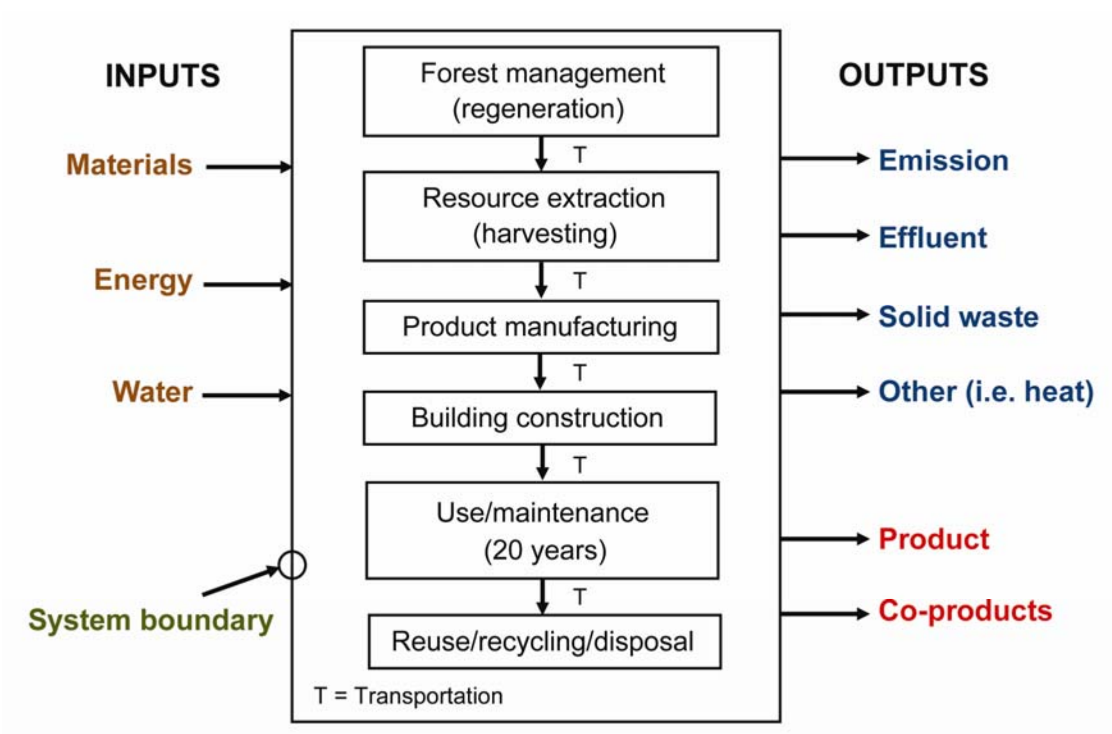


Figure 3-2: System boundary for flooring from cradle-to-grave

3.3 Allocation procedures

Defining the allocation between co-products for LCI flows of emission data and energy and material inputs is a necessary step of the LCA process. Manufacturing LCI data were developed using mass allocation (Hubbard and Bowe 2010; Bergman and Bowe 2011a). To be consistent, mass allocation was used to develop the emission profiles and to estimate the environmental impacts.

3.4 Flooring (prefinished solid strip hardwood and prefinished engineered wood)

SSHF is quite similar to EWF in many ways. For both SSHF and EWF, logs cut from trees in naturally regenerating hardwood forests in the eastern United States are transported to the production plants for further processing. For SSHF production, rough green lumber sawn from hardwood logs are kiln-dried and then machined into flooring. For EWF production, logs rotary sliced into veneer are dried and then glued into panels before machining into EWF. Wood residues derived from flooring production included green and dry residues burned on-site for energy or sold as a co-product that leaves the system boundary. **Figure 3-3** describes the basic unit processes and the system boundaries for cradle-to-gate manufacturing of wood flooring (Hubbard and Bowe 2010; Bergman and Bowe 2011a; Bergman and Bowe 2012). Puettmann and others (2010) provide cradle-to-gate LCI data for some wood products including softwood and hardwood lumber and SSHF.

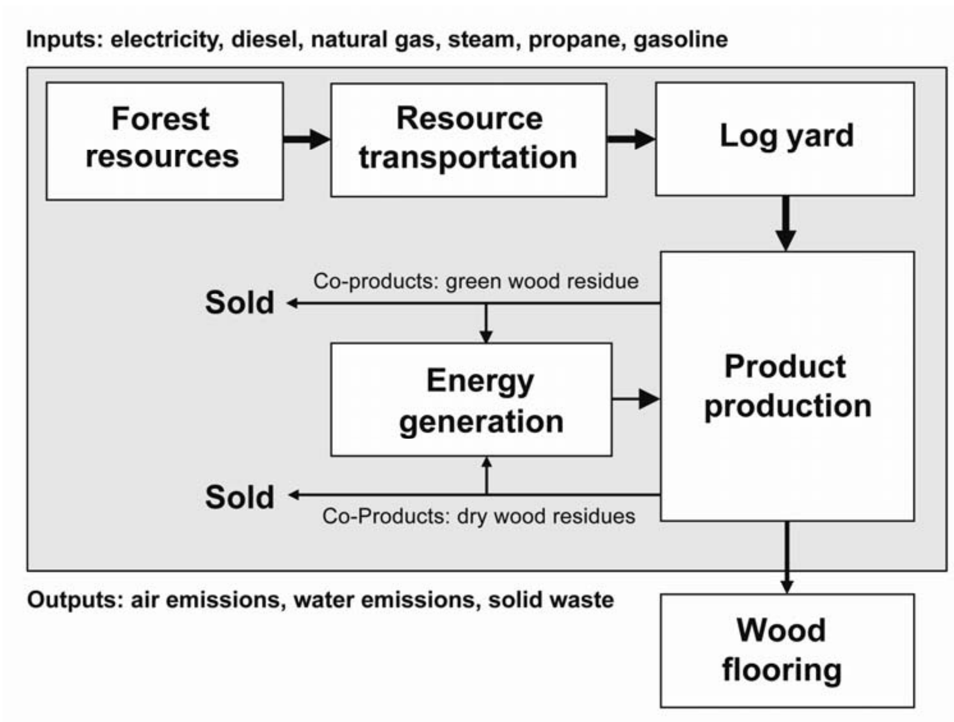


Figure 3-3: Cradle-to-gate wood flooring manufacturing.

Source: Puettmann et al. (2010)

3.5 Life-cycle Impact Assessment methodology and types of impacts

Once the complete cradle-to-grave LCI had been constructed for wood flooring, the following environmental mid-point impact categories of global warming potential (GWP) (kgCO2-eq), acidification potential (H^+ moles-eq), respiratory effects (PM 2.5-eq), eutrophication potential (kg N-eq), ozone depletion (kg CFC-11-eq), and smog potential (kg O_3-eq) were calculated using TRACI 2 impact estimators. The International Panel on Climate Change (IPCC) 2007 100-year horizon impact estimator was used for global warming potential (GWP). Cumulative energy demand (primary energy) (MJ-eq), including both the biomass and fossil fuel contributions, were calculated and reported directly from LCI flows. Standard LCA practice does not include biogenic carbon dioxide (CO_2) emissions when calculating GWP (Bare 2011; Brandão and Levasseur 2011). A sensitivity analysis was completed for GWP using IPCC 2007 20- and 500-year time horizons.

3.6 Interpretation used

In conducting the LCIA, the present study did not go beyond the mid-point impact categories highlighted in ISO 14044. LCI flows were converted to the above impact categories according to IPCC 2007 and TRACI 2 method found in SimaPro 7 (PRé Consultants 2012). Carbon sequestration was not considered when calculating GWP in the present study.

3.7 Assumptions

Many assumptions are listed in the following CORRIM reports (Bergman and Bowe 2011b, Hubbard and Bowe 2008; Oneil et al. 2010a). Oneil and others (2010b) developed the life-cycle data for the northeast/north central (NE/NC) forest resources used to create the full LCA in the present study. The remaining assumptions were dispersed throughout the present study.

3.8 Value choices and optional elements

Optional LCIA steps such as normalization, grouping, and weighting were not completed. End-point impact categories such as Eco-Indicator 99 were not used because of their higher level of uncertainty as compared to the mid-point categories reported such as the TRACI method.

3.9 Limitations

3.9.1 Omissions of life-cycle stages, processes, input or output flows

Human labor and the manufacturing LCA of machinery and infrastructure, including logging roads, was outside the system boundaries and therefore not modeled in this analysis.

3.9.2 Decision criteria (cut-off rule, if applicable)

All materials used in the logging and manufacturing process that have a significant environmental impact were tracked. Mass and energy that contributed less than 1% to the total output were not modeled in the SimaPro LCA software used for this study. However, any mass or energy resource regardless of meeting the above mentioned limits that resulted in a greater than a 2% change to an impact category were included in the analysis.

3.10 Data quality requirements

Data quality requirements were listed for the two cradle-to-gate LCIs in the three abovementioned CORRIM Reports (Bergman and Bowe 2011b (Paper #1), Hubbard and Bowe

2008; Oneil et al. 2010a). Questionnaires were used to survey the wood flooring industry to collect primary data. The questionnaires are included in the two related CORRIM Reports (Hubbard and Bowe 2008; Bergman and Bowe 2011b (Paper #1)).

3.11 Type of critical review

No critical review conducted. The basis for this study was to estimate GHG emissions for the various life cycles to aid in creating a new dynamic LCA methodology for building products, not a comparative assertion.

4 METHODOLOGY

4.1 Objectives for the cradle-to-gate LCI:

Developing LCI data includes the following steps.

4.1.1 Primary Data Collection

Collected primary data from industry using a survey instrument and followed up with telephone calls and site visits as appropriate. Primary annual production data collected from industry occurred over one-year time-period. Data included material and energy resources consumed during the year as well as the products and co-products produced.

4.1.2 Aggregated Primary Data

A spreadsheet algorithm developed in Microsoft Excel analyzed the surveyed mill's primary data. Previous CORRIM reports used the following equation to aggregate primary data as in Milota and others (2004):

$$\overline{P}_{\text{weighted}} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i}$$

where $\overline{P}_{\text{weighted}}$ is the weight average of the values reported by the mills, P_i is the reported mill value, and x_i is the fraction of the mill's value to total production for that specific value.

4.1.3 Modeling Aggregated Data

The weight-averaged primary data were modeled on a per cubic meter basis using SimaPro LCA software as outlined by the CORRIM guidelines (CORRIM 2010; PRé Consultants 2012). Weight-averaged data were entered into SimaPro 7 for each unit process and linked the processes together. Secondary data found in the US LCI Database within SimaPro provided additional life-cycle data. The additional life-cycle data included generation and delivery of electricity by region and fossil fuel processes. LCI outputs from SimaPro included allocated raw material consumption, solid waste and emission to air and water. The allocation method also partitioned the environmental impact between the products and co-products. The output of SimaPro provided the cradle-to-gate LCI data.

4.2 Objectives for constructing the life-cycle assessment for solid strip hardwood and engineered wood flooring

1) Linked the LCI stages of NE/NC forest resources to the two wood flooring manufacturing stages to develop the cradle-to-gate LCI
2) Constructed the LCAs of SSHF and EWF
3) Sensitivity analyses

4.2.1 Linking LCI stages

Linking individual life-cycle stages together is a vital step in ensuring continuity when constructing the LCA. Following ISO standards 14040 and 14044, this study determined the appropriate functional unit to link the resource harvesting LCI through resource transportation to the product manufacturing LCI in developing the cradle-to-gate LCI. A functional unit (a reference unit) is a quantitative amount of the studied product that allows for comparison between alternative products capable of performing the same task. Functional units for products are typically measured in physical units such as volume, area or mass of the product with respect to consumer utility. This detail will allow clear interlinking of the various life-cycle stages. Puettmann and others (2010) provide the interlinking and subsequent reporting of life-cycle results for cradle-to-gate LCI of SSHF. The same approach was utilized for EWF.

4.2.2 Constructing LCAs

Life-cycle assessment (LCA) is a compilation of the entire life cycle from resource extraction to final disposition of the product. This study combined the cradle-to-gate LCI developed into what was a gate-to-grave LCI to construct the full LCA. A gate-to-grave LCI focuses on product transportation, the construction and use phase considering installation and refinishing the flooring as necessary and the end-of-life phase. The study utilized available LCI data from literature and incorporated the results into SimaPro to develop the LCI data for the individual stages. The expected end-of-life for wood flooring was a landfill. The landfilled flooring emitted landfill gas (LFG) as the wood decomposes. Seventy-five percent of the emitted LFG was captured and burned and the resultant energy recovered to substitute for natural gas. In addition, a scenario analysis was conducted considering burning the demolished flooring for energy substituting for coal. Once the full cradle-to-grave LCI was constructed, the LCIA phase was next. The environmental impact categories of GWP (kgCO2-eq), acidification (H^+ moles-eq), respiratory effects (PM 2.5-eq), eutrophication (kg N-eq) and smog (kg NOx-eq) were calculated using TRACI 2.0 (V4.0). In addition, cumulative energy demand (primary energy) (MJ-eq) including biomass and fossil fuel contribution were reported. The impact categories were reported per m^3, m^2 and functional unit.

As the studied product flows through the whole cycle, physical properties were recorded for the flooring material so we were able to convert the final product to any functional unit (a reference flow) required. In order to track material properly from cradle-to-grave, material properties including density, moisture content[1] and flooring thickness were tracked and recorded. For example, other wood LCA studies have logs examined on a volume basis and once converted into the final product the material is tracked on a mass basis. Therefore, displaying the final results including physical properties can be done on an area basis.

Selection of the functional unit is critical. For this LCA study, the functional unit was calculated on a square meter basis with a specified service life. Square meter basis considers the floor area that a consumer would utilize. Additionally, specifying a service life permits alternative flooring materials that have an expected shorter or longer life to be measured accurately. Furthermore, any preventative maintenance such as floor refinishing was considered over the expected life of the floor. The two wood floors were required to be refinished every 20 years. SSHF are refinished three times before replacement was required. However, EWF are refinished once before needing replacement. Therefore, a SSHF could stay installed for the duration of a house lasting 80 years whereas EWF would require replacement after 40 years.

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[1] $Moisture\ content\ (dry\ basis) = \frac{Mass\ of\ water\ in\ wood}{Oven\text{-}dried\ mass\ of\ wood} * 100\%$

4.2.3 Sensitivity Analyses

Sensitivity analyses conducted evaluated the effect of changing parameters of the base-line scenario. Results of the sensitivity analysis offered insights into how changing the time horizons for calculating GWP would alter their product's climate change impact.

5 CRADLE-TO-GATE LIFE-CYCLE INVENTORY DATA

This section covered the life cycle of flooring products from resource extraction to creation of final product at mill gate. Flooring production occurred within the first year of the life cycle.

5.1 Forest resources

For this LCA study, raw materials in the form of trees, was harvested from the NE/NC hardwood forests to produce wood flooring. The NE/NC was chosen because LCI data were available in the US LCI Database to create the cradle-to-gate. Regardless, hardwood forests were assumed to naturally regenerate. Harvesting equipment included chainsaws, loaders and skidders. The chainsaws saw the trees into sawlogs and veneer logs, skidders moved the logs to the forest road and the loaders loaded the logs onto logging trucks. Sawlogs and veneer logs had the same material and energy requirements for their production. Sawlogs end up as SSHF (28%) and veneer logs end up as EWF (35% by mass) (Bergman and Bowe 2008; Hubbard and Bowe 2010; Bergman and Bowe 2011b). Log transportation was included in this life-cycle stage. The forest resource stage consumed gasoline, lubricants and diesel. Harvesting stage including log transportation contributes to roughly 5% of the total cradle-to-gate energy consumed (Puettmann et al. 2010). For the NE/NC forest resources, the average management intensity comprised of 59% low-intensity, 27% medium-intensity and 14% high-intensity.

5.2 Product production

Product production consumes the most energy of all life-cycle stages for most building products (Puettmann and Wilson 2005; Puettmann et al. 2010). Hubbard and Bowe (2010) and Bergman and Bowe (2011a) provided the product production LCI data. Product production usually occurred within weeks after harvesting. Cradle-to-gate SSHF used LCI data developed from the NE/NC hardwood lumber LCI (Bergman and Bowe 2008).

5.3 Cradle-to-gate LCI profile

Table 5-1 shows the cradle-to-gate results of unfinished SSHF (Puettmann et al. 2010). Using the results as a basis, a cradle-to-gate LCI for EWF was constructed.

Table 5-1: Cradle-to-gate cumulative energy consumption of unfinished solid strip hardwood flooring

Energy Source	Solid strip hardwood flooring[1] (MJ/m^3)
Coal	748
Crude oil	768
Natural gas	934
Uranium	48
Biomass	4195
Hydropower	9
Other	7
Total	6710

[1] Puettmann et al. (2010)

6 INSTALLATION PHASE

This section covered the ancillary material requirements and processes involved in the installation, use, and maintenance of flooring products throughout their service lives. The use phase inventories took into account all the material and energy inputs and processes associated with the final products leaving the mill gate and the installation, use and maintenance.

The flooring installation LCIs included the transportation of the flooring from the mill to the selected building sites and the materials and energy used in the installation, use and maintenance of the wood floors. Energy use by the pneumatic nail guns and staplers during installation was included. All flooring materials were assumed to have similar cleaning guidelines thus not included. Prefinishing inputs and outputs were considered the same per area of SSHF and EWF.

6.1 Product transportation

Wood flooring materials were transported from the manufacturing site to a wholesale location by rail and truck. Because wood products production is regionally located in the US and new wood products must be transported long distances to local markets, we assumed an average distance of travel from manufacturer to wholesaler based on data from USDOT (2010) for SSHF and EWF (NAICS 337). **Table 6-1** shows the transportation data for moving the final product from the manufacturing site to wholesaler to the construction site. It was assumed that transporting wood flooring from wholesaler to construction site for the wood flooring was 24 km. Note that the unit conversions for SSHF and EWF and 2.36 m^3/thousand board feet (Mbf), respectively.

Table 6-1: Wood flooring product transportation data

	Wood flooring (tkm/m^3)[1]	Wood flooring (tm/Mbf)[2]
Gate to wholesaler, by diesel truck	813	1314
Gate to wholesaler, by rail	4	6
Wholesaler to construction site, by diesel truck	17	26

[1] tkm/m^3 = tonne-kilometer per cubic meter of wood
[2] tm/Mbf = ton-mile per thousand board feet of wood

6.2 Installation

Installation specifications for the two flooring materials evaluated are shown in **Table 6-2**. The only difference to note during installation was if the wood floor was glued or nailed to the subfloor. All other materials are the same. Installing 20-mm thick SSHF typically used nails and staples whereas the 10-mm thick EWF used carpenter glue and staples.

Table 6-2: Installation guidelines for the two flooring products

Flooring Material	Nominal size of board (in)	Joist Span (inches)	Subfloor	Fasteners
SSHF[1,2,3]	3/4 x 2 1/4	16[4]	¾” CDX plywood[4]	Brad nails and staples[5]
EWF[6]	3/8 x 2 1/4	16[4]	¾” CDX plywood[4]	Staples and glue[3,6,7]

[1] Hubbard and Bowe (2010)
[2] Mahalle (2011)
[3] Nebel and others (2006)
[4] Anderson Family of Brands (2005)
[5] Personal communication 02/11/2011, Arvo Mather, Owner, Schreffler Custom Flooring
[6] Bergman and Bowe (2011a)
[7] Personal communication 04/09/2012, Arvo Mather, Owner, Schreffler Custom Flooring

Table 6-3 shows the listing of materials and energy necessary to install the two different types of wood flooring. Gluing quantities came from a Canadian study done on hardwood flooring (Mahalle 2011). The rest of the data came from an actual installation.

Table 6-3: List of ancillary materials and energy consumed during flooring installation

Material/energy	Unit	Amount (per m²)	Solid strip hardwood Amount (per m³)	Engineered wood Amount (per m³)
Glue	kg	6.83E-02	3.57E+00	6.83E+00
Nails	kg	1.92E-03	1.00E-01	1.92E-01
Staples	kg	2.54E-03	1.33E-01	2.54E-01
Felt paper	kg	7.35E-03	3.84E-01	7.35E-01
Electricity	kWh	5.13E-01	2.68E+01	5.13E+01

7 USE PHASE

For wood flooring, wear and tear requires the finished product to be re-surfaced (i.e. refinished). Refinishing extends the service life of the products and maintains the aesthetic qualities of the flooring. Bergman and Bowe (2011b) show prefinishing wood flooring at the production facilities consumes huge amounts of electricity not only to apply the finish to protect the wood, but also to prevent uncontrolled release of VOCs.

Data quality is of the highest quality when collected from actual manufacturing operation. In this LCI, materials consumed and electrical consumption data came from a wood floor refinishing operation. Table 7-1 shows the materials and energy necessary to refinish wood flooring. SSHF and EWF are refinished using the same process per square meter of flooring. The only difference is that EWF can only be refinished once and SSHF can be refinished three times before floor replacement is necessary. The determining factor is the thickness of the top part of the floorboard. SSHF is twice as thick as EWF. During the refinishing process for wood flooring already installed, typically no emission controls for VOCs exist. As a result, VOCs are the primary emissions tracked during this part of the life-cycle stage. As mentioned previously, data collected came from a wood floor refinishing operation. For the LCA study, sandpaper was used to remove old finish and prepare the surface for the new finish. A dust control apparatus was used to collect fugitive wood dust. The wood collection apparatus consumed 2.4 L/m^2 of gasoline. The drum sander, the edger and the buffer consumed electricity at a rate of 0.62 kWh/m^2. Refinished wood floor has three coatings applied; a single sealer coating and two finish coatings. There are typically no emission controls for the refinishing operations except for dust control.

Table 7-1: List on materials and energy necessary to refinish wood flooring

Material/energy	Flooring	Units	Solid strip hardwood	Engineered wood	Units
Sandpaper	0.16	kg/m^2	8.3	16.6	kg/m^3
Gasoline	2.4	L/m^2	127	253	L/m^3
Electricity	0.62	kWh/m^2	32.3	64.6	kWh/m^3
Sealer #1 (250 gVOCs/L)					
Application rate	0.10	L/m^2	5.3	11	L/m^3
VOCs released	0.025	kgVOCs/m^2	1.33	2.67	kgVOCs/m^3
Finish #1 (150 gVOCs/L)					
Application rate	0.10	L/m^2	5.3	11	L/m^3
VOCs released	0.025	kgVOCs/m^2	0.80	1.60	kgVOCs/m^3
Finish #2 (150 gVOCs/L)					
Application rate	0.08	L/m^2	4.3	9	L/m^3
VOCs released	0.012	kgVOCs/m^2	0.64	1.28	kgVOCs/m^3

8 END-OF-LIFE PHASE

Final disposition of old wood floorboards had a substantial influence on the environmental impacts depending on how the material is disposed of. In previous studies, when wood flooring was simply disposed of in a landfill, the material was considered inert without any environmental impact (Petersen and Solberg 2004). Therefore, only transportation to the landfill and equipment used to process the waste wood was included in the analysis. In contrast, the present study assumed that while wood flooring was disposed of in a landfill, the flooring was not inert. Research has shown that a portion of the discarded wood flooring (about 23%) breaks down anaerobically when stored in a landfill (Skog 2008). The wood decomposes into methane and carbon dioxide, major GHGs on a 50:50 molar ratio in the landfill. As the methane rises to the surface of the landfill, 10% of the methane oxidizes into CO_2. Therefore, the CH_4:CO_2 molar ratio at the surface is 45:55 (Salazar and Meil 2009). Demolition was included in the end-of-life (EOL) phase.

8.1 Demolition

Using demolition, buildings are cleared from the site by the most expedient means possible, typically using a "track-hoe" or other heavy machinery to reduce the building to as small pieces as possible for easy loading and transport to a landfill. Winistorfer and others (2005) report diesel usage for variety of residential structures including steel-, concrete- and wood-framed. The average diesel consumption is 2.8 L per square meter of demolished structure.

8.2 Landfill gas

In order to help mitigate climate change, it is desirable that methane, a much more potent GHG than CO_2, ought to be captured and burned. Additionally, energy may be recovered which is an additional benefit as the landfill gas captured and burned avoids the production of natural gas. The US Environmental Protection Agency (EPA) (2011), Skog (2008) and Salazar and Meil (2009) provide the background calculations found in **Appendix A: Landfill Gas Equations**. **Table 8-1** shows the GHG emission profile for the baseline scenario, a landfill with energy recovery. Additionally, for EWF, approximately 10% of the final product is resin thus not available for decomposition.

Table 8-1: GHG emissions from wood landfilled with standard methane capture

GHG Emissions	kg GHG per OD kg wood	kg GHG per m^2 solid strip hardwood flooring, unfinished	kg GHG per m^2 engineered wood flooring, unfinished
Methane, biogenic[a]	0.0173	0.216	0.095
Carbon dioxide, biogenic[b]	0.058	0.726	0.320
Carbon dioxide, biogenic[c]	0.221	2.77	1.218
Carbon dioxide, biogenic[d]	0.0949	1.19	0.523

[a] Released directly into air
[b] Released directly into air
[c] Released after energy recovery (70%)
[d] Release after flaring (30%) – energy not recovered

Landfill gas (LFG) contains methane, the primary component of natural gas. Therefore, it was assumed that LFG capture for energy production offset natural gas production. The amount of avoided natural gas production due to the capture of LFG was estimated to be 0.052 kg (0.0784

m^3) of natural gas production per OD kg of wood decomposing in the landfill, assuming a 75% capture rate of 0.1045 m^3 per OD kg at landfill surface. The remaining 25% of methane (0.0173 kg) was emitted to the atmosphere. For one m^2 of unfinished SSHF (12.5 OD kg) sent to a landfill with methane capture, 0.980 m^3 of natural gas production was avoided. For one m^2 of unfinished EWF, 0.432 m^3 natural gas production was avoided assuming EWF was 90% wood.

9 CRADLE-TO-GRAVE LIFE-CYCLE INVENTORY RESULTS

The goal of this study was to develop air emission data involving GHGs to be used as a precursor for developing a new methodology on a dynamic LCA approach for building products using wood flooring as an example. Therefore, only GHGs and biogenic CO_2 emission data were shown to focus on the goal of the study. Air emissions were reported in kg gas per m^3. All cradle-to-gate LCI flows per m^3 are shown in Appendix B (pg. 50) for SSHF and Appendix C (pg. 62) for EWF.

Table 9-1 lists the major GHGs and biogenic CO_2 emitted during the whole life cycle of SSHF by stage by values for one cubic meter product produced. Most fossil CO_2 emissions occurred during product production (365 kg/m^3) and during the use phase from refinishing (246 kg/m^3). Almost all emitted methane to the atmosphere came from the breakdown of wood in the landfill. This occurred because 25% of the methane coming to the surface escaped to the atmosphere despite having methane capture equipment installed at the landfill.

Table 9-1: List of major gases emitted for solid strip hardwood flooring by stage by values

Air emissions (kg/m^3)	Cradle-to-gate	Product Transp.	Installation	Use	Disposal	Total
CO_2, biogenic	427	0	1	34	250	712
CO_2, fossil	365	96	20	246	-2	724
Methane	0.93	0.14	0.04	0.49	11.02	12.6
Nitroux oxide	5.83E-03	2.04E-03	8.17E-05	6.76E-03	5.00E-05	1.48E-02

Table 9-2 shows the breakdown by percentages for one cubic meter product produced. As shown previously in **Table 9-1**, methane production occurred primarily at the EOL (87.3%), not during the previous life-cycle stages. Additionally, most of biogenic CO_2 was released during cradle-to-gate product production (59.9%). Biogenic CO_2 is one of the primary components of landfill gas with methane being the other. More biogenic CO_2 occurred at EOL then just from the decomposing wood as the emitted methane was burned emitting biogenic CO_2 as one of the products.

Table 9-2: List of major gases emitted for solid strip hardwood flooring by stage by percentage

Air emissions	Cradle-to-gate	Product Transp.	Installation	Use	Disposal	Total
CO_2, biogenic	59.9%	0.0%	0.2%	4.7%	35.2%	100%
CO_2, fossil	50.4%	13.2%	2.8%	33.9%	-0.3%	100%
Methane	7.3%	1.1%	0.4%	3.9%	87.3%	100%
Nitrous oxide	39.5%	13.8%	0.6%	45.8%	0.3%	100%

Table 9-3 lists the major GHGs and biogenic CO_2 emitted during the whole life cycle of EWF by stage by values for one cubic meter product produced. Similar to SSHF, most fossil CO_2 emissions for EWF occurred during product production (1,066 kg/m^3). Most methane came wood decomposing in the landfill because methane capture equipment only captured 75% of the methane emitted from the landfill.

Table 9-3: List of major gases for engineered wood flooring emitted by stage by values

Air emissions (kg/m^3)	Cradle-to-gate	Product Transp.	Installation	Use	Disposal	Total
CO_2, biogenic	550	0	2	23	245	820
CO_2, fossil	1066	94	56	164	-2	1377
Methane	2.70	0.13	0.17	0.33	10.79	14.1
Nitrous oxide	1.10E-02	2.00E-03	5.21E-04	4.51E-03	4.89E-05	1.81E-02

Table 9-4 shows the breakdown by percentages for one cubic meter product produced. Once again, methane production occurred primarily at EOL (76.4%) not during the other four life-cycle stages. The percentage was lower for EWF than SSHF because the floor was about 90% wood with the remainder resins and coatings. As with SSHF, cradle-to-gate product production released the most biogenic CO_2 (67.0%).

Table 9-4: List of major gases for engineered wood flooring emitted by stage by percentage

Air emissions	Cradle-to-gate	Product Transp.	Installation	Use	Disposal	Total
CO_2, biogenic	67.0%	0.0%	0.3%	2.7%	29.9%	100%
CO_2, fossil	77.4%	6.8%	4.1%	11.9%	-0.1%	100%
Methane	19.1%	0.9%	1.2%	2.3%	76.4%	100%
Nitrous oxide	60.9%	11.1%	2.9%	24.9%	0.3%	100%

10 LIFE-CYCLE IMPACT ASSESSMENT

This section of the report covered the impact assessment of the life-cycle assessment. The LCI flows from the two wood flooring products provided the basis for the LCIA. The TRACI 2 method incorporated into SimaPro 7 provided the framework for calculating the environmental mid-point categories listed in Section 3-5 (PRé Consultants 2012). The TRACI method was developed through the US EPA (Bare 2002; Bare 2011). The LCIA provides input for builders, architects, engineers, and designers on the various attributes of raw materials, product choices, and disposal methods. Learning the LCIA of a particular material allows stakeholders to make informed product choices based on science rather than anecdotal evidence, assuming that the LCIA analysis is transparent. The present study provided the LCIA data for a wood floor built in the United States. Results from the six impact categories were reported per m^3, m^2, and FU.

10.1 Prefinished solid strip hardwood flooring

Table 10-1 shows the impacts generated for a cubic meter of flooring. **Table 10-2** shows the impacts generated on a square meter basis. **Table 10-3** shows the results per functional unit of SSHF. SSHF lasts 80 years thus requires three refinishes during its installation. Because SSHF is the basis for the functional unit, **Table 10-2** has the same results as **Table 10-3**. These tables show that the greatest impacts occurred mostly during the cradle-to-gate manufacturing. The cumulated allocated total energy consumption was 321 MJ/functional unit (16,100 MJ/m^3) of floor with about 64% (206/321) of energy consumption associated with the cradle-to-gate manufacturing. Biomass contributes 28% (91 MJ/functional unit) towards the total energy use. The in-service use phase had a large impact on the LCIA because of refinishing the wood floor every 20 years. The high impacts mostly occurred because of the uncontrolled releases of VOCs and the electrical equipment used for sanding and wood dust collection. Disposing wood into landfill with methane capture equipment still resulted in methane emissions of 5.47 kg CO_2-e/functional unit for GWP thus had a substantial impact on overall GWP, about 26% (5.47/20.9).

Table 10-1: LCIA for one m^3 of solid strip hardwood flooring

Impact Category	Unit (per m^3)	Cradle-to-gate	Product Transp.	Install.	Use (3x)	Disposal	Total
Global warming	kg CO_2 eq	390	100	21	260	273	1044
Ozone depletion	kg CFC-11 eq	1.91E-05	4.10E-09	3.31E-08	3.18E-06	1.67E-10	2.24E-05
Smog	kg O_3 eq	49.4	16.1	1.4	91.4	1.4	160
Acidification	mole H+ eq	177	36	10	145	-48	319
Eutrophication	kg N eq	2.35E-01	3.25E-02	3.39E-03	1.70E-01	-3.33E-03	4.38E-01
Resp. effects	kg PM10 eq	0.000	0.000	0.000	0.000	0.000	0.000
Total Energy	MJ	10300	1310	310	4060	51	16100
Fossil Energy	MJ	4900	1280	237	3780	51	10300
Biomass Energy	MJ	4570	0	0	0	0	4570

Table 10-2: LCIA for one m^2 of solid strip hardwood flooring

Impact Category	Unit (per m^2)	Cradle-to-gate	Product Transp.	Install.	Use (3x)	Disposal	Total
Global warming	kg CO_2 eq	7.79	1.99	0.43	5.20	5.47	20.9
Ozone depletion	kg CFC-11 eq	3.83E-07	8.19E-11	6.63E-10	6.36E-08	3.35E-12	4.47E-07
Smog	kg O_3 eq	0.99	0.32	0.03	1.83	0.03	3.19
Acidification	mole H+ eq	3.55	0.71	0.19	2.90	-0.97	6.38
Eutrophication	kg N eq	4.70E-03	6.50E-04	6.78E-05	3.40E-03	-6.65E-05	8.76E-03
Resp. effects	kg PM10 eq	4.45E-07	2.57E-08	8.66E-10	6.52E-08	-8.71E-09	5.28E-07
Total Energy	MJ	206	26	6	81	1	321
Fossil Energy	MJ	97.9	25.6	4.7	75.6	1.0	205
Biomass Energy	MJ	91.3	0.0	0.0	0.0	0.0	91

Table 10-3: LCIA per functional unit of solid strip hardwood flooring

Impact Category	Unit (per FU[a])	Cradle-to-gate	Product Transp.	Install.	Use (3x)	Disposal	Total
Global warming	kg CO_2 eq	7.79	1.99	0.43	5.20	5.47	20.9
Ozone depletion	kg CFC-11 eq	3.83E-07	8.19E-11	6.63E-10	6.36E-08	3.35E-12	4.47E-07
Smog	kg O_3 eq	0.99	0.32	0.03	1.83	0.03	3.19
Acidification	mole H+ eq	3.55	0.71	0.19	2.90	-0.97	6.38
Eutrophication	kg N eq	4.70E-03	6.50E-04	6.78E-05	3.40E-03	-6.65E-05	8.76E-03
Resp. effects	kg PM10 eq	4.45E-07	2.57E-08	8.66E-10	6.52E-08	-8.71E-09	5.28E-07
Total Energy	MJ	206	26	6	81	1	321
Fossil Energy	MJ	97.9	25.6	4.7	75.6	1.0	205
Biomass Energy	MJ	91.3	0.0	0.0	0.0	0.0	91

[a] FU=functional unit

10.2 Prefinished engineered wood flooring

Table 10-4 shows the impacts generated for a cubic meter of flooring. **Table 10-5** shows the impacts generated on a square meter basis. **Table 10-6** shows the results per functional unit of

EWF. EWF lasted 40 years thus required a full replacement at 40 years. As shown in **Table 10-6**, most impacts for EWF were much higher than the impacts for SSHF shown in **Table 10-3** including GWP, ozone depletion acidification, eutrophication, respiratory effects and total energy. The one exception was smog and that was primarily because of refinishing. The SSHF wood floor was refinished three times versus twice for EWF in reference to the functional unit. Similar to SSHF, EWF showed that the greatest impact mostly occurred during the cradle-to-gate manufacturing process. The cumulated allocated total energy consumption was 570 MJ per functional unit (28,600 MJ per m^3) of floor with about 82% (467/570) of total energy use associated with the cradle-to-gate manufacturing process. Biomass contributed 20% (398 MJ/functional unit) towards the total energy use. The same as SSHF, the in-service use phase had a large impact on the LCIA because of refinishing the wood floor at 20 years. The high impacts mostly occurred due to uncontrolled releases of VOCs and operation of the electrical equipment used for sanding and wood dust collection. Disposing wood into landfill with methane capture equipment still resulted in methane emissions of 5.4 kg CO_2-e/functional unit for GWP thus has a substantial impact on overall GWP, about 16% (5.4/34.7).

Table 10-4: LCIA for one m³ of engineered wood flooring

Impact Category	Unit (per m³)	Cradle-to-gate	Product Transp.	Install.	Use (1x)	Disposal	Total
Global warming	kg CO_2 eq	1137	98	60	173	268	1736
Ozone depletion	kg CFC-11 eq	7.10E-05	3.66E-09	2.35E-06	2.12E-06	1.64E-10	7.55E-05
Smog	kg O_3 eq	110.7	15.7	3.6	60.9	1.3	192
Acidification	mole H+ eq	518	35	23	97	-47	625
Eutrophication	kg N eq	6.08E-01	3.19E-02	2.36E-02	1.13E-01	-3.26E-03	7.74E-01
Resp. effects	kg PM10 eq	0.000	0.000	0.000	0.000	0.000	0.000
Total Energy	MJ	23400	1290	1110	2710	50	28600
Fossil Energy	MJ	15100	1250	972	2520	50	20000
Biomass Energy	MJ	5672	0	0	0	0	5680

Table 10-5: LCIA for one m² of engineered wood flooring

Impact Category	Unit (per m²)	Cradle-to-gate	Product Transp.	Install.	Use (1x)	Disposal	Total
Global warming	kg CO_2 eq	11.4	0.98	0.60	1.7	2.7	17.4
Ozone depletion	kg CFC-11 eq	7.10E-07	3.66E-11	2.35E-08	2.12E-08	1.64E-12	7.55E-07
Smog	kg O_3 eq	1.11	0.16	0.04	0.61	0.01	1.92
Acidification	mole H+ eq	5.18	0.35	0.23	0.97	-0.47	6.25
Eutrophication	kg N eq	6.08E-03	3.19E-04	2.36E-04	1.13E-03	-3.26E-05	7.74E-03
Resp. effects	kg PM10 eq	8.36E-07	1.26E-08	2.28E-09	2.17E-08	-4.26E-09	8.68E-07
Total Energy	MJ	234	13	11	27	0.5	285
Fossil Energy	MJ	151	12.5	9.7	25	0.5	199
Biomass Energy	MJ	56.7	0	0	0	0	57

Table 10-6: LCIA per functional unit of engineered wood flooring

Impact Category	Unit (per FU[a])	Cradle-to-gate (2x)	Product Transp. (2x)	Install. (2x)	Use (2x)	Disposal (2x)	Total
Global warming	kg CO_2 eq	22.7	2.0	1.2	3.5	5.4	34.7
Ozone depletion	kg CFC-11 eq	1.42E-06	7.31E-11	4.69E-08	4.24E-08	3.28E-12	1.51E-06
Smog	kg O_3 eq	2.21	0.31	0.07	1.22	0.03	3.85
Acidification	mole H+ eq	10.35	0.70	0.46	1.93	-0.95	12.50
Eutrophication	kg N eq	1.22E-02	6.37E-04	4.72E-04	2.27E-03	-6.51E-05	1.55E-02
Resp. effects	kg PM10 eq	1.67E-06	2.52E-08	4.56E-09	4.35E-08	-8.53E-09	1.74E-06
Total Energy	MJ	467	26	22	54	1	570
Fossil Energy	MJ	302	25	19	50	1	398
Biomass Energy	MJ	113	0	0	0	0	113

[a] FU=functional unit

10.3 Overall LCIA

Figure 10-1 compares the six impact categories plus the cumulative energy consumption for the two wood flooring products evaluated in the report on a percentage basis per functional unit. As noted earlier, nearly all impacts for SSHF were considerably less than EWF except for smog and biomass energy. For example, ozone depletion for SSHF was about 30% of the value for EWF. For eutrophication impacts, EWF outweighed SSHF because of the glue and gluing process during the panel-making process in the EWF plant. Biogenic CO_2 has a characterization factor of zero for calculating GWP (Bare 2011).

Figure 10-1: LCIA per functional unit of the two wood flooring products by percentage

Table 10-7 shows the percentage values for the six impact categories plus cumulative energy per functional unit of flooring. **Table 10-8** shows the numerical values for the six impact categories plus cumulative energy generated per functional unit of flooring.

Table 10-7: LCIA per functional unit of the two flooring products by percentage

Impact category	Solid strip hardwood	Engineered wood
Global warming	60%	100%
Ozone depletion	30%	100%
Smog	83%	100%
Acidification	51%	100%
Eutrophication	57%	100%
Respiratory effects	30%	100%
Total energy	56%	100%
Fossil energy	51%	100%
Biomass energy	81%	100%

Table 10-8: LCIA per functional unit of the two flooring products by value

Impact Category	Unit (per functional unit)	Solid strip hardwood	Engineered wood
Global warming	kg CO_2 eq	20.9	34.7
Ozone depletion	kg CFC-11 eq	4.47E-07	1.51E-06
Smog	kg O_3 eq	3.2	3.8
Acidification	mole H+ eq	6.4	12.5
Eutrophication	kg N eq	8.76E-03	1.55E-02
Respiratory effects	kg PM10 eq	5.28E-07	1.74E-06
Total energy	MJ	321	570
Fossil energy	MJ	205	398
Biomass energy	MJ	91	113

Table 10-9 and **Table 10-10** show the major gases including the GHGs emitted per functional unit of SSHF and EWF, respectively used in calculating the GWP. Biogenic CO_2 is not included in the GWP calculation per standard LCA practice. Values for biogenic CO_2 are 21.8 and 16.4 kg/functional unit for SSHF and EWF, respectively. The values for biogenic CO_2 are provided as a precursor for the future development of a dynamic LCA that will utilize the GHGs listed.

Table 10-9: Major gases emitted over the life cycle of solid strip hardwood flooring

Air emissions	Units (kg per m^3)	Units (kg per m^2)	Units (kg per functional unit)
Biogenic CO_2	1088	21.8	21.8
Fossil CO_2	728	14.6	14.6
Methane	13.4	0.27	0.27
Nitrous oxide	1.48E-02	2.95E-04	2.95E-04

Table 10-10: Major gases emitted over the life cycle of engineered wood flooring

Air emissions	Units (kg per m^3)	Units (kg per m^2)	Units (kg per functional unit)
Biogenic CO_2	820	8.2	16.4
Fossil CO_2	1377	13.8	27.5
Methane	14.1	0.14	0.28
Nitrous oxide	1.81E-02	1.81E-04	3.62E-04

11 SENSITIVITY ANALYSIS - ALTERNATIVE TIME HORIZONS FOR GWP

For the baseline scenario for GWP, this study used the 100-year time horizon for the TRACI method. The 100-year time horizon is the preferred time horizon selected for calculating GWP (Forster et al. 2007). The time horizon was independent of the 80-year service life selected for the functional unit of flooring. To show the influence of time horizons on GWP, GWP values were calculated for the three typical time horizons using the IPCC 2007 values for 20 years (GWP_{20}), 100 years (GWP_{100}), and 500 years (GWP_{500}).

Table 11-1 shows the GWP values for the three time-horizons conducted for the IPCC 2007 values and for TRACI. At higher time horizons, the values of GWP decreased. Primarily, the GWP values decreased because of the long atmospheric lifetime of carbon dioxide compared to the other GHGs, methane and nitrous oxide. Approximately 20% of CO_2 remains in the atmosphere after 500 years from time of emission (Forster et al. 2007). The long lifetime of carbon dioxide continues to influence climate change long after methane (CH_4) and nitrous oxide (N_2O) have decayed away in the atmosphere. Methane and nitrous oxide have atmospheric lifetimes of 12 and 114 years, respectively (Forster et al. 2007). IPCC (2007) 100-year time-horizon and TRACI use the same characterization factors to determine GWP_{100} (Bare 2011).

Table 11-1: Global Warming Potentials for the two flooring products by various methods

GWP Method	Solid strip hardwood (kg CO_2-e)	Engineered wood (kg CO_2-e)
IPCC 2007 GWP_{20}	32.8	48.0
IPCC 2007 GWP_{100}	20.9	34.7
IPCC 2007 GWP_{500}	16.5	29.8
TRACI V4.0 GWP_{100}	20.9	34.7

12 SCENARIO ANALYSIS - BURNING WOOD INSTEAD OF LANDFILLING

As shown in the results of this LCA study, the effects at EOL were substantial for GWP because of the release of methane as wood decomposed in a landfill. EOL alternatives do exist such as burning the flooring at EOL to generate power. In this analysis, the power generated from burning the flooring avoided coal power production. Additionally, not only were the type of emissions changing, but the timing of the emissions changed because wood power production immediately released biogenic CO_2 into the atmosphere whereas in the landfill, wood took time to break down into biogenic CO_2 and methane. Results for LCIA were shown per functional unit and for air emissions shown per m^3.

Table 12-1 and **Table** 12-2 show the major GHGs and biogenic CO_2 emitted during the whole life cycle for SSHF and EWF, respectively. The results were expected for biogenic and fossil CO_2 because wood power avoided coal power production thus decreasing fossil CO_2 and increasing biogenic CO_2 emissions to the atmosphere. For SSHF and EWF, fossil CO_2 emissions at EOL were highly negative, -751 and -735 kg fossil CO_2/m^3 product whereas biogenic CO_2 rose to 644 and 630 kg biogenic CO_2/m^3 product, respectively. An unexpected carbon benefit of not burning coal was considerably less methane was released into the atmosphere. Some methane is released during coal production. The disposal method did not affect the cradle-to-gate manufacturing emissions as shown for example by comparing the fossil CO_2 emissions (1066 kg/m^3) from **Table 9-3** to the fossil CO_2 value in **Table 12-2**.

Table 12-1: Major gases emitted for solid strip hardwood flooring – Alternative Scenario

Air emissions (kg/m^3)	Cradle-to-gate	Product Transp.	Installation	Use	Disposal	Total
CO_2, biogenic	427	0	1	35	644	1107
CO_2, fossil	365	96	20	257	-751	-13
Methane	0.926	0.137	0.045	0.517	-1.389	0.2
Nitrous oxide	5.83E-03	2.04E-03	8.17E-05	7.08E-03	6.90E-03	2.19E-02

Table 12-2: Major gases emitted for engineered wood flooring – Alternative Scenario

Air emissions (kg/m3)	Cradle-to-gate	Product Transp.	Installation	Use	Disposal	Total
CO_2, biogenic	550	0	2	11	630	1194
CO_2, fossil	1066	94	56	82	-735	562
Methane	2.704	0.134	0.172	0.165	-1.360	1.8
Nitrous oxide	1.10E-02	2.00E-03	5.21E-04	2.25E-03	6.75E-03	2.26E-02

Table 12-3 shows the LCIA for a functional unit of SSHF. The GWP is 0.0 because the old wood flooring was burned for power instead of landfilled which avoided coal power production.

Burning coal emits fossil CO_2 where burning wood emits biogenic CO_2 that is not included in GWP per standard LCA practice. The negative GWP in the disposal stage came from the wood power displacing coal power.

Table 12-3: LCIA per functional unit of solid strip hardwood flooring

Impact Category	Unit (per FU[a])	Cradle-to-gate	Product Transp.	Install.	Use (3x)	Disposal	Total
Global warming	kg CO_2 eq	7.79	1.99	0.43	5.45	-15.67	0.0
Ozone depletion	kg CFC-11 eq	3.83E-07	8.19E-11	6.63E-10	6.65E-08	-2.91E-10	4.50E-07
Smog	kg O_3 eq	0.99	0.32	0.03	1.91	2.56	5.81
Acidification	mole H+ eq	3.55	0.71	0.19	3.04	-6.69	0.79
Eutrophication	kg N eq	4.70E-03	6.50E-04	6.78E-05	3.56E-03	-1.42E-03	7.57E-03
Resp. effects	kg PM10 eq	1.26E-02	8.90E-04	5.05E-04	4.84E-03	-1.91E-02	-2.68E-04
Total Energy	MJ	206	26	6	85	-211	113
Fossil Energy	MJ	97.9	25.6	4.7	79.1	-210.8	-3
Biomass Energy	MJ	91.3	0	0	0	0	91

[a] FU=functional unit

Table 12-4 shows the LCIA for a functional unit of EWF when burning wood at EOL. The results are similar to **Table 12-3** in that the disposal stage has a large negative GWP although not sufficient to result in a total GWP of zero like for SSHF.

Table 12-4: LCIA per functional unit of engineered wood flooring

Impact Category	Unit (per FU[a])	Cradle-to-gate (2x)	Product Trans. (2x)	Install. (2x)	Use (2x)	Disposal (2x)	Total
Global warming	kg CO_2 eq	22.7	2.0	1.2	1.7	-15.3	12.3
Ozone depletion	kg CFC-11 eq	1.42E-06	7.31E-11	4.69E-08	2.12E-08	-2.85E-10	1.49E-06
Smog	kg O_3 eq	2.21	0.31	0.07	0.61	2.50	5.72
Acidification	mole H+ eq	10.35	0.70	0.46	0.97	-6.55	5.92
Eutrophication	kg N eq	1.22E-02	6.37E-04	4.72E-04	1.13E-03	-1.39E-03	1.30E-02
Resp. effects	kg PM10 eq	3.97E-02	8.72E-04	1.26E-03	1.54E-03	-1.87E-02	2.47E-02
Total Energy	MJ	467	26	22	27.1	-206.4	336
Fossil Energy	MJ	302	25	19	25.2	-206.4	166
Biomass Energy	MJ	113	0	0	0	0	113

[a] FU=functional unit

Figure 12-1 compares the six impact categories plus the cumulative energy consumption for the two wood flooring products evaluated in the report on a percentage basis per functional unit. As noted earlier, nearly all impacts for SSHF were considerably less than EWF except for smog. For example, ozone depletion for SSHF was about 30% of the value for EWF.

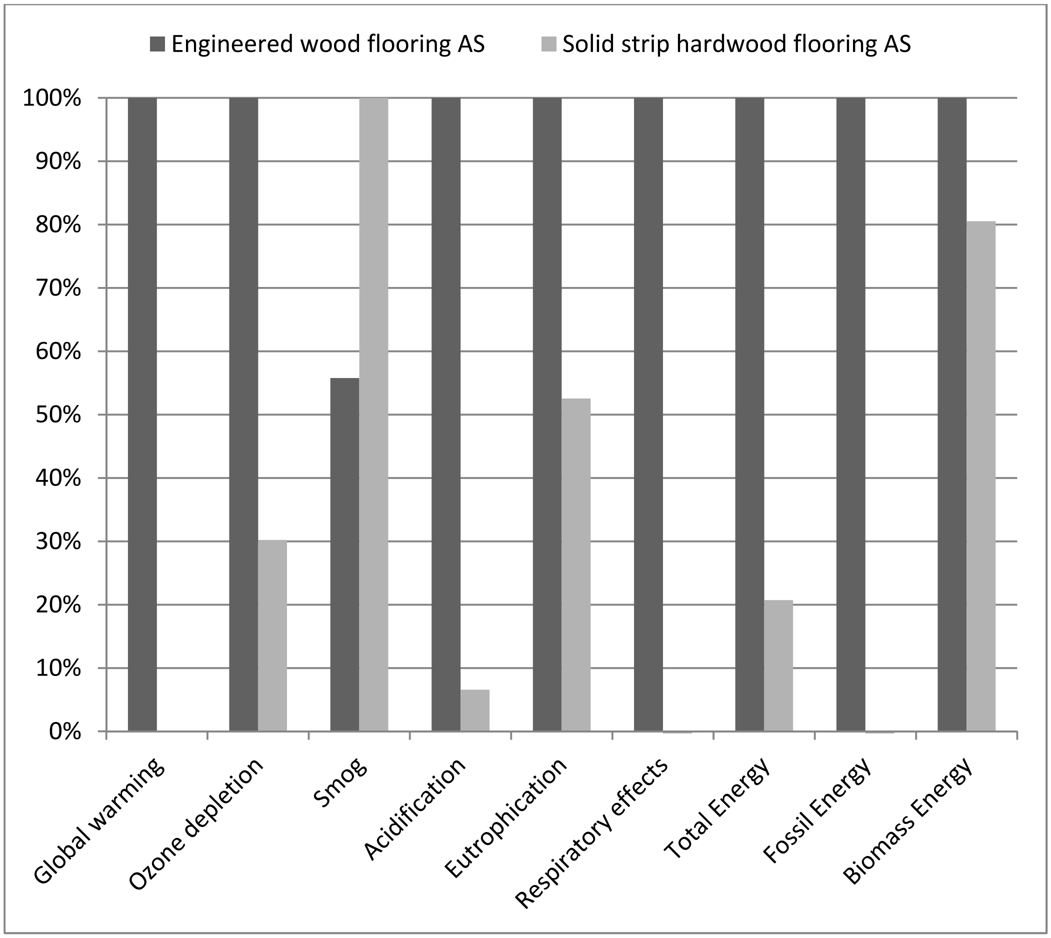

Figure 12-1: LCIA for the two flooring products by percentage

Table 12-5 shows the percentage values for the six impact categories plus cumulative energy per functional unit of flooring. **Table 10-8** lists the numerical values for the six impact categories plus cumulative energy generated per functional unit of flooring. Fossil energy and respiratory effects were dramatically lower because coal power production was avoided by burning the old flooring at EOL thus less particulate was emitted to the atmosphere. However, the tradeoff was that smog increased when burning wood for power.

Table 12-5: LCIA for the two flooring products by percentage per functional unit-Alternative Scenario

Impact category	Solid strip hardwood	Engineered wood
Global warming	0%	100%
Ozone depletion	30%	100%
Smog	100%	56%
Acidification	7%	100%
Eutrophication	53%	100%
Respiratory effects	-1%	100%
Total energy	21%	100%
Fossil energy	-1%	100%
Biomass energy	81%	100%

Table 12-6: LCIA for the two flooring products by value per functional unit-Alternative Scenario

Impact Category	Unit (per functional unit)	Solid strip hardwood	Engineered wood
Global warming	kg CO_2 eq	0.0	33.4
Ozone depletion	kg CFC-11 eq	4.50E-07	1.49E-06
Smog	kg O_3 eq	5.8	3.2
Acidification	mole H+ eq	0.8	12.0
Eutrophication	kg N eq	7.57E-03	1.44E-02
Respiratory effects	kg PM10 eq	-2.68E-04	4.18E-02
Total energy	MJ	113	544
Fossil energy	MJ	-3	373
Biomass energy	MJ	91	113

13 CONCLUSIONS AND RECOMMENDATIONS

Based on the LCA developed for the two flooring products, the following conclusions are made.

A static LCA was performed here; however, it does not fully consider the timing of GHG for long-lived products such as flooring. Large GHG emissions occur at EOL through either landfilling or burning the old wood. Changing the time horizon for GWP attempts but does not capture this effect. However, incorporating the timing of GHG emissions requires further study to show the effect GHG emissions are having on climate change.

Emissions of biogenic CO_2 are significant compared to the emissions of GHGs. However, standard LCA practice does not include biogenic CO_2 emissions in calculating GWP. However, in this study tracking biogenic CO_2 provides the option of using the emission data for later study.

Functional units matter when conducting flooring product LCAs. Flooring has different material thicknesses for the different flooring products. Therefore, a thinner product requires less material on a volume basis. In the present LCA study, EWF is 50% as thin as SSHF thus only 50% of EWF is necessary as SSHF is by volume on a square meter basis.

Service life of the product matters. Replacing products instead of refinishing products may most likely have greater environmental impact. In the present study, EWF lasts only half as long as SSHF thus a replacement of EWF at 40 years is necessary for an expected residential housing service life of 80 years. Installing EWF twice during a service life of a residential housing unit increases its environmental impact roughly by 90%. If product-refinishing technology could increase the service life of EWF from 40 to 60 years or even 80 years, a significant reduction in environmental impacts would occur. Therefore, from a design standpoint, durability in material choices is significant.

Refinishing of wood flooring results in large environmental impacts. Refinishing wood floors uses coatings with VOCs. VOCs are uncontrolled during refinishing unlike during prefinishing at the product production plant. Therefore, smog impacts are significant during the use phase for the two wood flooring products. Producing coatings with less VOCs would lower the smog impact.

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15 APPENDICES

APPENDIX A: Landfill Gas (LFG) Equations

Equation 1: Where GHGDE is GHGs directly emitted to atmosphere:

$$GHG_{DE} = (W_{kg})(C)(C_{CO_2})(D)(1 - LFGC)\left(^{44}/_{12}\right) + (Wkg)(C)(C_{CH_4})(D)(1 - LFGC)\left(CH_4\text{GWP} * {}^{16}/_{12}\right)$$

Equation 2: Where GHGLFGR is GHG emitted from LFG energy recovery:

$$GHG_{LFGR} = (W_{kg})(C)(D)(LFG_C)(LFG_R)\left(^{44}/_{12}\right)$$

Equation 3: Where GHGLFGF is GHG emitted from LFG flaring:

$$GHG_{LFGF} = (W_{kg})(C)(D)(LFG_C)(1 - LFG_R)\left(^{44}/_{12}\right)$$

Equation 4: EOLFGR is the energy offset by LFG recovery:

$$EO_{LFGR} = (LFG_{HHV})(W_{kg})(C)(D)(LFG_C)(LFG_R)[\left(^{44}/_{12}\right)(C_{CO_2}) + \left(^{16}/_{12}\right)(C_{CH_4})$$

Wkg: Wood Mass in kg

C: Carbon Content of Wood = 0.5

D: Decomposition of Wood in Landfill = 0.23 (Skog 2008)

CCO2: Carbon content of wood converted to CO2 = 0.55

CCH4: Carbon content of wood converted to CH4 = 0.45

CH4GWP: Global Warming Potential of CH4 = 25

LFGC: Landfill Gas Capture Efficiency = 75%

LFGR: Landfill Gas Energy Recovery Efficiency = 70%

LFGHHV: Landfill Gas Higher Heating Value = 15.8 MJ/kg

16 GLOSSARY

Characterization factors, factors from characterization models such as TRACI used to assign a value to the life-cycle inventory flows to produce the output of the impact category in a common unit such as the value of 25 for methane for the 100-year time horizon. For GWP_{100}, 25 is multiplied by the methane emitted (output) from the system to calculate the contribution of methane in kg CO_2-eq.

Cradle, the point the life cycle starts, usually at the point of extraction.

Cradle-to-gate, the point the life cycle starts, usually at the point of extraction (i.e. cradle) and ends at a specific gate. The gate may occur after primary production (i.e. hardwood lumber, polyvinyl chloride) or secondary production (i.e. solid strip hardwood flooring, plastic decking) of a product.

Functional unit, quantity of the studied product providing a reference unit to compared alternative products capable of performing the same task for a pre-determined service life. Functional units (a reference unit) for building products are typically measured in physical units such as volume, area, or mass of the product.

Gate, the point in the life cycle where raw materials enter a facility and at the point the final product leaves the facility. Product production, processing or service occurs in the facility. In addition, the first product may be an input to a second facility where further processing occurs and would also be referred as the gate. For example, kiln-dried hardwood lumber (the primary product) is an input to produce prefinished solid strip hardwood flooring (the secondary product).

Gate-to-gate, a single life cycle without any upstream or downstream stages included.

Grave, when the life cycle ends (i.e. the final disposition).

Impact category, represents the class of environmental issues that have life-cycle inventory flows assigned to.

Life-cycle inventory (LCI), measures all the raw material and energy inputs and outputs to manufacture a particular product, process, or service on a per unit basis within carefully defined system boundaries (i.e. a detailed mass and energy balance).

Life-cycle impact assessment (LCIA), the phase that estimates the potential environmental impact (i.e. damage) for individual impact categories from the life-cycle inventory flows

Life-cycle assessment (LCA), a scientific methodology used to evaluate a product or suite of products for their environmental performance. LCA provides the environmental outcomes for a particular product, process, or service per functional unit over the whole life cycle (i.e. cradle-to-grave)

Primary data, all data collected e.g. from a production facility, measured e.g. from a water effluent test or created from activity data e.g. electrical generation, within delineated system boundaries particular to the studied product, process, or service.

Primary energy, energy found with naturally occurring substances that have not been processed in any form such as coal ore, uranium ore, trees, and crude oil.

Paper 4: Dynamic life-cycle assessment of solid strip hardwood flooring and engineered wood flooring in the United States

Paper #4 covers dissertation pages 187-251.

Dynamic Life-Cycle Assessments of Solid Strip Hardwood Flooring and Engineered Wood Flooring in the United States

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EXECUTIVE SUMMARY

Study Goals

The goal of the present study was to develop a new methodology to incorporate timing of emissions of greenhouse gases (GHGs) from the whole life cycle of building products using wood flooring as an example. The question answered was how evaluating building products that emit GHG emissions at various times affected its climate change impact compared to the traditional metric of global warming potential (GWP).

Methodology

The new methodology demonstrated the time-dependent climate change impact using the concept of cumulative radiative forcing. The new approach refer to as the time-zero equivalent (TIZE) used the same reporting metric as global warming potential (GWP), kg CO_2-eq. Similar to the concept of net present value, TIZE generates a single value where future negative and positive impacts are brought back to year zero. TIZE values for carbon dioxide, methane, and nitrous oxide were found for two flooring products, prefinished solid strip hardwood (SSHF) and prefinished engineered wood flooring (EWF). Results were reported in kg CO_2-eq per functional unit of wood flooring.

Key Findings

The following table lists the $TIZE_{100}$ and GWP_{100} values for a functional unit of flooring. For both SSHF and EWF, the $TIZE_{100}$ values are lower than the GWP_{100} values. Methane contribution to $TIZE_{100}$ for SSHF on a percentage basis had the greatest reduction (60.3%) with respect to GWP_{100}. Removal and landfilling of the SSHF did not occur until after 80 years thereby dramatically reducing the time for the old wood to decompose in the landfill and emit methane. Landfilled EWF released most of its methane from its first life and some from the second life thus only had a 12.7% reduction. The total $TIZE_{100}$ values were about 25% and 17% less than the GWP_{100} values. SSHF had the greatest reduction for $TIZE_{100}$ mainly because its longer service life delayed landfilling.

Table 1: Time-zero equivalent and GWP values for a functional unit of flooring[a]

	Solid strip hardwood			Engineered wood		
	$TIZE_{100}$	GWP_{100}	Percent change	$TIZE_{100}$	GWP_{100}	Percent change
Greenhouse gas	(kg CO_2-eq)		(%)	(kg CO_2-eq)		(%)
Fossil carbon dioxide	13.0	14.5	-10.3%	22.6	27.5	-17.8%
Methane	2.5	6.3	-60.3%	6.2	7.1	-12.7%
Nitrous oxide	0.075	0.088	-14.8%	0.075	0.092	-18.5%
Total	15.6	20.9	-25.4%	28.9	34.7	-16.8%

[a] 100 year time horizon

Conclusions

Incorporating timing of GHG emissions by using the TIZE (dynamic) methodology provides a more precise estimation of GHG impacts on climate change over a given time-period than the static LCA approach does. Static LCAs aggregate individual emissions to measure LCIA thus potentially overestimating certain impacts such as for climate change. Time-dependent metrics show results closer to what the Earth and its atmosphere are experiencing over a given time-period.

TIZE offers a more accurate climate change metric than GWP by including the impacts from timing of GHG emissions while maintaining its simplicity. Researchers and policy-makers are familiar with using kg CO_2-eq. The TIZE methodology uses kg CO_2-eq thus would be easier to accept changing from GWP to TIZE.

Long-lived building products ought to consider using TIZE instead of GWP when reporting climate change impacts for environmental product declarations (EPDs). EPDs are LCA-based eco-labels for products similar to nutritional labels on food.

Table of Contents

Table of Figures

Table of Tables

1 INTRODUCTION

The sun keeps the Earth warm and habitable along with the Earth's atmosphere. The atmosphere made up of five major layers weighs about $5x10^{18}$ kg, 80% contained within the first layer, the troposphere. Animal and plant life are found within the troposphere only. The atmosphere is primarily composed of nitrogen and oxygen with many others gases comprising the remainder including carbon dioxide, methane, argon and water vapor. Everything on Earth has the ability to absorb and emit heat (i.e. infrared radiation). However, some gases called greenhouse gases (GHGs) have an especially unique ability to trap infrared radiation emitting from the Earth's surface. The ability to trap the outgoing infrared radiation by these GHGs is a natural process and thus keeps the Earth warm and habitable (Schneider 1989; Rodhe 1990; Bazzaz 1990; IPCC 1990; IPCC 1996; Joos et al. 2001; Oreskes 2004; IPCC 2007).

The natural process of trapping heat by GHGs is referred to as the "greenhouse effect". Without the greenhouse effect provided by the GHGs, the Earth would not be habitable. Many natural activities including rotting vegetation and erupting volcanoes emit a major GHG, carbon dioxide. However, in the last 200 years or so, human activity has increased the amount (i.e. atmospheric concentrations) of GHGs in the atmosphere. As a result, the Earth's atmosphere (troposphere) traps increasing amounts of infrared radiation reflecting it back to the Earth's surface resulting in a warming effect. The warming effect by GHGs is primarily responsible for what has been termed "climate change" (Schneider 1989; Rodhe 1990; Bazaz 1990; IPCC 1990; IPCC 1996; Joos et al. 2001; Oreskes 2004; IPCC 2007).

Human activity has generated additional GHG emissions to the atmosphere affecting the climate (Oreskes 2004). In the present study, climate change refers mainly to the influence of human activity has on the greenhouse effect. Additional impacts to climate change results from the increase of the well-mixed and long-lived greenhouse gas (LLGHG) emissions to the Earth's atmosphere (Forster et al. 2007). LLGHGs are present in the atmosphere for a decade or longer and thus become well-mixed in the Earth's atmosphere. Major GHGs include water vapor (H_2O), halogenated compounds, carbon dioxide (CO_2), methane (CH_4), ozone, and nitrous oxide (N_2O) (Ramaswamy et al. 2001; Forster et al. 2007).

Carbon dioxide has become the primary concern for climate change because of its increasing atmospheric concentrations and that human activity has a huge direct influence on its atmospheric levels (Joos et al. 2001, Fuglestvedt et al 2003; NOAA 2011). Human activities emitting CO_2 include burning fossils fuels, gas flaring, and cement production. (Forster et al. 2007). Pre-industrial level of CO_2 (year 1750) was 278 ppm with current concentration of 394 ppm with a current annual growth rate of about 2 ppm (NOAA 2011; NOAA 2012; Blasing 2012). The current CO_2 annual growth rate is increasing (Forster 2007; NOAA 2011). As previously mentioned, increasing atmospheric concentrations of GHGs such as CO_2 contribute to warming the Earth's surface by absorbing additional infrared radiation (i.e. heat) and reflecting it back to the Earth's surface (i.e. climate change) (IPCC 2007).

1.1 Global warming potential

Burning fossil fuels and cement production that emit huge quantities of CO_2 into the environment primarily drive climate change (Forster et al. 2007). The effects of GHG emissions on change are typically measured through a metric referred to as global warming potential (GWP) (IPCC 2007). GWP is one of several impact categories that help determine environmental impacts for a product, process, or service (ISO 2006a; 2006b). GWPs are noted by the selected time horizons of 20, 100, and 500 years with the 100-year time horizon used by the United Nation Framework Convention for Climate Change (i.e. UNFCCC) for the Kyoto Protocol (Shine et al. 2005; IPCC 2007; Brandão and Levasseur 2011). The various time horizons take into consideration the lifetime of the individual GHGs.

1.1.1 IPCC 1996 equation

The value of GWP lists the climate change affects for the individual GHGs in kilograms of carbon dioxide equivalents (i.e. kg CO_2-eq). GWP is a measure that measures the amount of heat that a GHG traps in the atmosphere (IPCC 1996). CO_2 is used as the reference gas in determining the GWP thus has a GWP value of one regardless of the given time horizon. The following equation shows how GWP is calculated (Ramaswamy et al. 2001; Forster et al. 2007).

$$GWP = \frac{\int_0^{TH} RF_i(t)dt}{\int_0^{TH} RF_r(t)dt} = \frac{\int_0^{TH} \sigma_i C_i(t)dt}{\int_0^{TH} \sigma_r C_r(t)dt} \qquad (1)$$

Where TH is the selected time horizons; RF_i is the mean global radiative forcing of the GHG (time-dependent); σ_i is the radiative efficiency in the atmosphere for a GHG (concentration-dependent); C_i (t) is the current concentration of the GHG emitted to the atmosphere at time zero (time-dependent); $C_i(0) = C_O$; *i* is the emitted GHG; *r* is the reference gas (i.e. CO_2).

1.1.2 Aggregated global warming potential

The numerator and denominator of Eqns (1) and (2) are referred to as the Aggregated Global Warming Potential (AGWP) and have units of W-year/m^2/kg GHG) (Boucher et al 2009; Ramaswamy et al. 2001; Forster et al. 2007). AGWP for a GHG is the integration of radiative forcing (RF) for a given time horizon from a pulse emission under current atmospheric concentration of 1 kg of the gas (Boucher et al. 2009). As noted previously, because CO_2 is the reference gas, its GWP is one. AGWP is also referred to as the cumulative radiation forcing (CRF) for a GHG pulse emission (Cherubini et al. 2011).

$$GWP = \frac{AGWP_i}{AGWP_r} \qquad (2)$$

1.2 Decay curves

1.2.1 Carbon dioxide

For $C_i(t)$ in this study, a pulse emission of CO_2 is described by the updated Bern carbon cycle-change (CC) model (Joos et al. 2001). The decay curve for CO_2 is more complex than the other two GHGs examined in this study, CH_4 and N_2O. Eqn (3) shows the decaying of a pulse emission of CO_2 into the atmosphere using the updated Bern CC model with a background concentration of 378 ppm (Forster et a. 2007; Levasseur et al. 2010; Cherubini et al 2011; NOAA 2012; Joos et al. 2001). **Figure 1-1** shows the decay curve of the CO_2 unit emission pulse into the atmosphere at time zero. Carbon dioxide is removed from the atmosphere by the ocean, plants and carbonate formation.

$$C(t) = a_O + \sum_{i=1}^{3} a_i e^{\frac{-t}{\tau_i}} \quad (3)$$

Where $a_O = 0.217$; $a_1 = 0.259$; $a_2 = 0.338$, $a_3 = 0.186$; $\tau_1 = 172.9$ years; $\tau_2 = 18.51$ years, $\tau_3 = 1.186$ years.

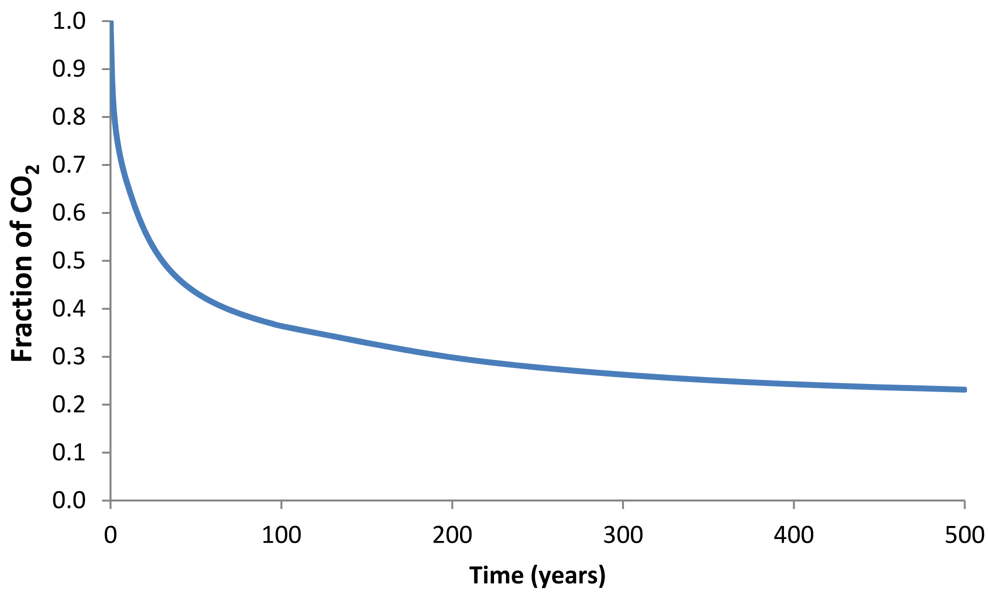

Figure 1-1: Atmospheric decay of an emission pulse of CO_2

1.2.2 Methane and nitrous oxide

The following first order decay equations illustrate the decay rate of a pulse emission into the atmosphere for the two other GHGs studied, CH_4 and N_2O. Eqn (4) is the first order decay equation with the decay constant (k) whereas Eqn (5) shows the substitution of the expected atmospheric lifetime (τ) which is the inverse of k. Eq (5) illustrates the decay rate for methane and nitrous oxide.

$$C(t) = C_O e^{-kt} \quad (4)$$

$$C(t) = C_O\, e^{\frac{-t}{\tau}} \quad (5)$$

Where: τ is the atmospheric lifetime of the GHG (τ is 12 years for CH_4 and 114 years for N_2O) (Forster et al. 2007); $\tau = 1/k$ where k is the decay constant; C_O is the unit pulse.

1.2.3 Individual decay rates

Figure 1-2 shows the individual decay rates for CO_2 (solid), CH_4 (dotted), and N_2O (dashed) for a unit pulse emission into the atmosphere at time zero. Methane is a LLGHG. However, methane decays much faster in the atmosphere than CO_2 and N_2O. Methane decays faster primarily because of its reaction with the free radical (OH) in the atmosphere (Forster et al. 2007). As a result, regardless of its radiative efficiency; the climate change impacts for methane are relatively short-lived compared to CO_2 and N_2O. Because of methane's relatively high decay rate compared to carbon dioxide, the amount of cumulative radiative forcing thus GWP for methane decreases as the given time horizons increase (Ramaswamy et al. 2001; Forster et al. 2007). **Table** 1-1 shows the GWP characterization factors for CO_2, CH_4 and N_2O. Methane decreases from 72 for the 20-year time horizon to 7.6 for the 500-year time horizon (Forster et al. 2007).

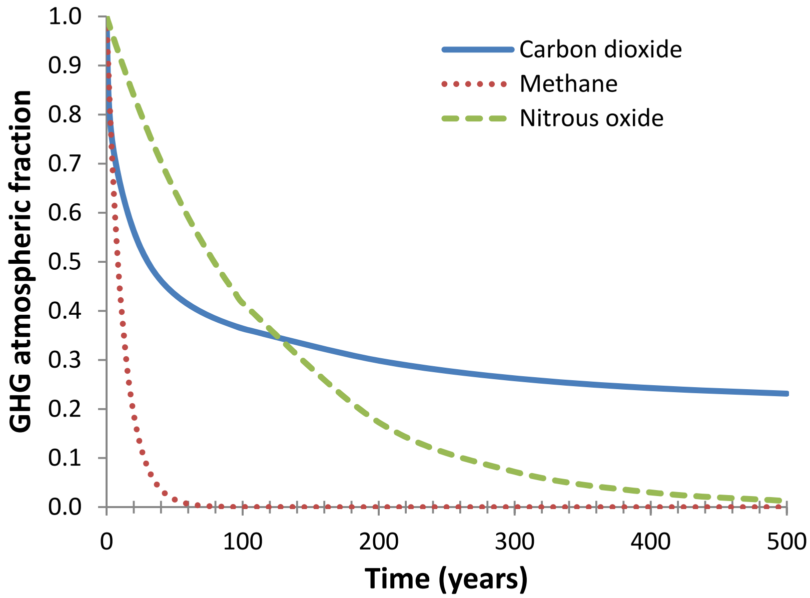

Figure 1-2: Decay rate of a pulse emission for CO_2, CH_4, and N_2O

Table 1-1: GWP characterization factors for CO_2, CH_4, and N_2O by time-horizons

	GWP characterization factors		
Greenhouse gas	20-year	100-year	500-year
Carbon dioxide	1	1	1
Methane	72	25	7.6
Nitrous oxide	289	298	153

1.2.4 Interaction of GHGs with the atmosphere

Methane GWP characterization factor incorporates the indirect effects of methane emissions related to the concentrations of stratospheric water vapor (15%) and ozone (25%) as well as direct effects (Forster et al. 2007; Boucher et al. 2009). Additionally, methane decays much faster in the atmosphere than nitrous oxide as indicated by nitrous oxide's higher atmospheric lifetime (τ). Nitrous oxide in the atmosphere primarily breaks down from sunlight. Atmospheric lifetimes represent the time for the atmosphere to regain equilibrium after a decrease or increase in GHG. Unlike the other two LLGHGs, CO_2 does not have a set atmospheric lifetime as its removal from the atmosphere involves a range of processes that can span thousands of years (Forster et al. 2007). Carbon dioxide initially decays faster than nitrous oxide but its decay rate after 50 to 100 years begins to slow dramatically (**Figure 1-2**). After 500 years, over 20% of the emission pulse of CO_2 remains in the atmosphere whereas CH_4 and N_2O both approach zero.

1.3 Radiative forcing

Radiative forcing (RF) is the measure of the effect of a climatic factor has in changing the balance of incoming and outgoing energy in the Earth's atmosphere (expressed in W/m^2). Positive forcing tends to warm the Earth's surface whereas negative forcing tends to cool the Earth's surface (Forster et al. 2007). Increasing GHG atmospheric concentrations results in positive forcing thus warm the Earth's surface (Forster et al. 2007; Schwietzke et al. 2011). Negative forcing which cools the Earth's surface primarily derives from direct and cloud albedo effect of aerosols (Forster et al. 2007). Climatic factors not only include GHG emissions and aerosols but other factors such as black carbon and ozone. GHGs have certain qualities that promote the greenhouse effect such as radiative efficiency. Radiative efficiency means the infrared-absorbing ability of a GHG in the atmospheric, expressed in $W/m^2/ppb$ (Forster et al. 2007).

1.3.1 Radiative efficiencies

Eqn (6) calculates the radiative efficiency for CO_2 through pulsing one ppm of CO_2 given the current CO_2 atmospheric concentration. Assuming 378 ppm as background CO_2 concentration from the updated Bern CC model (Bern 2.5CC), the radiative efficiency (α) for CO_2 is 1.41×10^{-3} W/m^2/ppm (Joos et al. 2001; Forster et al. 2007). For CH_4, and N_2O, radiative efficiencies are 3.07×10^{-4} and 3.03×10^{-3} W/m^2/ppb, respectively (Forster et al. 2007; Montzka et al. 2003; Velders et al. 2005). The radiative efficiencies for CH_4 and N_2O are listed in ppb versus ppm for CO_2 and thus the radiative forcing effects of a same-size pulse are larger than for CO_2.

$$\alpha_i = 5.35 \ln\left(\frac{[CO_2^*]}{[CO_2]}\right) \qquad (6)$$

1.3.2 Instantaneous radiative forcing curves

Figure 1-3 shows the instantaneous radiative forcing (IRF) from a kg pulse emission. The IRFs from either a nitrous oxide (dashed) or methane (dotted) pulse far outweighs the IRF from carbon dioxide (solid), particularly nitrous oxide. The initial large effect is from the large radiative efficiency values for both CH_4 and N_2O. However, the declining IRF curves for the two GHGs occur at a faster rate because CO_2 remains in the atmosphere for a longer period especially when compared to methane (Forster et al. 2007; Sathre and Gustavsson 2011). **Figure 1-4** provides for a clearer graphical representation by multiplying the IRF values for CO_2 by a factor of 100 and methane by a factor of two. The high initial IRFs for methane and nitrous oxide correspond to the results shown in **Table 1-1** for the GWP characterization factors of the 20-year, 100-year, and 500-year time horizons.

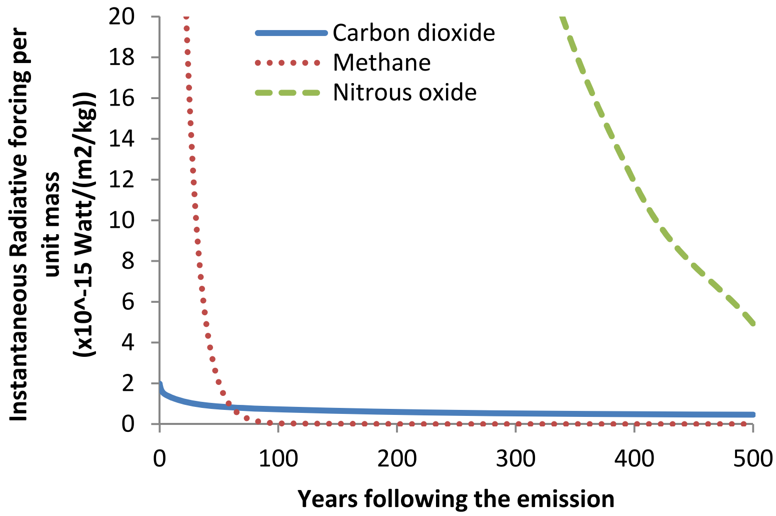

Figure 1-3 Radiative forcing curve for CO_2, CH_4, and N_2O from a pulse emission (as is)

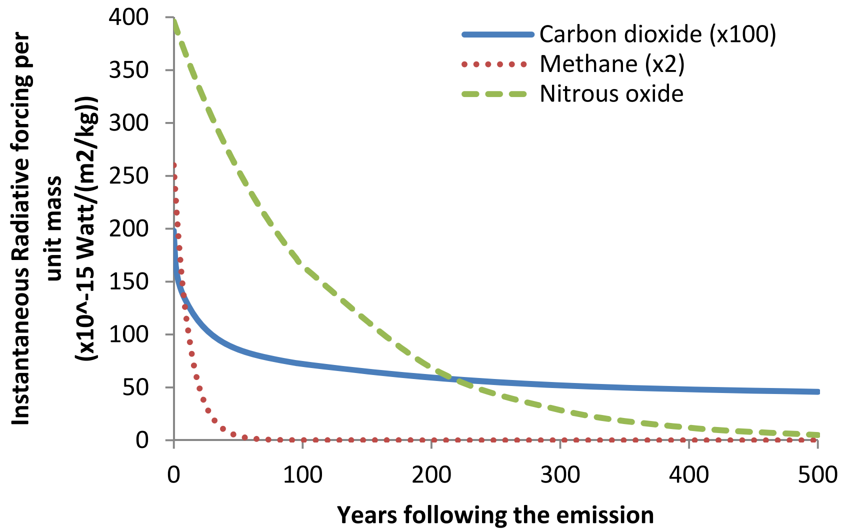

Figure 1-4: Radiative forcing curve for CO_2, CH_4, and N_2O from a pulse emission (adjusted for viewing)

GWP uses the concept of radiative forcing (RF) to measure and rank the climate change impact for a particular GHG (Ramaswamy et al. 2001; Forster et al. 2007). RF captures the climate effect over a given time horizon. Because of different radiative properties and atmospheric lifetimes, GHGs vary in their warming influence (positive radiative forcing) on the Earth. These warming influences may be estimated through a common metric based on the radiative forcing of CO_2 such as CO_2-equivalent emission (i.e. GWP) or CO_2-equivalent concentration. The usability of GWP depends on the estimates of atmospheric lifetimes for the GHGs and the strength of RF concept (Fuglestvedt et al. 2003). However, uncertainty exists in the atmospheric lifetimes and most likely; the current GWP characteristic factors will change with new information on determining lifetimes as well as from the changing atmosphere (Fuglestvedt et al. 2003; Boucher et al. 2009).

1.4 Change in radiative forcing since 1750 for the major GHGs

The Third Assessment Report from the International Panel on Climate Change provides the equations and background on the development of the change in RF (ΔRF) from the year 1750 for a given GHG (IPPC 2001). The ΔRF values describe the change in impacts to climate that climatic factors including GHG emissions have on the Earth whether positive or negative since 1750, the base year. Values derived for ΔRF indicates the importance of studying the following three GHGs, CO_2, CH_4, and N_2O.

1.4.1 Measuring the change in radiative forcing since 1750

The ΔRF values measured in W/m^2 are calculated on a global scale and for over a period of years (NOAA 2011; Forster et al. 2007). Major GHGs are well-mixed thus have a global affect versus other impacts than may have only local or regional effects (Forster et al. 2007). ΔRF from CO_2 conributed more than any other cause of climate change, about 64% of total ΔRF of 2.81 W/m^2 in 2010 (Forster 2007; NOAA 2011). Methane (0.504 W/m^2) and nitrous oxide (0.175 W/m^2) provide the second and third highest ΔRF, about 18% and 6% in 2010 (Boucher et al. 2009; Heimann 2011; Forster et al. 2007, NOAA 2011). Overall, these three LLGHGs make up over 75% of the positive ΔRF impact. The ΔRF equations for the primary GHGs, e.g. from producing building products, CO_2 (Eqn 7), CH_4 (Eqn 8), and N_2O (Eqn 9) are given below (Ramaswamy et al. 2001).

$$\Delta F_{CO_2} = 5.35 \ln(\frac{C}{C_O}) \quad (7)$$

$$\Delta F_{CH_4} = 0.036\,(M^{0.5} - M_O^{0.5}) - [f(M, N_O) - f(M_O, N_O)] \quad (8)$$

$$\Delta F_{N_2O} = 0.12\,(N^{0.5} - N_O^{0.5}) - [f(M_O, N) - f(M_O, N_O)] \quad (9)$$

Where: $f(M,N) = 0.47\ \ln(1 + 2.01x10^{-5}(MN)^{0.75} + 5.31x10^{-15}M(MN)^{1.52}$
C is the concentration of CO_2 in ppm, C_O = 278 ppm
M is the concentration of CH_4 in ppb, M_O = 700 ppb
N is the concentration of N_2O in ppb, N_O = 270 ppb

Solution examples:
ΔFCO_2 = 1.66 W/m^2 for 379 ppm (2005) Forster et al. (2007)
ΔFCO_2 = 1.81 W/m^2 for 390 ppm (2010) NOAA (2012)
ΔFCH_4 = 0.495 W/m^2 for 1774 ppb (2005) Forster et al. (2007)
ΔFCH_4 = 0.505 W/m^2 for 1800 ppb (2010) Heimann (2011)
ΔFN_2O = 0.162 W/m^2 for 319 ppb (2005) Forster et al. (2007)
ΔFN_2O = 0.175 W/m^2 for 323 ppb (2012) Blasing (2012)

1.5 Selection of GHGs to study

ΔRFs for the three GHGs, CO_2, CH_4 and N_2O continue to increase (Fraser et al. 2011; NOAA 2011). Human activity continues to generate huge amounts of the three GHGs and no indication exists of a slowdown in their production (Kort et al. 2012; Nema et al. 2012). Additionally, impacts to climate change from wood products primarily come from CO_2, N_2O and CH_4 (Puettmann and Wilson 2005; Puettmann et al. 2010; Bergman and Bowe 2011).

1.6 Converting from atmospheric to mass radiative efficiencies

Radiative efficiencies for the three LLGHGs can be found by atmospheric concentration (W/m^2/ppb) or by mass (W/m^2/kg). In the present study, radiative efficiencies by mass are necessary as the LCI flows list GHG emissions in mass. However, reports such as IPCC (2007) list radiative efficiencies by atmospheric concentration. Use Eqn (10) to convert radiative efficiency from atmospheric concentration to mass (Shine et al. 2005; Forster et al. 2007).

$$RE\ (kg)_i = RE\ (ppb)_i * \frac{MW_{AIR}}{MW_i * W_{ATM}} x10^9 \quad (10)$$

Where RE is radiative efficiency; i is the GHG gas; MW_{AIR} is the molecular weight of air, 28.96 kg/kmole; MW_i is the molecular weight of gas i in kg/kmole; W_{ATM} is the weight of Earth's atmosphere ($5.148x10^{18}$ kg)

1.7 Traditional

Life-cycle inventory (LCI) data are major components of a life-cycle assessment (LCA). LCA uses rigorous methodology to find the critical environmental impact for a particular product referred to as “cradle-to-grave” (raw material extraction to waste disposal) analysis. LCI measures all the raw material and energy inputs and outputs required to manufacture a particular product on a per unit basis within carefully defined system boundaries. LCI studies include extraction (forest resources), product manufacturing, product transportation, final product use/maintenance, and final disposal (**Figure 1-5**) (ISO 2006a; 2006b).

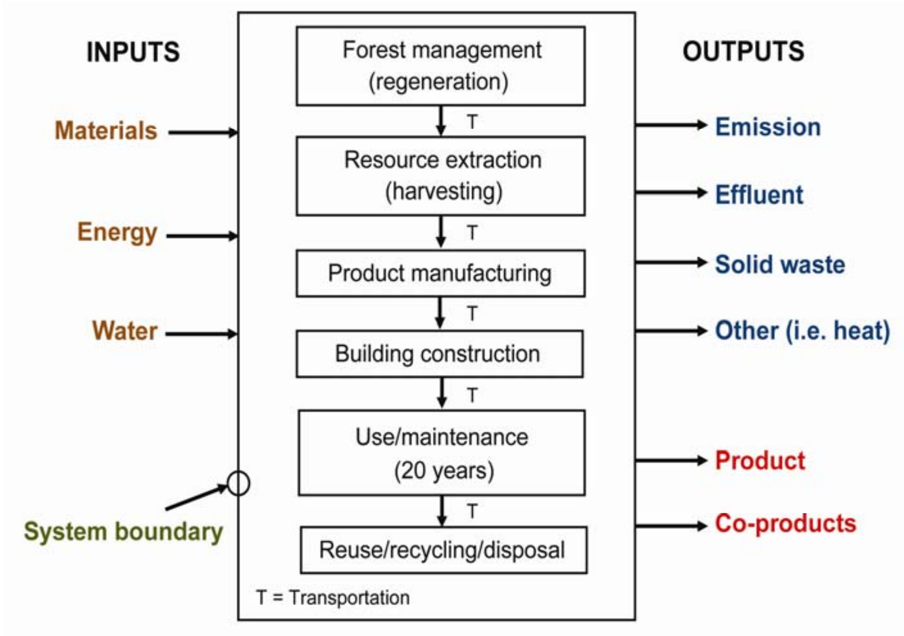

Figure 1-5: Complete life-cycle from regeneration of trees to disposal of wood materials

(Source: Based on Fava et al 1994)

1.7.1 Phases of life-cycle assessment

A LCA is comprised of four phases as defined by the ISO. These are 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (**Figure 1-6**). A LCA study includes all stages but a LCI study does not include stage 3, the impact assessment (SAIC 2006, ISO 2006a; 2006b). LCI flows include air and water emissions, primary energy products, raw material, and solid waste by quantities per functional unit. Air emission data particularly GHGs were the focus of the present study. Functional units are usually derivatives of a production unit for building products such as m^2 with stated thickness or m^3.

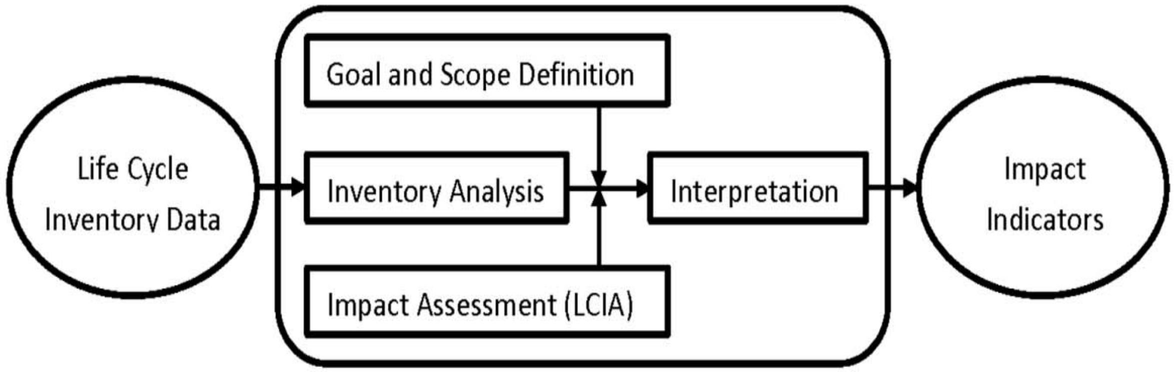

Figure 1-6: Life-cycle assessment phases

The full life-cycle study can provide information about the potential environmental impacts associated with a product or service, or the impacts implied by any product selection decision. It represents a holistic yardstick of environmental performance that helps us understand and avoid possible "burden shifting;" such as from the manufacturing to the use phase of the product's life-cycle, or resolving environmental problems while simultaneously creating economic or social problems. Communicating the results of life-cycle studies have become increasingly important.

1.7.2 Environmental product declarations (eco-labeling)

Life-cycle models in conjunction with environmental product declarations (EPDs) through product category rules can communicate a product's environmental performance in a transparent and credible way (ISO 2006c; 2007). EPDs for products are provided as a way to communicate LCA results in a standardized format, somewhat similar to nutritional labels on food. LCAs along with EPDs allow variety of decision-makers including government, environmental non-government organizations, academia, and industry to make sound scientific judgments on competing products (Bergman and Taylor 2011). EPDs provide a listing of the LCIA results including GWP in kg CO_2-eq per functional unit of product. GWP does not include the impacts from the timing of GHG emissions. Thus, the new methodology presented here included the timing of GHG emissions thus providing a more precise value on the impact to climate change.

1.7.3 Functional unit

Setting system boundaries selects the unit processes to include in the life-cycle study and standardizes material flows, energy use, and emission data to a production unit. The present study selected the functional unit of one m^2 of installed flooring material in service for 80 years. Product thickness depended on material selection. Service life varies between 40 years for engineered wood flooring (EWF) and 80 years for solid strip hardwood flooring (SSHF). Based on U.S. industry measures, 1 thousand board feet (bf) of wood flooring equals 2.36 m^3 (Bergman 2010). For 20-mm thick SSHF, one m^2 equals 0.02 m^3 (8.47 bf). For 10-mm thick EWF, one m^2 equals 0.01 m^3 (4.24 bf). Therefore, half the volume of EWF was needed per square meter of flooring compared to SSHF because of the differences in thickness. In the United States, flooring is usually sold by the square foot. The oven-dried mass of SSHF and EWF minus resins and coatings are 657 and 579 kg/m^3, respectively. EWF is about 10% resin (Bergman and Bowe 2011). **Table 1-2** shows reference flows and actual thicknesses for the two wood flooring products.

Table 1-2: Reference flow for the two wood flooring products

Flooring Material	Mass (OD kg/m^3)	Reference Flow (OD kg/m^2)	Conversion (m^2/m^3)	Functional Unit (OD kg/FU[d])	Thickness (mm)
SSHF, unfinished[a]	657	-	-	-	20
EWF, unfinished[b]	643	-	-	-	10
SSHF, prefinished[c]	670	12.8	50	12.8	20
EWF, prefinished[b]	656	6.56	100	13.12	10

[a] Hubbard and Bowe 2010 (SSHF: solid strip hardwood flooring) 20-mm thick
[b] Bergman and Bowe 2011 (EWF: engineered wood flooring) 10-mm thick
[c] Unfinished wood flooring weighs 98% of prefinished wood flooring (Bergman and Bowe 2011)
[d] FU=functional unit

1.7.4 Decomposing wood stored in landfill

Final disposition of old wood floorboards has a substantial influence on the environmental impacts including the climate depending on how the material is disposed of. In previous studies, wood flooring was simply disposed of and was assumed to be an inert material in a landfill without any additional burdens or burned for energy (Petersen and Solberg 2004; Nebel et al. 2006). Therefore, if considered inert, only transportation to the landfill and equipment used to process the waste wood was considered. In contrast, the present study assumed wood flooring disposed of in a landfill would decompose to a degree.

1.7.4.1 Information on decomposing wood

Research has estimated that a portion of discarded wood (about 23%) breaks down anaerobically when stored in a landfill with half-life of 29 years (Skog 2008). The wood decomposes into methane and carbon dioxide, on a 50:50 molar ratio. As the methane rises to the surface of the landfill, 10% of the methane oxidizes into CO_2. Therefore, the CH_4:CO_2 molar ratio at the surface is 45:55 (Salazar and Meil 2009). To calculate on a mass basis, use the following molecular weights of CO_2 (44g/mole) and CH_4 (16 g/mole).

In order to help mitigate climate change, it is desirable that methane, a much more potent GHG than CO_2, ought to be captured and burned. Additionally, energy may be recovered which is an additional benefit as the landfill gas captured and burned avoids the production of natural gas. **Table 1-3** shows the GHG emission profile for the baseline scenario, a landfill with energy recovery. Additionally, for EWF, approximately 10% of the final product is resin thus not available for decomposition.

Table 1-3: GHG emissions from wood landfilled with standard methane capture

GHG Emissions	kg GHG per OD kg wood	kg GHG per m^2 (Solid strip hardwood flooring, unfinished)	kg GHG per m^2 (Engineered wood flooring, unfinished[e])
Methane, biogenic[a]	0.0173	0.216	0.095
Carbon dioxide, biogenic[b]	0.058	0.726	0.320
Carbon dioxide, biogenic[c]	0.221	2.77	1.218
Carbon dioxide, biogenic[d]	0.0949	1.19	0.523

[a] Released directly into air
[b] Released directly into air
[c] Released after energy recovery (70%)
[d] Release after flaring (30%) – energy not recovered
[e] Engineered wood flooring is about 90% wood/10% resin

1.7.4.2 Capturing methane from landfill

Landfill gas (LFG) contains methane, the primary component of natural gas. Therefore, the present study assumed that LFG capture for energy production offset natural gas production based on energy content per volume. The amount of avoided natural gas production due to the capture of LFG was estimated to be 0.052 kg (0.0784 m^3) of natural gas production per OD kg of wood decomposing in the landfill, assuming a 75% capture rate of 0.1045 m^3 per OD kg at landfill surface. The remaining 25% of methane (0.0173 kg/OD kg wood) was emitted to the atmosphere. Therefore, for one m^2 of unfinished SSHF (12.5 OD kg) sent to a landfill with methane capture, 0.980 m^3 of natural gas production was avoided. For one m^2 of unfinished EWF, 0.432 m^3 natural gas production was avoided, assuming that 10% of the EWF (i.e. resin) stayed inert.

1.7.5 Static LCA

Standard (i.e. static) LCA practice evaluates the aggregation of individual emissions regardless of when or how much of the emissions occur at a certain time (ISO 2006a; ISO 2006b). The metric used to quantify the impact to climate change in GWP. For some LCA, the static approach would provide an accurate environmental performance of the product, process, or service. However, several studies examining the effect of climate change impacts on biofuels have shown various differences because some air emissions including GHGs occur late in the process (Levasseur et al. 2010; Schwietzke et al. 2011; Cherubini et al. 2011). GHG emissions emitted late will cause a lower CRF than earlier emissions of the same type and quantity (Schwietzke et al. 2011). The lower CRF occurs because the impact from the GHG emission will only be measured from the initial time of the pulse until the end of the given time horizon. Therefore, long-lived products may have a different climate change impact if the timing of GHG emissions is included. Building products such as flooring are long-live products because their service life extends up to several decades from the time of product production and installation (Werner et al. 2010; Eriksson et al. 2011; Lippke et al. 2011). Thus, any delay in the release of carbon stored in building products may result in less warming potential (Brandão and Levasseur 2011).

GWP has a time-dimension components because the CRF is estimated over a given time horizon. The three most common time horizons with the 100-year time horizon being the preferred one are used when calculating GWP (Shine et al. 2005; Forster et al. 2007). Other time horizons can be used as the the 20-, 100- and the 500-year time horizons for GWP are artificial constructs. **Figure 1-7** shows the inconsistent time boundary when using GWP for a given time-horizon, 100 years in this example. The IRF value for the second pulse (dotted) emitted at 25 years last until year 125, 25 years pass the selected time horizon. Therefore, in this example, the GWP value overestimates the impacts to climate change because the effect from timing of the CO_2 pulse at 25 years was not included in the climate change metric, GWP.

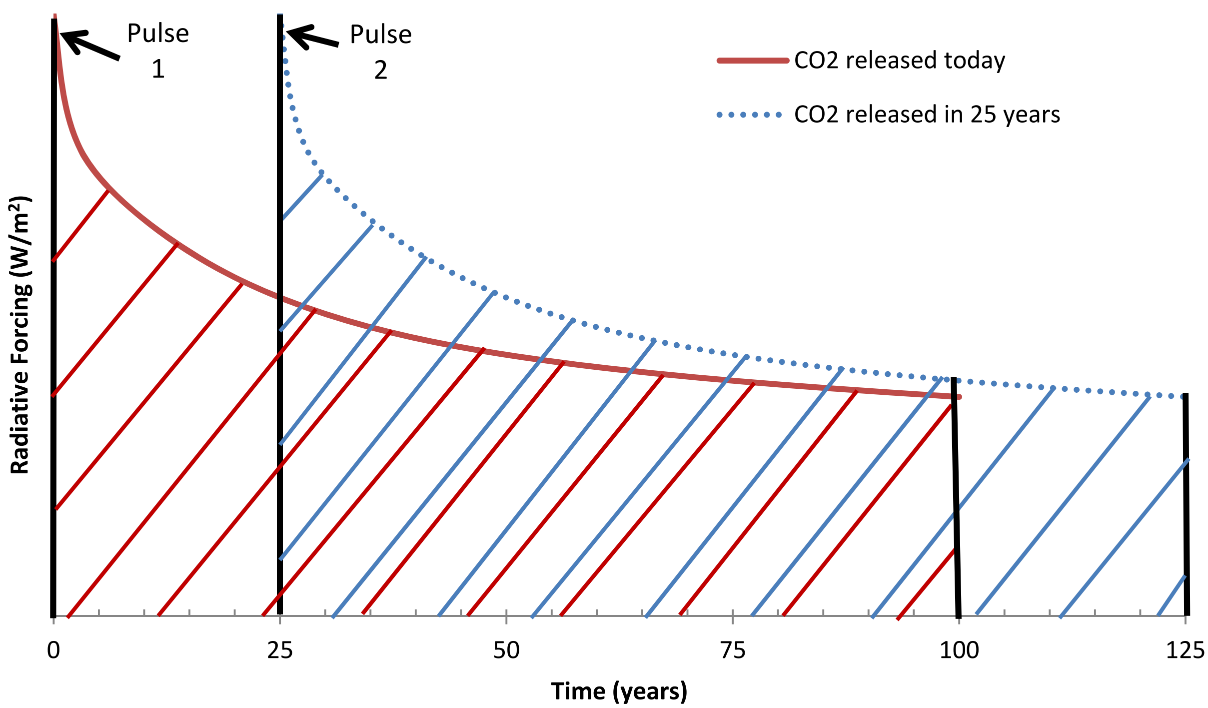

Figure 1-7: Instantaneous radiative forcing curves for CO_2 when calculating GWP

As shown by **Figure 1-7**, GHG emissions that occur past the given time horizon are included thus violating the time boundary for the given time horizons. Furthermore, most traditional LCAs consider all the methane emitted to the atmosphere from decomposing wood when evaluating the impacts to climate change (i.e. GWP). A problem arises because some methane emissions occur pass the 100-year time horizon. Therefore, the underlying premise for traditional LCA is that the wood decomposes immediately by 23% emitting methane and biogenic CO_2.

1.8 Dynamic LCA

Dynamic LCA evaluates the timing of LCI flows such as GHG emissions to categorize the impacts more accurately. Of particular interest is timing of GHG emissions and their influence on climate change. GWP is the standard index that measures the warming potential caused by the increase in atmospheric GHG concentrations, which affects the energy balance of the atmosphere (IPCC 2007). A positive net energy balance leads to an increased average global temperature (IPCC 2007). In this study, the timing of the GHG emissions was evaluated for their effect on their warming potential using the concept of RF.

Figure 1-8 illustrates the effect of delaying a pulse emission of CO_2 emission (Schwietzke et al. 2011). The emissions pulse pertains to the instantaneous radiative forcing (IRF) with units of W/m^2. Whereas CRF is equal to the area under the IRF curve from the time of the pulse until the end of the time-horizon, 100 years in this case ($W/m^2/yr$). The present study used numerical integration to find the area under the curve. At time zero, the pulse emission (pulse 1) has the highest CRF (solid) because the effect of the pulse lasts over the whole time-horizon. The pulse emission at 50 years (pulse 3) has the lowest CRF (dashed) because the radiative forcing of the pulse is considered only for the last 50 years. The pulse at 25 years (pulse 2) falls in between the 0-year and the 50-year pulse and results in a CRF (dotted) smaller than from pulse 1 but greater than from pulse 3. The radiative forcing from pulse 1 corresponds to how GWP would be calculated over the 100-year time horizon.

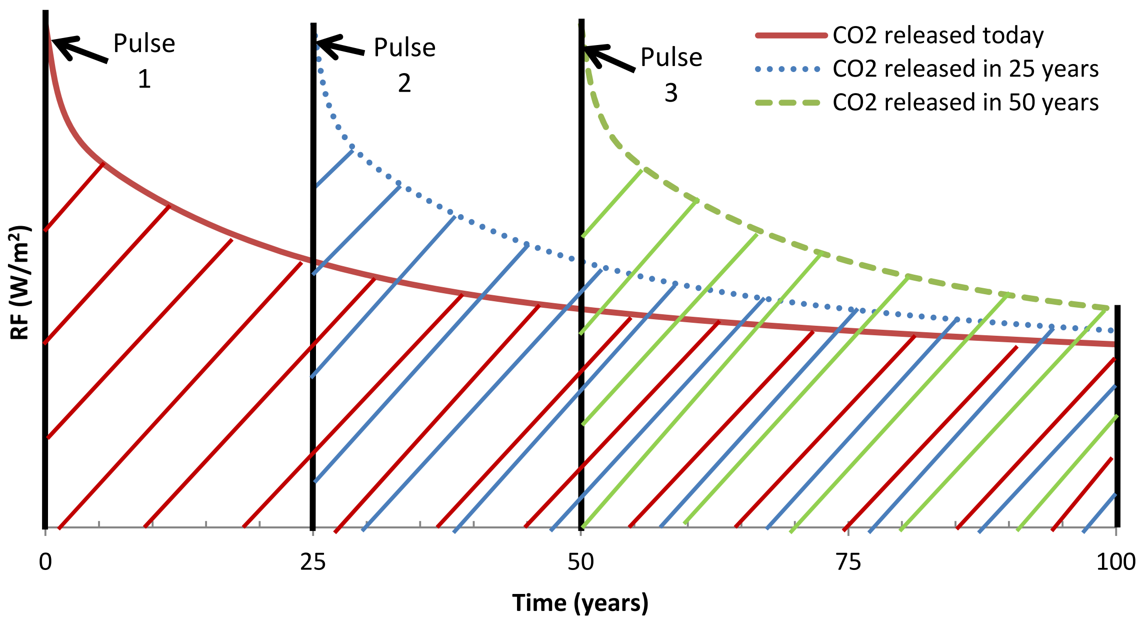

Figure 1-8: Instantaneous radiative forcing curves for a pulse emission of CO_2 at different times

1.9 Different time horizons

Different time horizons exist when conducting LCA studies (Levasseur et al. 2010). The present study identified five different time periods: 1) functional unit time period, 2) infinite time horizon for analyses of GHG fluxes (traditional approach), 3) static LCA time horizon, 4) dynamic LCA time horizon and 5) time zero equivalent time horizon.

1.9.1 Functional unit time period

The time period for the functional unit pertains to the product studied. In the present study, wood flooring was the studied product. Emissions occurring over the specified time that the product was to be in service as defined by the functional unit were tracked. The functional unit ought to be less than or equal to the given time horizon used to calculate the impact on climate change to not result in a time boundary violation. A time boundary violation results when the product in-service life for the functional unit exceeds the given time horizon because product emissions continue to occur.

1.9.2 Infinite time horizon for analysis of GHG fluxes

The static LCA approach incorporates emissions regardless when released or removed from the atmosphere. The present study considered the following approach when accounting for forest carbon and biogenic CO_2 emissions. This approach underlies all static LCA as biogenic CO_2 is given a characteristic factor of zero when estimating the impacts on climate change. The forest carbon uptake during tree growth balances out the biogenic CO_2 emissions released regardless of the time they occur. Therefore, the forest is considered to regrow to its original state because time is not considered. This occurs even if the GHG fluxes from re-sequestering forest carbon occur outside the given time horizon for calculating the impact on climate change.

1.9.3 Static LCA time horizon

For the static LCA time horizon, calculating GWP for a given time horizon assumes the individual GHG emissions are aggregated to a single GHG and that the radiative forcing effect occurs over the given time horizon (from t=0 to t=given time horizon) regardless of when the

GHG was released. The GHG may even be released after the given time horizon has expired but the GWP would be the same regardless whether the emission was released at time zero or after the end of the given time horizon.

1.9.4 Dynamic LCA time horizon

For a dynamic LCA time horizon, all emissions occurring within the given time horizons are accounted for. No emissions are accounted for outside the given time horizon unlike the static LCA approach.

1.9.5 Time zero equivalent metric time horizon

For the new TIZE time horizon, GHG emissions generate the radiative forcing effect at the time of emission to the end of the given time horizon. Therefore, GHGs emitted near the end of a given time horizon will have a smaller cumulative radiative forcing for TIZE than when calculating GWP for the static LCA time horizon.

2 METHOD

The concept outlined above and shown in **Figure 1-8** provided the initial concept for the new methodology for calculating what is called the time-zero equivalent (TIZE) CRF for the two wood flooring products. TIZE and GWP are both expressed in units of kg CO_2-eq. The new approach included the CRF outcomes for emissions timing for fossil CO_2, CH_4, and N_2O for the whole cycle of the two products. The three LLGHGs provided all the climate change impact for the two wood flooring products. CO_2, CH_4, and N_2O only contributing to the impact on climate change for wood products is consistent with other life-cycle studies conducted (Puettmann and

Wilson 2005; Puettmann et al 2010; Bergman and Bowe 2012). The question answered was how evaluating building products that emit GHG emissions at various times affected its climate change impact compared to the traditional LCA metric of GWP. The issue was that including emission timing of the GHGs might provide a more precise estimation of the impact to climate change for long-lived products than found through the traditional LCA approach (Reap et al. 2008).

2.1 Categorizing temporal GHG emissions

The first step in categorizing the timing of GHG emissions was quantifying the three GHG emissions for the given time horizon. For the present study, the selected time horizon was 100 years. However, other time-horizons could be selected as alternatives. Therefore, any GHG emission during the 100-year time period was evaluated for its impact on climate change. Five major GHG pulses occur for the two wood flooring products. For the wood flooring life cycle, GHG emissions occur at year 0 for cradle-to-gate manufacturing, product transportation, and installation for SSHF and EWF (**Figure 2-1**). Cradle-to-gate manufacturing includes extraction (i.e. harvesting), resource transportation, and product production. At various intervals for SSHF, large GHG emissions occur again at 20, 40, and 60 years for refinishing (maintenance) and at 80 years during disposal to a landfill. Methane generated from decomposing wood in the landfill was included up to 100 years but not passed 100 years when calculating $TIZE_{100}$. Unlike $TIXE_{100}$, calculating GWP_{100} considers the wood to decompose by 23% instantaneously. For EWF, large GHG emissions occur at 20 year for refinishing, 40 years for replacement, 60 years for refinishing the second installation, and at 80 years during disposal to a landfill. Final disposal included transportation from the demolished structure to final disposition site.

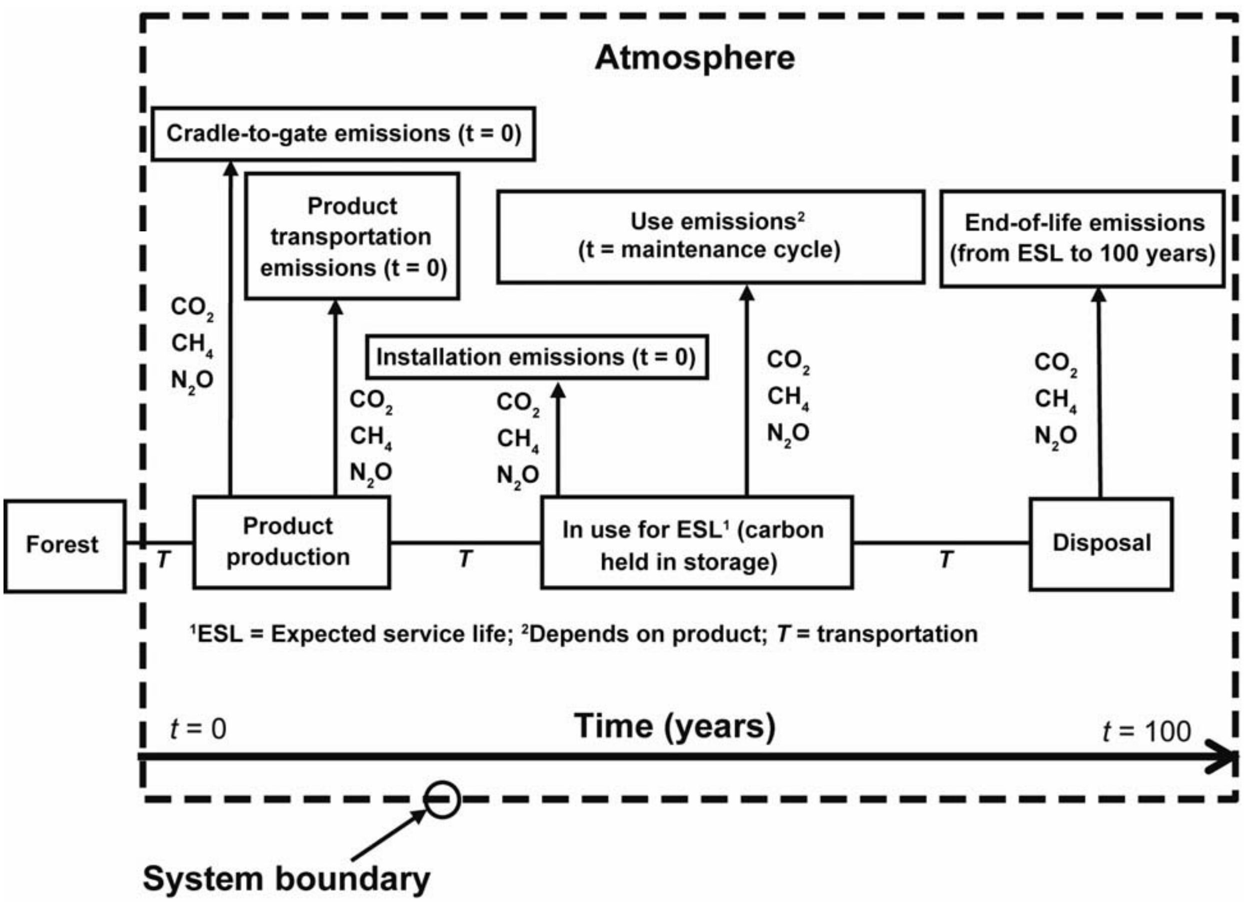

Figure 2-1: Dynamic system boundary for building products including flooring

2.2 Finding the instantaneous radiative forcing for each GHG

The second step was to find the IRF for the two flooring products depending on the amount and time of the GHG emissions. Because major GHG emissions occurred at certain intervals for building products including flooring, the IRF values for the five different times listed in Section 2.1 were determined separately. The GHG emissions were taken from cradle-to-grave LCI flows estimated in paper #3 for the two flooring traditional LCAs. The last life-cycle stage considered the slow decomposition of wood emitting methane and biogenic carbon dioxide. Methane occurs because of the human activity of landfilling wood thus methane is included in the calculating the GWP and the new time zero equivalent unlike the biogenic carbon dioxide emitted. Naturally decaying wood emits biogenic CO_2 and is part of the natural carbon cycle.

2.3 Cumulative radiative forcing for each GHG

IRFs were calculated for each GHG and the IRF curves plotted for the flooring products versus time. Then, the area under the curve was calculated to find the individual CRFs from the time of the emission to t=100. Results were found in $W/m^2/yr$. Eqns 11-15 show how the equations to calculating the total CRF for each building product for a given time horizon and given GHG.

$$CRF^i_{TH_T}(t) = \sum_{j=1}^{5} CRF^i_{TH_j}(t) \qquad (11)$$

$$CRF^i_{TH_T}(t) = CRF^i_{TH_1}(t) + CRF^i_{TH_2}(t) + CRF^i_{TH_3}(t) + CRF^i_{TH_4}(t) + CRF^i_{TH_5}(t) \quad (12)$$

Where $CRF^i_{TH_j}(t) = \int_t^{TH} IRF^i_j\,(t)dt \qquad (13)$

$$CRF^i_{TH_T}(t) = \sum_{j=1}^{5} \int_t^{TH} IRF^i_j\,(t)dt \qquad (14)$$

$$CRF^i_{TH_T}(t) = \int_t^{TH} IRF^i_1\,(t)dt + \int_t^{TH} IRF^i_2\,(t)dt + \int_t^{TH} IRF^i_3\,(t)dt + \int_t^{TH} IRF^i_4(t)dt + \int_t^{TH} IRF^i_5\,(t)dt \qquad (15)$$

Where: t is the time the GHG emissions occurs.

$CRF^{i}_{TH_T}(t)$ is the total CRF for the given product. All CRFs expressed in W/m^2/year.

$CRF^{i}_{TH_1}(t)$ is the CRF for the cradle-to-gate, product transportation, and installation GHG emissions.

$CRF^{i}_{TH_2}(t)$ is the CRF for the first refinishing GHG emissions.

$CRF^{i}_{TH_3}(t)$ is the CRF for the second refinishing (SSHF) or replacement (EWF) GHG emissions.

$CRF^{i}_{TH_4}(t)$ is the CRF for the last refinishing GHG emissions.

$CRF^{i}_{TH_5}(t)$ is the CRF for the disposal GHG emissions

2.4 Time-zero equivalent

Once the total $CRF^{i}_{TH_T}(t)$ was calculated, the next step was to find the TIZE in kg-CO_2-eq. Both TIZE and GWP metric use the same reporting measure, i.e. kg CO_2-eq. Furthermore, the concept of TIZE is similar to the economic term of net present value (NPV). Levasseur and others (2010) discussed the NPV concept when analyzing the climate change impacts of corn ethanol versus gasoline. The NPV brings all future cash inflows and outflows back to year zero to arrive at a single value. NPV is time-dependent just like TIZE. Eqn. (16) shows the total CRF value calculated for GHG *i* for a given time horizon from Eqn. (11-15) and the corresponding GHG emission pulse, E_O at time zero that produced the same CRF value. The TIZE value is equal to E_O as shown in Eqn. (17). The concept is that the area under both IRF curves would be equal but the TIZE value would provide a CRF value corresponding to releasing the amount of the GHG emission at t=0 to illustrate graphically the differences between GWP and TIZE. The TIZE value would generate an IRF curve similar to the IRF curves generated by GWP for each GHG by starting at t=0.

$$CRF^{i}_{TH_T} = CRF^{i}_{TH}(E_0) \quad (16)$$

$$TIZE^{i}_{TH}\left(CRF^{i}_{TH_T}(t)\right) = E^{i}_{0} \quad (17)$$

$$TIZE^{GHGs}_{TH} = \sum_{i=1}^{3} E^{i}_{0} \quad (18)$$

Given that a pulse emission at time-zero provides a certain CRF for a chosen time horizon for each GHG, the pulse emission at time-zero was found that corresponds to the total CRF found from Eqn (17). The TIZE kg-CO_2-eq values will be equal to or less than GWP values found for the chosen time-horizon. Static LCA uses the single GHG aggregated value at time-zero to calculate GWP thus does not consider the timing of the GHG emission. GWP measures the CRF for each GHG from t=x to t=TH+x for a given time horizon where x is the time the GHG was released. The value of x may be zero for all emissions thus TIZE would equal GWP but that is not the case for building products. GHG emissions for building products can occur many decades later. Fossil CO_2, CH_4, and N_2O have their own IRF curves as shown in **Figure 1-4** resulting in different CRF values for the same-size pulse and time horizons. For each wood flooring product, TIZE values for each GHG were calculated and then compared to the corresponding GWP values found through the traditional LCAs in paper #3.

3 RESULTS

The goal of the present study was to develop a new methodology to incorporate timing of emissions in building products. The new approach showed the time-dependent climate change impact through CRF while using a metric similar to GWP, the most widely-accepted metric. The values of $TIZE_{100}$ for the new approach were compared to the GWP values for the 100-year time-horizon, referred to as GWP_{100}.

The new approach used the concept of CRF to calculate a time-zero equivalent in kg CO_2-eq. GWP reports in the same unit, kg CO_2-eq. Results for $TIZE_{100}$ and GWP_{100} were reported in kg CO_2-eq per functional unit of wood flooring product. Two graphs were plotted for each GHG per wood flooring product. The first graph showed the five individual IRF curves and their sum. The second graph had three curves. The first curve (solid) of the second graph corresponded to the sum of the individual IRF curves shown in the first graph. The second curve (dashed) corresponded to the CRF generated from the amount of GHG emitted at time zero associated with the $TIZE_{100}$ value. The third curve (dotted) corresponded to the CRF generated from the amount of GHG associated with the GWP_{100} value (i.e. traditional LCA) estimated in paper #3 emitted at time zero. EWF lasts about 50% as long as SSHF thus the EWF was replaced once during the 80 years, at 40 years.

3.1 Solid strip hardwood flooring

3.1.1 Fossil carbon dioxide

Figure 3-1 shows the individual IRF curves for fossil CO_2 for the five GHG emission pulses over the service life of SSHF and the sum of the five individual IRF curves. The first fossil CO_2 pulse was the largest pulse (dotted) while the next smaller pulses all occurred at 20 (dash), 40 (dash-dash-dot), and 60 (dash-dot-dash) years. The final disposition effect (long dash-dot-dot) was much smaller than the other pulses as only transportation fuel consumed in moving the old wood to landfill emitted fossil CO_2. The IRF sum curve (solid) overlaps the first IRF curve until additional fossil CO_2 emissions occur from the refinishing process at 20 years.

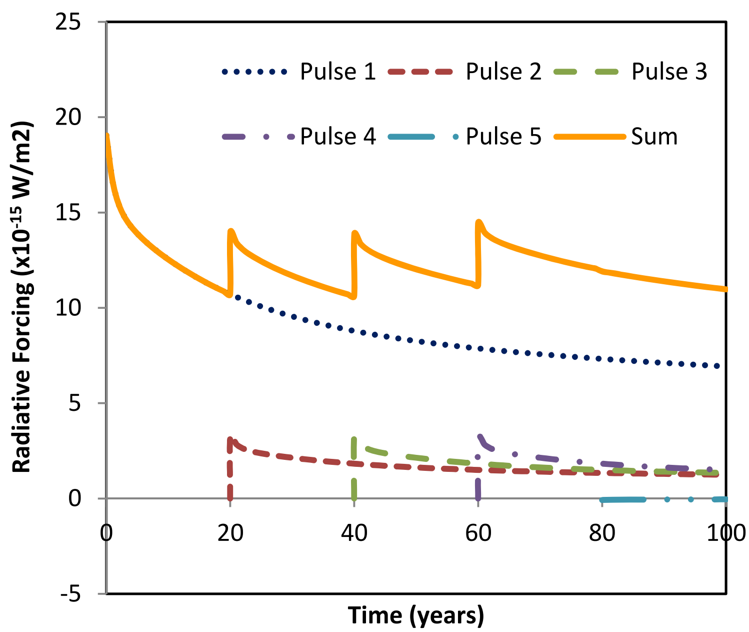

Figure 3-1: Individual fossil carbon dioxide instantaneous radiative forcing curves per functional unit of solid strip hardwood flooring

Figure 3-2 shows the total IRF curve from **Figure 3-1** (solid), the IRF curve from the $TIZE_{100}$ for fossil CO_2 (dashes) and the IRF curve from the static LCA (dots) for SSHF. The emission pulse corresponding to the static LCA value produced the largest CRF. To develop IRF profile for the static LCA, all fossil CO_2 emissions were emitted at time zero. For SSHF, the static LCA had a fossil CO_2 contribution to GWP_{100} of 14.5 kg CO_2-eq/functional unit. The $TIZE_{100}$ value was 13.0 kg CO_2-eq/functional unit, over a 10% decrease from the static case.

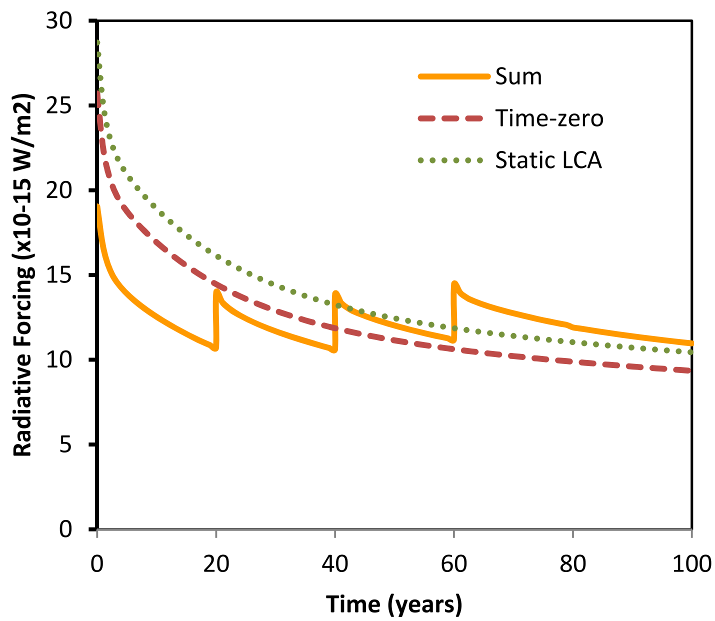

Figure 3-2: Total fossil carbon dioxide instantaneous radiative forcing curves of per functional unit of solid strip hardwood flooring

3.1.2 Methane

Figure 3-3 shows the individual IRF curves for CH_4 for the five GHG emission pulses over the service life of SSHF and the sum of the five individual IRF curves. The initial CH_4 pulse was the second largest pulse while the largest pulse occurred at 80 years. The final disposition effect was far larger than the other pulses as wood decomposed into the landfill and emitted methane. Although most methane was captured, about 25% escaped to the atmosphere. The captured methane substituted for natural gas production. As the present study was examining temporal impacts of emissions, wood did not composed instantaneously as it is assumed in the static LCA approach. Instead, landfilled wood decomposed over a number of decades and only a portion of wood did decay, about 23% overall. Landfilled wood has a half-life of 29 years (Skog 2008). The IRF sum curve overlaps part of the first IRF curve and all of the last IRF curves corresponding to end-of-life emissions.

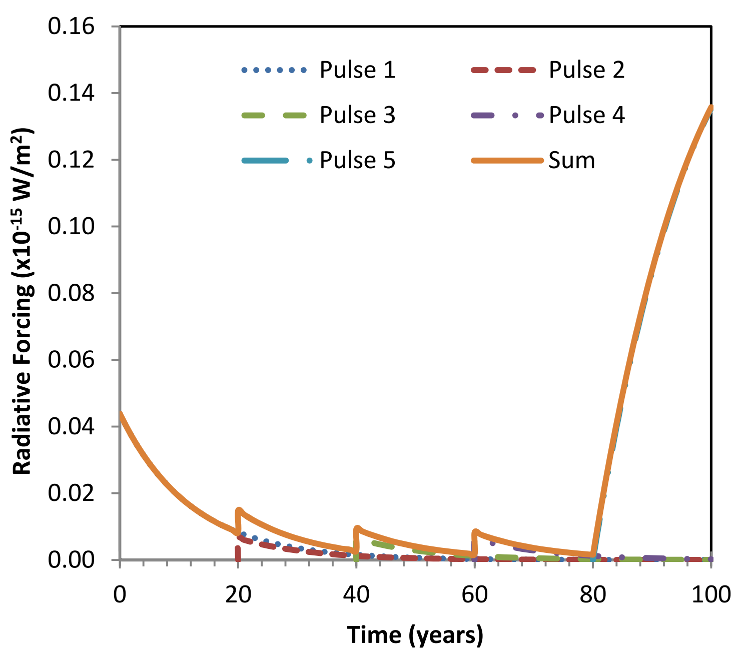

Figure 3-3: Individual methane instantaneous radiative forcing curves per functional unit of solid strip hardwood flooring

Figure 3-4 shows the total IRF curve from **Figure 3-3**, the IRF curve from the $TIZE_{100}$ and the IRF curve from the static LCA for CH_4 for SSHF. The emission pulse corresponding to the static

LCA value produced the largest CRF. For SSHF, the static LCA had a CH_4 contribution to GWP_{100} of 6.3 kg CO_2-eq/functional unit. The $TIZE_{100}$ value was 2.5 kg CO_2-eq/functional unit, over 60% decrease from the static case.

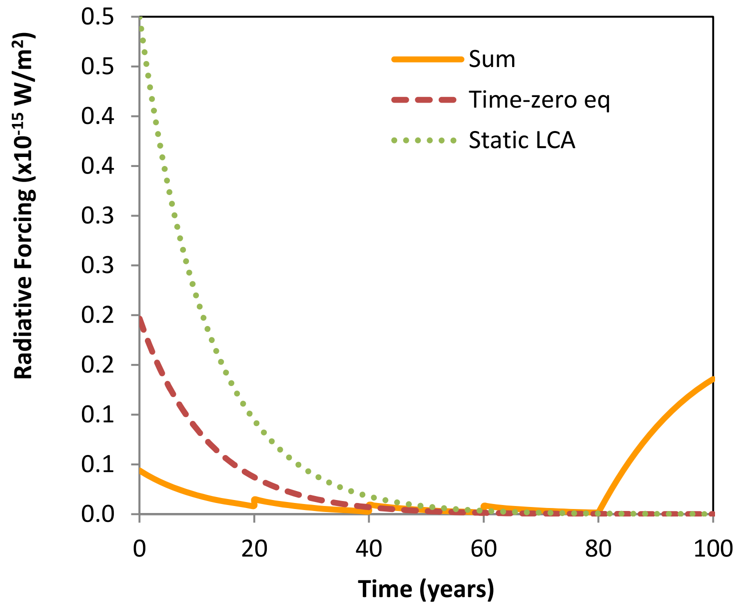

Figure 3-4: Total methane instantaneous radiative forcing curves per functional unit of solid strip hardwood flooring

3.1.3 Nitrous oxide

Figure 3-5 shows the IRF curves for N_2O for the five GHG emission pulses over the service life of SSHF and the sum of the five individual RF curves. Similar to CO_2, the initial N_2O pulse was the largest pulse while the smallest pulse occurred at 80 years. The IRF sum curve overlaps the first IRF curves. As noted by the y-axis values, the IRF values for N_2O were much smaller than the IRF values associated with CO_2 but consistent with the N_2O contributions to GWP.

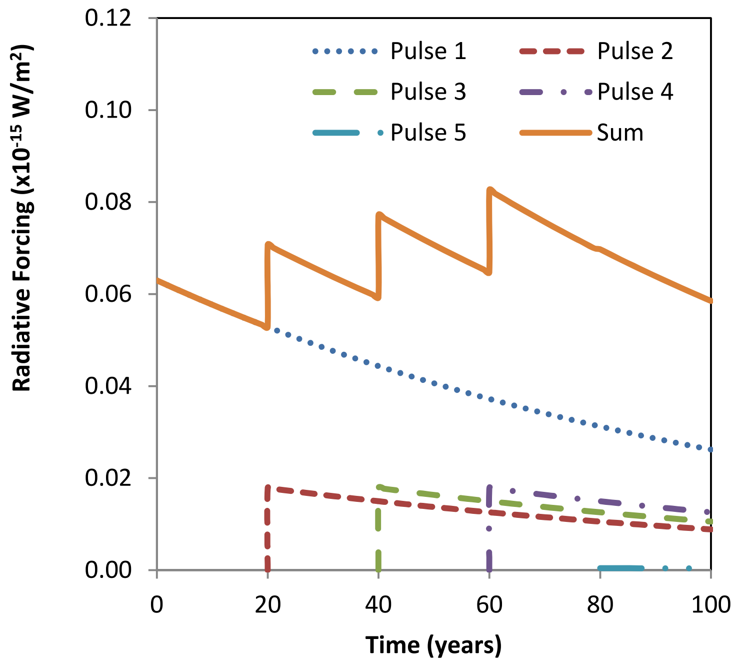

Figure 3-5: Individual nitrous oxide instantaneous radiative forcing curves per functional unit of solid strip hardwood flooring

Figure 3-6 shows the total IRF curve from **Figure 3-5**, the IRF curve from the $TIZE_{100}$ and the RF curve from the static LCA for N_2O for SSHF. The emission pulse corresponding to the static LCA value produced the largest CRF. For SSHF, the static LCA had a N_2O contribution to GWP_{100} of 0.088 kg CO_2-eq. The $TIZE_{100}$ value was 0.075 kg CO_2-eq, over a 14% decrease from the static case.

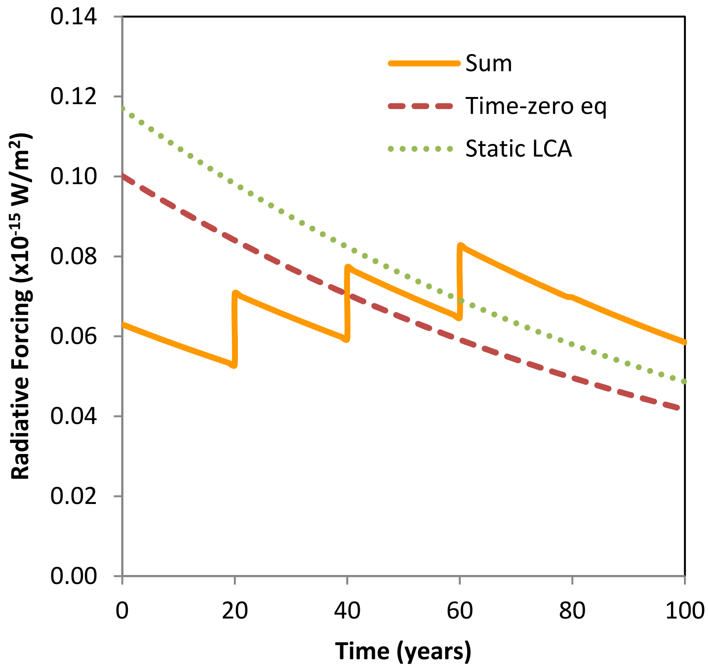

Figure 3-6: Total nitrous oxide instantaneous radiative forcing curves per functional unit of solid strip hardwood flooring

3.2 Engineered wood flooring

3.2.1 Fossil carbon dioxide

Figure 3-7 shows the IRF curves for fossil CO_2 for the five GHG emission pulses and the sum of the five individual IRF curves over one functional unit of EWF. One functional unit covers two service lives of EWF. The initial (dotted) and the third (long dashes) fossil CO_2 pulse were the largest pulses while the next smaller pulses occurred at 20 (short dashes) and 60 (dash dot dash) years due to refinishing. The first and third pulses were associated with floor manufacturing and replacement, a much more energy-intensive activity than refinishing. The final disposition effect was much smaller than the other pulses as only transportation fuel consumed in moving the old wood to landfill emitted fossil CO_2. In addition, the last pulse included the reduction in fossil CO_2 emissions from avoiding natural gas production due to methane capture. The IRF sum curve (solid) overlaps the first IRF curve until additional CO_2 emissions occur from the refinishing process at 20 years.

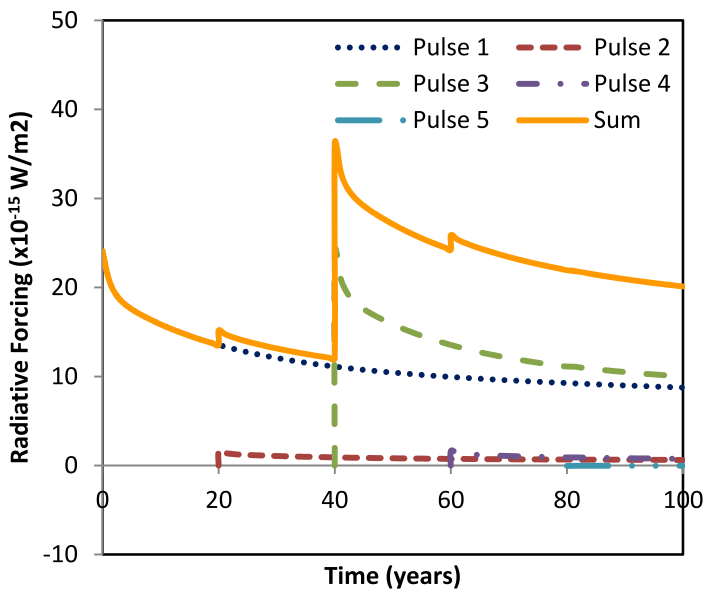

Figure 3-7: Individual fossil carbon dioxide instantaneous radiative forcing curves per functional unit of engineered wood flooring

Figure 3-8 shows the total IRF curve from **Figure 3-7** (solid), the IRF curve from the $TIZE_{100}$ (dotted) and the IRF curve from the static LCA for CO_2 for EWF (dashed). The static LCA value produced the largest CRF. For EWF, the static LCA had a fossil CO_2 contribution to GWP_{100} of 27.5 kg CO_2-eq/functional unit. The $TIZE_{100}$ value was 22.6 kg CO_2-eq/functional unit, about an 18% decrease from the static case.

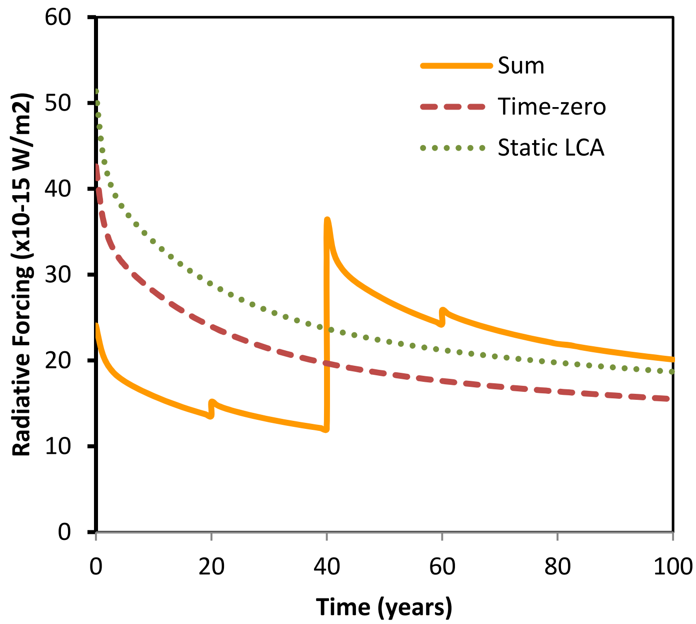

Figure 3-8: Total fossil carbon dioxide instantaneous radiative forcing curves per functional unit of engineered wood flooring

3.2.2 Methane

Figure 3-9 shows the IRF curves for CH_4 for the five GHG emission pulses and the sum of the five individual IRF curves for a functional unit of EWF. The initial CH_4 pulse was the second largest pulse while the largest pulses occurred at 40 years due to new product replacement and old product disposal. The final disposition effect was large as wood decomposed into the landfill and emitted methane starting at year 40 and 80 for the old wood. Although most methane was captured, about 25% escaped to the atmosphere. The captured methane substituted for natural gas production. As the present study was examining temporal influences of emissions, wood did not composed instantaneously as assumed in the static LCA approach. Instead, landfilled wood decomposed over a number of decades and only a portion of wood did decay, about 23% total. In addition, landfilled wood has a half-life of 29 years (Skog 2008). Therefore, about 2.39% of wood decayed each year emitting biogenic carbon dioxide and methane. The first landfilled floor emitted about 75% of the methane possible after 60 years whereas the second landfilled floor emitted 38% in 20 years. As with other IRF curves, the IRF sum curve overlaps the first IRF curve.

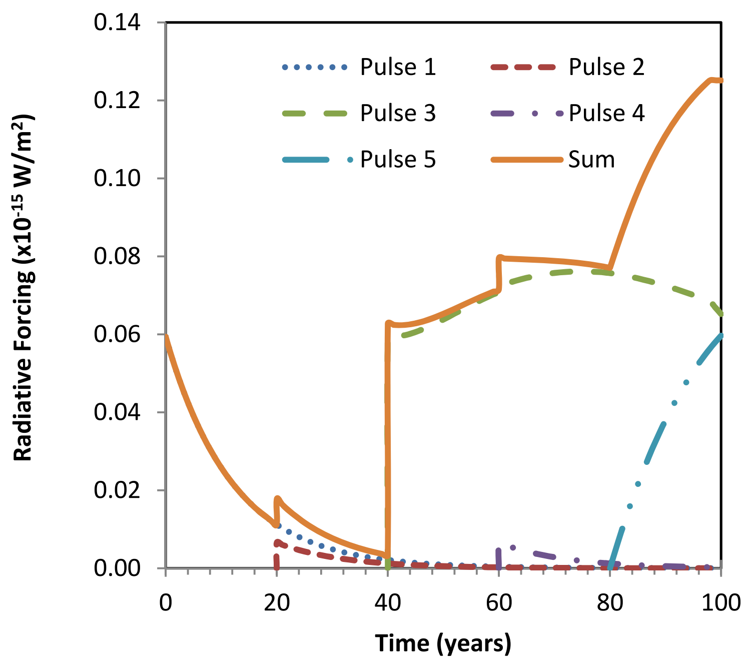

Figure 3-9: Individual methane instantaneous radiative forcing curves per functional unit of engineered wood flooring

Figure 3-10 shows the total IRF curve from **Figure 3-9**, the IRF curve from the static $TIZE_{100}$ and the IRF curve from the static LCA for CH_4. The IFR for the static LCA value produced the largest CRF. For SSHF, the static LCA had a CH_4 contribution to GWP_{100} of 7.1 kg CO_2-eq/functional unit. The $TIZE_{100}$ was 6.2 kg CO_2-eq/functional unit, about a 12% decrease from the static case.

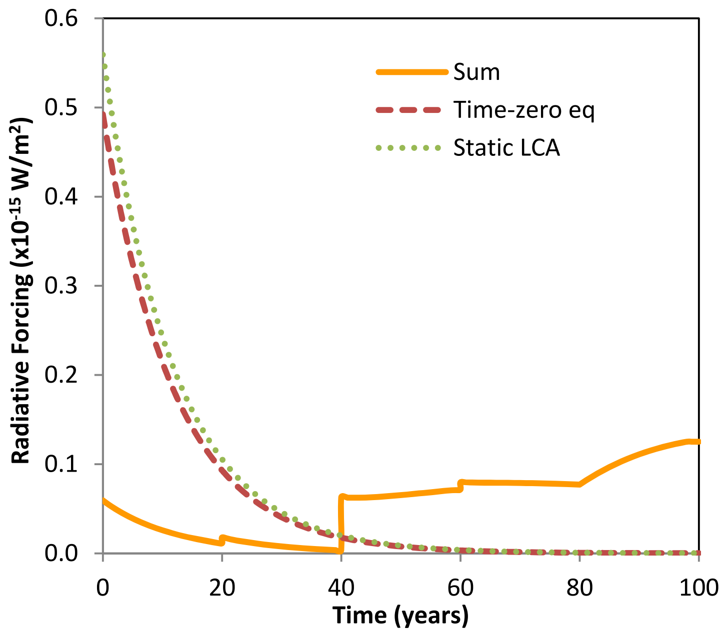

Figure 3-10: Total methane total radiative forcing curves per functional unit of engineered wood flooring

3.2.3 Nitrous oxide

Figure 3-11 shows the IRF curves for N_2O for the five GHG emission pulses over the service life of SSHF and the sum of the five individual RF curves. Similar to CO_2, the initial N_2O pulse was the largest pulse while the smallest pulse occurred at 80 years. The IRF sum curve overlaps the first IRF curve until another N_2O emission occurred for the first 20 years from refinishing. The same as for SSHF, the IRF values for N_2O were much smaller than the IRF values associated with fossil CO_2.

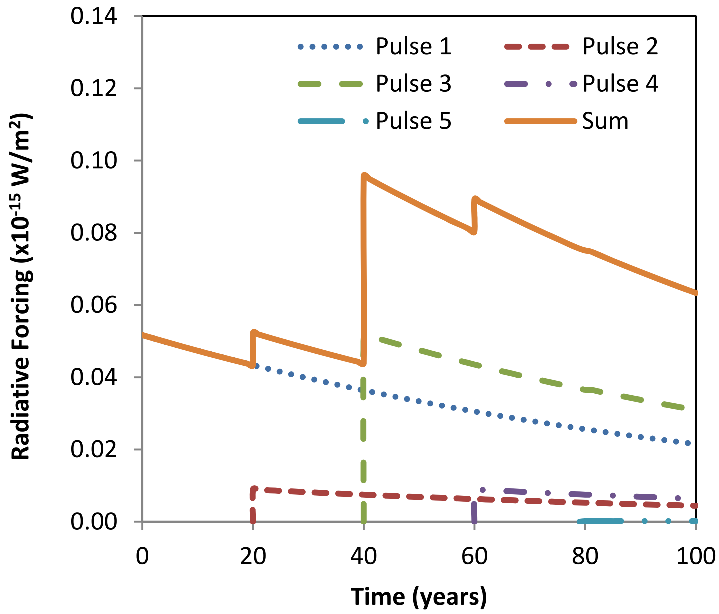

Figure 3-11: Individual nitrous oxide radiative forcing curves per functional unit of engineered wood flooring

Figure 3-12 shows the total IRF curve from **Figure 3-11**, the IRF curve from the $TIZE_{100}$ and the IRF curve from the static LCA for N_2O. The IFR for the static LCA produced the largest CRF. For SSHF, the static LCA had a N_2O contribution to GWP_{100} of 0.092 kg CO_2-eq/functional unit. The $TIZE_{100}$ was 0.075 kg CO_2-eq/functional unit, about a 18% decrease from the static case.

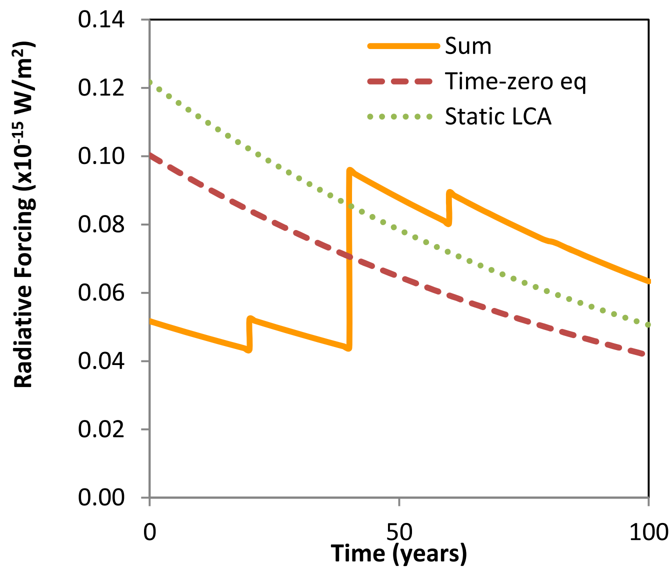

Figure 3-12: Total nitrous oxide total radiative forcing curves per functional unit of engineered wood flooring

3.3 Summary of results

Figure 3-13 illustrates the $TIZE_{100}$ and GWP_{100} values by GHG for a functional unit of SSHF. Fossil CO_2 had the greatest influence on both $TIZE_{100}$ and GWP_{100} but methane contribution shows the biggest difference. Nitrous oxide had little effect overall for either $TIZE_{100}$ or GWP_{100}.

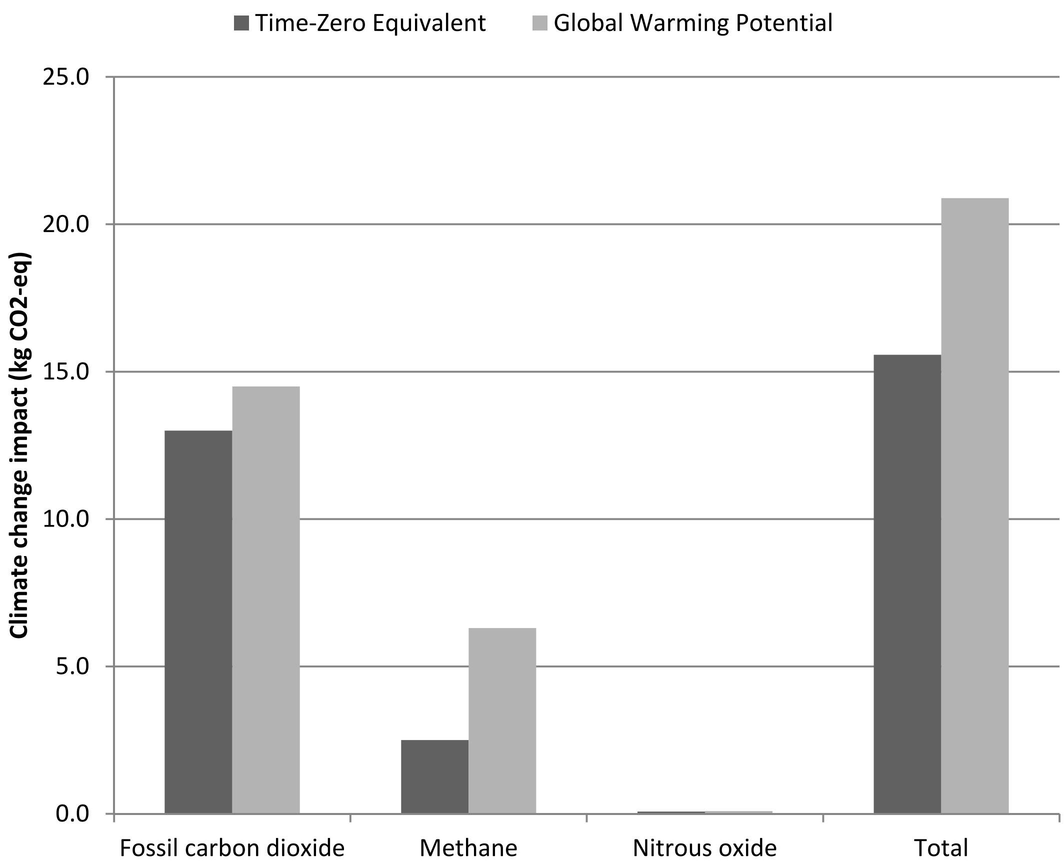

Figure 3-13: Two metrics for quantifying impacts on climate change for a functional unit of solid strip hardwood flooring (100-year time horizon)

Figure 3-14 illustrates the $TIZE_{100}$ and GWP_{100} values by GHG for a functional unit of EWF. Fossil CO_2 had the greatest influence on both $TIZE_{100}$ and GWP_{100}. Unlike SSHF, fossil CO_2 contribution shows the biggest difference. Nitrous oxide had little effect overall for either $TIZE_{100}$ or GWP_{100}.

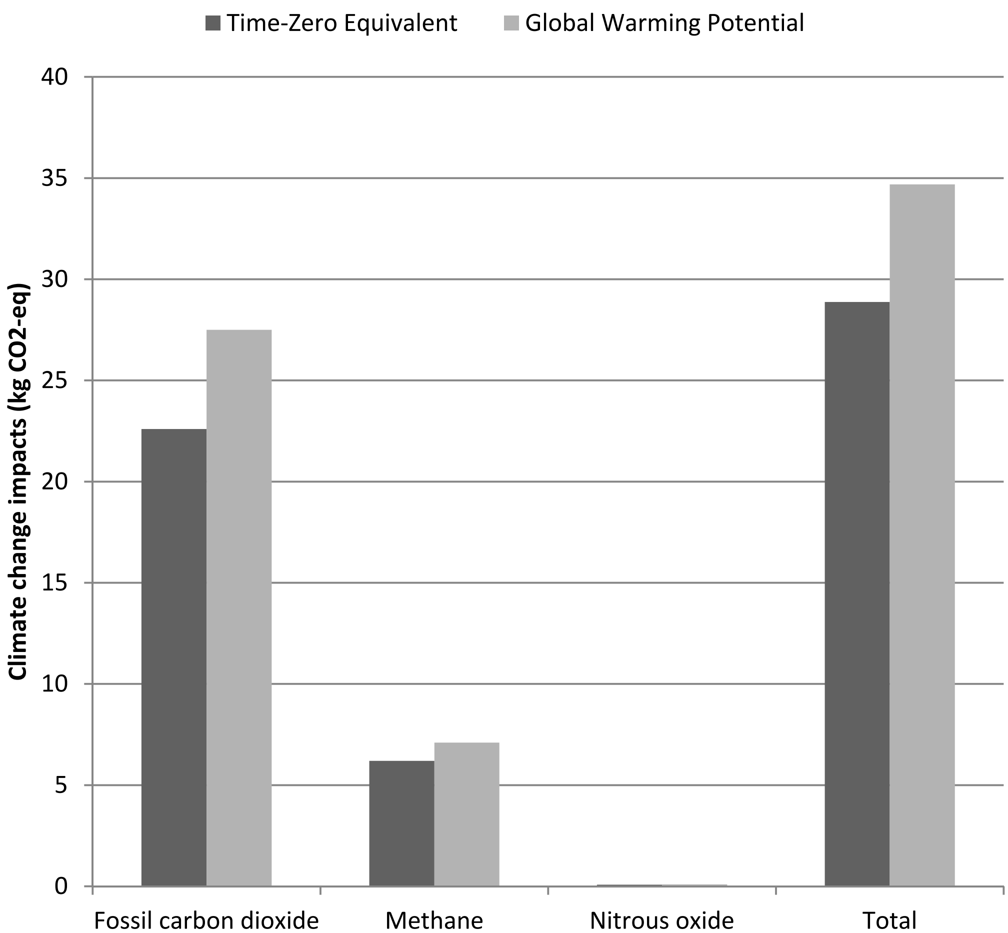

Figure 3-14: Two metrics for quantifying impacts on climate change for a functional unit of engineered wood flooring (100-year time horizon)

Table 3-1 lists the $TIZE_{100}$ and GWP_{100} values for a functional unit of flooring. For both SSHF and EWF, the $TIZE_{100}$ values are lower than the GWP_{100} values. Methane contribution to $TIZE_{100}$ for SSHF on a percentage basis had the greatest reduction (60.3%) with respect to GWP_{100}. Removal and landfilling of the SSHF did not occur until after 80 years thereby dramatically reducing the time for the old wood to decompose and emit methane. EWF released most of its methane from its first life and some from the second life thus only had a 12.7%

reduction. The total $TIZE_{100}$ values were about 25% and 17% less than the GWP_{100} values. SSHF had the greatest reduction for $TIZE_{100}$ mainly because of its longer service. The longer service life for SSHF kept the wood product in use for 80 years whereas the first EWF installation left after 40 years. Once the wood product left service and was disposed of in a landfill, the wood began to decompose and began to emit methane. The trend indicated that GWP_{100} for building products with a longer service considerably overstated the climate change impact.

Table 3-1: Time-zero equivalent and GWP values per functional unit of flooring

	Solid strip hardwood			Engineered wood		
	$TIZE_{100}$	GWP_{100}	Percent change	$TIZE_{100}$	GWP_{100}	Percent change
Greenhouse gas	(kg CO_2-eq)		(%)	(kg CO_2-eq)		(%)
Fossil carbon dioxide	13.0	14.5	-10.3%	22.6	27.5	-17.8%
Methane	2.5	6.3	-60.3%	6.2	7.1	-12.7%
Nitrous oxide	0.075	0.088	-14.8%	0.075	0.092	-18.5%
Total	15.6	20.9	-25.4%	28.9	34.7	-16.8%

4 CONCLUSIONS

Based on the new dynamic LCA methodology, the following conclusions are made.

Incorporating timing of emissions by using the TIZE (dynamic) methodology provides a more precise estimation of the impacts from GHGs on climate change than the static LCA approach (i.e. GWP) does. Static LCAs aggregate individual emissions to use to measure LCIA thus potentially overestimating certain impacts such as for climate change. Time-dependent metrics show results closer to the impacts to what the Earth and its atmosphere are experiencing.

TIZE offers a more accurate metric than GWP while maintaining simplicity. Researchers and policy-makers are familiar with using kg CO_2-eq. The TIZE methodology uses kg CO_2-eq thus would be easier to accept as an alternative metric.

Long-lived building products ought to consider using TIZE instead of GWP when reporting climate change impacts especially for environmental product declarations (EPDs). EPDs are LCA-based eco-labels for products similar to nutritional labels on food.

Increasing service life of wood building products would likely reduce their environmental impacts. Wood disposed of in landfills decomposes and emits methane and biogenic carbon dioxide. Methane is a potent GHG. As a result, maintaining the product in service as long as possible would aid in lowering the climate change impact especially in a 100-year time period by delaying the release of methane.

Length of service matters concerning environmental performance. The two flooring products studied have different service lives. Engineered wood flooring was required to replace after 40 years and replacement results in greater impacts than refurbishing the floor. However, because the floor replacement occurred 40 years after the first installation, the TIZE for the second installation at 40 years was lower than the value for the first installation.

Functional unit matters concerning environmental performance. Solid strip hardwood flooring is twice as thick as engineered wood flooring therefore requires twice as much material on a volume basis. Tradeoffs exist between processing more wood per square for solid strip hardwood flooring versus its longer service life. Presently, the two tradeoffs of increased service life and thicker flooring cancel each other out.

Limitations of the present study are as flows. One limitation is not including the impacts from timing of carbon uptake in the forest and the release of biogenic CO_2 during the given time horizon. The present study assumes the forest will regenerate to its original state on an indefinite time horizon to balance out the biogenic CO_2 emissions released during the life cycle of the products. Future work can incorporate these carbon impacts once better defined. The second limitation relates to radiative forcing effect over time. There may be some issues with assuming that the impact from radiative forcing does not change over time but it is a complex issue without any current solution. Therefore, the present study did not weight or discount radiative forcing over time.

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6 GLOSSARY

Aggregated global warming potential (AGWP), the integration of radiative forcing for a given time horizon from a pulse emission of 1 kg of GHG given current atmospheric concentration (expressed in W*year/m^2 per kg GHG).

Atmospheric lifetime (τ), the time necessary to restore equilibrium following a sudden increase or decrease of GHG concentration in the atmosphere.

Carbon dioxide equivalent (CO_2-eq), a unit of measurement used to compare the climate effects of all greenhouse gases to each other. CO_2-eq is calculated by multiplying the quantity of a greenhouse gas by its global warming potential characterization factor.

Characterization factors, factors from characterization models such as TRACI used to assign a value to the life-cycle inventory flows to produce the output of the impact category in a common unit. For example, methane has a GWP characterization factor of 25 for the 100-year time horizon. To calculate the methane contribution in kg CO_2-eq for the 100-year time-horizon GWP, the LCI flow of methane emitted (outputted) in kilograms to the atmosphere per functional unit is multiplied by the methane characterization factor of 25.

Cumulative radiative forcing (CRF), the summing of radiative forcing occurring over a period of years that was caused by a climatic factor such as GHG emissions. CRF is expressed in

$W/m^2/year$ (can be mathematically found by integrating the area under the radiative forcing curve).

Climatic factor, any condition, natural or human, that influences the climate in a given area.

Global warming potential (GWP), an index that measures the relative strength and potency of a greenhouse gas as well as its projected life span in the atmosphere (expressed in kg CO_2-equivalents). Mathematically, GWP means the cumulative radiative forcing – both direct and indirect effects – integrated over a certain time from an emission of a unit mass of GHG relative to carbon dioxide, the most common greenhouse gas.

Greenhouse effect, the absorption of thermal infrared radiation by the atmosphere thereby warming the Earth. GHGs effectively absorb thermal infrared radiation emitted by the Earth's surface, by the atmosphere itself due to the same gases and by clouds. An increase in the concentration of greenhouse gases from human activity has led to an increased infrared opacity of the atmosphere causing additional radiative forcing leading to an increased greenhouse effect.

Greenhouse gas (GHG), atmospheric gases, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. GHGs are the primary cause of the greenhouse effect. GHGs include carbon dioxide, ozone, water vapor, methane, and nitrous oxide.

Half-life ($t_{1/2}$), the time for a substance to decay to half (50%) of its original amount. Half-life can be expressed by the flowing equation: $t_{1/2} = \frac{\ln(2)}{\lambda}$ where λ is the substance's decay constant.

Instantaneous radiative forcing (IRF), radiative forcing where no stratospheric temperature changes are taken into consideration (expressed in W/m^2).

Long-lived greenhouse gas (LLGHG), a chemical stable greenhouse gas present in the Earth's atmosphere for over ten years thus having a long-term impact on Earth's climate. LLGHGs become well-mixed because of their longevity in the Earth's atmosphere.

Net present value (NPV), the current value of adding together all the revenue over a project's whole life and deducting all the costs involved, discounting both future costs and revenue at a suitable rate.

Radiative forcing (RF), a measure of the effect of a climatic factor has in changing the net energy balance in the Earth's atmosphere (expressed in watts per square meter). Positive forcing tends to warm the Earth's surface whereas negative forcing tends to cool the Earth's surface.

Radiative efficiency (RE), the infrared-absorbing ability of a greenhouse gas (expressed in W/m^2/ppb or W/m^2/ppm) and is referred to as the radiative forcing per unit greenhouse gas mass increase in the atmosphere.

Thermal infrared radiation, radiation emitted by the Earth's surface, the atmosphere and the clouds.

4 CONCLUSION

Based on the new impact on climate change index, the following conclusions are made.

Incorporating timing of emissions by using the TIZE (dynamic) methodology provides a more precise estimation of the impacts from GHGs on climate change than the static LCA approach (i.e. GWP) does. Static LCAs aggregate individual emissions regardless of when they are released to measure LCIA thus potentially overestimating certain impacts such as for climate change. Time-dependent metrics show results closer to the impacts to what the Earth and its atmosphere are experiencing.

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Long-lived building products ought to consider using TIZE instead of GWP when reporting climate change impacts especially for environmental product declarations (EPDs). EPDs are LCA-based eco-labels for products similar to nutritional labels on food.

Increasing service life of wood building products would likely reduce their environmental impacts. Wood disposed of in landfills decomposes and emits methane and biogenic carbon dioxide. Methane is a potent GHG. As a result, maintaining the product in service as long as possible would aid in lowering the climate change impact especially in a 100-year time horizon by delaying the release of methane.

Length of service matters concerning environmental performance. The two flooring products studied have different service lives. Engineered wood flooring is replaced after 40 years and replacement results in greater impacts than refurbishing the floor. However, because the floor replacement occurred 40 years after the first installation, the TIZE for the second installation was lower than the value for the first installation.

For wood products, different EOL scenarios results in a large impact on climate change. Using the standard impact to climate change index, GWP, burning wood for power at EOL to avoid coal power production results in a substantially lower GWP than landfilling wood. Landfilling wood and capturing the methane for power production does provide carbon benefit. However, burning wood for power provides better carbon benefits compared to landfilling and ought to be pushed as an alternative to the preferred method of disposal, landfilling.

Functional unit matters concerning environmental performance. Solid strip hardwood flooring is twice as thick as engineered wood flooring therefore requires twice as much material on a volume basis. Tradeoffs exist between processing more wood per square for solid strip hardwood flooring versus its longer service life. Presently, the two tradeoffs of increased service life and thicker flooring cancel each other out.

Limitations of the present study are as flows. One limitation is not including the impacts from timing of carbon uptake in the forest and the release of biogenic CO_2 during the given time horizon. The present study assumes the forest will regenerate to its original state on an indefinite time horizon to balance out the biogenic CO_2 emissions released during the life cycle of the products. Future work can incorporate these carbon impacts once better defined. The second limitation relates to radiative forcing effect over time. There may be some issues with assuming that the impact from radiative forcing does not change over time but it is a complex issue without any current solution. Therefore, the present study did not weight or discount radiative forcing over time.

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6 GLOSSARY

Aggregated global warming potential (AGWP), the integration of radiative forcing for a given time horizon from a pulse emission of 1 kg of GHG given current atmospheric concentration (expressed in W*year/m^2 per kg GHG).

Atmospheric lifetime (τ), the time necessary to restore equilibrium following a sudden increase or decrease of GHG concentration in the atmosphere.

Carbon dioxide equivalent (CO_2-eq), a unit of measurement used to compare the climate effects of all greenhouse gases to each other. CO_2-eq is calculated by multiplying the quantity of a greenhouse gas by its global warming potential characterization factor.

Carbon cycle, used to describe the flow of carbon (in various forms, e.g., as carbon dioxide) through the atmosphere, ocean, terrestrial biosphere and lithosphere.

Carbon footprint, defined as the sum of GHGs emitted during the life of a product over a given timeframe

Characterization factors, factors from characterization models such as TRACI used to assign a value to the life-cycle inventory flows to produce the output of the impact category in a common unit such as the value of 25 for methane for the 100-year time horizon. For GWP, 25 is multiplied by the methane emitted (output) from the system to calculate the contribution of methane in kg CO_2-eq.

Climate change, a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

Cradle, the point the life cycle starts, usually at the point of extraction.

Cradle-to-gate, the point the life cycle starts, usually at the point of extraction (i.e. cradle) and ends at a specific gate. The gate may occur after primary production (i.e. hardwood lumber, polyvinyl chloride) or secondary production (i.e. solid strip hardwood flooring, plastic decking) of a product.

Climatic factor, any condition, natural or human, that influences the climate in a given area.

Cumulative radiative forcing (CRF), the summing of radiative forcing occurring over a period of years that was caused by a climatic factor such as GHG emissions. CRF is expressed in W/m^2/year (can be mathematically found by integrating the area under the radiative forcing curve).

Energy balance, the difference between the total incoming and total outgoing energy. If this balance is positive, warming occurs; if it is negative, cooling occurs. A perturbation of this global radiation balance, be it anthropogenic or natural, is called radiative forcing.

Equivalent carbon dioxide (CO_2) concentration, the concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases.

Equivalent carbon dioxide (CO_2) emission, the amount of carbon dioxide emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a well-mixed greenhouse gas or a mixture of well-mixed greenhouse gases. The equivalent carbon dioxide emission is obtained by multiplying the emission of a well-mixed greenhouse gas by its Global Warming Potential (GWP) for the given time horizon. For a mix of greenhouse gases, calculate GWP by summing the equivalent carbon dioxide emissions of each gas. Equivalent carbon dioxide emission is a standard and useful metric for comparing emissions of different greenhouse gases but does not imply exact equivalence of the corresponding climate change responses.

Functional unit, quantity of the studied product providing a reference unit to compared alternative products capable of performing the same task for a pre-determined service life. Functional units (a reference unit) for building products are typically measured in physical units such as volume, area, or mass of the product.

Gate, the point in the life cycle where raw materials enter a facility and at the point the final product leaves the facility. Product production, processing or service occurs in the facility. In addition, the first product may be an input to a second facility where further processing occurs and would also be referred as the gate. For example, kiln-dried hardwood lumber (the primary product) is an input to produce prefinished solid strip hardwood flooring (the secondary product).

Gate-to-gate, a single life cycle without any upstream or downstream stages included.

Global Warming Potential (GWP), an index (metric), based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas (GHG) in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times GHGs remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time horizon.

Grave, the life cycle ends (i.e. the final disposition).

Greenhouse effect, the absorption of thermal infrared radiation by the atmosphere thereby warming the Earth. GHGs effectively absorb thermal infrared radiation emitted by the Earth's surface, by the atmosphere itself due to the same gases and by clouds. An increase in the concentration of greenhouse gases from human activity has led to an increased infrared opacity of the atmosphere causing additional radiative forcing leading to an increased greenhouse effect.

Greenhouse gases (GHG), atmospheric gases, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. GHGs are the primary cause of the greenhouse effect. GHGs include carbon dioxide, ozone, water vapor, methane, and nitrous oxide.

Half-life ($t_{1/2}$), the time for a substance to decay to half (50%) of its original amount. Half-life can be expressed by the flowing equation: $t_{1/2} = \frac{\ln(2)}{\lambda}$ where λ is the substance's decay constant.

Impact category, represents the class of environmental issues that have life-cycle inventory flows assigned to.

Instantaneous radiative forcing (IRF), radiative forcing where no stratospheric temperature changes are accounted for (expressed in W/m^2).

Life-cycle inventory (LCI), measures all the raw material and energy inputs and outputs to manufacture a particular product, process, or service on a per unit basis within carefully defined system boundaries (i.e. a detailed mass and energy balance).

Life-cycle impact assessment, the phase that estimates the potential environmental impact (i.e. damage) for individual impact categories from the life-cycle inventory flows.

Life-cycle assessment, a scientific methodology used to evaluate a product or suite of products for their environmental performance. LCA lists the environmental outcomes for a particular product, process or service per functional unit over the whole life cycle (i.e. cradle-to-grave).

Long-lived greenhouse gas (LLGHG), a chemical stable greenhouse gas present in the Earth's atmosphere for over ten years thus having a long-term impact on Earth's climate. LLGHGs become well-mixed because of their longevity in the Earth's atmosphere.

Net present value (NPV), the current value of adding together all the revenue over a project's whole life and deducting all the costs involved, discounting both future costs and revenue at a suitable rate.

Primary data, all data collected e.g. from a production facility, measured e.g. from a water effluent test or created from activity data e.g. electrical generation, within delineated system boundaries particular to the studied product, process, or service.

Primary energy, energy found with naturally occurring substances that have not been processed in any form such as coal ore, uranium ore, trees and crude oil.

Radiative efficiency (RE), the infrared-absorbing ability of a greenhouse gas (expressed in W/m^2/ppb or W/m^2/ppm) and is referred to as the radiative forcing per unit greenhouse gas mass increase in the atmosphere.

Radiative forcing, the change in the net, downward minus upward, irradiance (expressed in W/m^2) in the atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun. Positive forcing tends to warm the Earth's surface whereas negative forcing tends to cool the Earth's surface.

Thermal infrared radiation, radiation emitted by the Earth's surface, the atmosphere and the clouds.