2005

'Green' manufacturing: A life cycle inventory of the automotive paint process and protocols for industry application.

Angelos Anastassopoulos
University of Windsor

Recommended Citation

Anastassopoulos, Angelos, "'Green' manufacturing: A life cycle inventory of the automotive paint process and protocols for industry application." (2005). *Electronic Theses and Dissertations*. 2247.
https://scholar.uwindsor.ca/etd/2247

'GREEN' MANUFACTURING:
A LIFE CYCLE INVENTORY OF THE AUTOMOTIVE PAINT PROCESS AND PROTOCOLS FOR INDUSTRY APPLICATION

by

Angelos Anastassopoulos
B.Eng., B.A.

A Thesis
Submitted to the Faculty of Graduate Studies and Research
through Civil & Environmental Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada
2005

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-17023-6
Our file Notre référence
ISBN: 978-0-494-17023-6

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ABSTRACT

In response to growing interest in 'green' vehicles, Life Cycle Analysis (LCA) and Life Cycle Inventory (LCI) concepts can quantify the automobile's environmental impacts. Potential benefits include Design-for-Environment (DfE) opportunities, increased manufacturing efficiencies, and future application to consumer-based eco-rating systems.

Detailed and up-to-date LCI data for general application by LCI practitioners does not exist at this time for the majority of Manufacturing / Assembly processes in North America, including the automotive paint process. With an Original Equipment Manufacturer (OEM) industry partner's commitment to a publicly available LCI database (i.e., NREL LCI Database), however, a representative vehicle assembly facility was selected for completion of a paint process LCI.

A detailed LCI reference dataset was developed to include materials, energy, and emissions associated with the Pretreatment, E-coat, and Top Coat paint unit processes. The challenges and industry realities of completing the LCI enabled a detailed set of guidelines to be developed, adapting existing protocols to the specifics of the manufacturing paint process. The guidelines can assist LCI practitioners augmenting the public LCI database or preparing comparative LCIs for other automotive manufacturing facilities or other industries.

Protocols were then developed for industry application of the manufacturing paint LCI dataset (i.e., scaling protocols), dependent primarily on painted vehicle surface area. Additional dependencies were shown for vehicle type, paint process type, and production period. Two scaling protocols were formulated and proposed for LCI practitioners intending to apply the paint LCI dataset to industry. Protocols were assessed against a 'test case' facility paint process:

(i) Scaling protocol I was based on BIW painted surface area and production volume and was shown to provide predicted results within 2% of actual data. It is limited, however, by the requirement for the BIW painted surface area of the predicted vehicle.

(ii) Scaling protocol II was shown to provide results within 13% of scaling protocol I. It is recommended for situations where the LCI practitioner must approximate BIW painted surface area using a surrogate. Quality of the predicted results was shown to depend on the surrogate surface area value being sufficiently representative of the predicted vehicle type and vehicle size.

to my wife for her patience and support displayed differently daily yet constant,
to my parents for cheering me on for a third time and a third university,
to my friends few and everywhere up and down the 401,
and to a fellow roadster driver who saw my potential; namely, to Serendipity.

ACKNOWLEDGEMENTS

For reasons of confidentiality, I am unable to individually thank all of the people that assisted this research. However, I would like to collectively thank all of the representatives from the partnered OEM as well as the paint supplier and energy consultant technical experts. Additionally, the expertise of the USCAR VRP representatives was helpful at several times in the project.

Finally, a particular thank you to Dr. Edwin Tam for his supervision of the research and to my research colleagues at University of Windsor: Lindita Prendi, Luis Alvarez, and Faiza Abdulrahem.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND NOMENCLATURE

ARDC	University of Windsor / DaimlerChrysler Canada Automotive Research and Development Centre
BIW	Body In White
CAD	Computer Aided Design
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EC	Environment Canada
HC	Hydrocarbons
HEV	Hybrid Electric Vehicle
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
Ni-MH	nickel-metal hydride battery
NO_X	oxides of nitrogen
NPRI	National Pollutant Release Inventory
NREL	National Renewable Energy Laboratory
NVH	noise, vibration, and harshness
OEM	Original Equipment Manufacturer
OBDII	Onboard Diagnostics system II
PM	Particulate Matter
SETAC	Society for Environmental Toxicology and Chemistry
SO_X	oxides of sulphur
$SSA_{MINIVAN}$	surrogate painted surface area for 'minivan / crossover' vehicle type
SSA_{SEDAN}	surrogate painted surface area for 'sedan' vehicle type
USCAR	United States Council for Automotive Research
VOC	Volatile Organic Compounds
VRP	Vehicle Recycling Partnership

1.0 INTRODUCTION

1.1 Problem statement

There is a growing consumer interest in 'green' vehicles, driven by increasing environmental and social awareness and rising operating costs. In response, industry and regulators look increasingly to quantitative methods of assessing the environmental impacts of the automobile, intending to legitimately benchmark, design and promote 'green' vehicles.

The automotive industry uses Life Cycle Analysis (LCA) and Life Cycle Inventory (LCI) concepts to quantify the automobile's environmental impacts. Potential benefits of environmental impact quantification via LCA and LCI include the use of Design-for-Environment (DfE) to reduce overall environmental impacts, reductions in material costs and increased manufacturing efficiencies, as well as future application to consumer-based eco-rating systems for the automobile.

In North America, the automotive industry is currently attempting to quantify and inventory the environmental impacts incurred during the automobile's manufacturing processes. The complexity of the contemporary automobile and the many complex processes required for its manufacture and assembly, however, poses a significant set of challenges for completing a manufacturing LCI and for the practical application of manufacturing LCI information.

1.2 Thesis objectives

This thesis develops a procedurally rational analysis of the environmental impacts incurred during a complex automotive manufacturing process. This will include completion of an LCI on the automotive paint process – a key process in manufacturing – and guidelines for additional LCIs in manufacturing paint operations. The thesis will then formulate protocols for practical application of reference LCI data across a range of North American vehicle assembly facilities and North American-market vehicle types.

1.2.1 Objective #1: LCI for manufacturing paint process

The thesis will examine the feasibility and practicality of collecting accurate and representative environmental impact data by completing an LCI for the automobile paint process – a key process in vehicle manufacture and assembly and one that is acknowledged as being environmentally significant. The dataset collected will be submitted to a public LCI database intended for use by LCI practitioners and is expected to lead to future DfE opportunities at the partnered manufacturer, including manufacturing process improvements and an improved materials selection process.

1.2.2 Objective #2: Guidelines for manufacturing paint process

The thesis will develop detailed guidelines to facilitate future additional LCI activities. The guidelines will enable LCI practitioners to assess the environmental impacts of manufacturing paint processes at other facilities and for other industries (e.g., 'white goods' manufacture).

1.2.3 Objective #3: protocols for industry application of paint LCI data

The thesis will formulate protocols for applying paint LCI information across different North American manufacturing facilities and North American-market vehicle types. Protocol development will reference and analyze environmental impact data from the completed automotive paint LCI. The formulation of protocols for industry application of paint LCI information will also inform Objective #2, contributing to the guidelines for future LCI completion. These protocols will also allow industry to better incorporate manufacturing LCI data into future environmental impact reduction efforts, such as DfE activities (i.e., either directly or indirectly via Design-to-Cost and economic-based benchmarking activities).

1.3 Scope

For each of the thesis objectives, scope is set to ensure project feasibility and adequate rigor in analysis. Industry applications of the research findings, however, will be shown to extend beyond the target manufacturing process through manufacturing process-oriented LCI guidelines and LCI data application protocols.

1.3.1 LCI and guidelines for manufacturing paint process

A research partnership has been established with a single North American-based Original Equipment Manufacturer (OEM). As per voluntary industry directive, the manufacturing LCI will be completed for a single North American vehicle assembly facility operated by the OEM. The LCI will quantify: (i) materials use, (ii) energy use, and (iii) emissions. The LCI system boundaries will be constrained to the materials use, energy use, and emissions incurred during the painting process (i.e., gate-to-gate within the selected assembly facility).

The manufacturing LCI will be limited to the automotive paint process. This is a key process in vehicle manufacture and assembly and is acknowledged as being environmentally significant due to the large quantities of chemicals, solvents and coatings involved as well as the high energy requirements of process equipment. To allow completion of the automotive paint LCI within project timelines, three key process sub-modules in the automotive paint process are scoped for assessment: (i) Pretreatment, (ii) E-coating, and (iii) Top Coat. Lessons learned from completion of the scoped LCI will allow development of guidelines to facilitate future LCI activities in automotive manufacturing.

1.3.2 Protocols for industry application of paint LCI data

The reference LCI dataset collected in Objective #1 is intended to be ‘scalable’ for predicting the environmental impacts of manufacturing at different facilities and for differing vehicle types. For the reference LCI dataset to be useful, however, application protocols (i.e., scaling protocols) are needed. The effects of several variables on LCI scaling will be assessed using detailed materials use data from the reference LCI dataset. A ‘test case’ will then be used to predict paint process materials use at a different facility operated by the partnered OEM, manufacturing a different vehicle type. The selected second facility uses a similar paint process as the assembly facility used to develop the reference LCI dataset and sources process materials from the same supplier pool.

1.4 Confidentiality

A confidentiality agreement has been signed with the partnered OEM and with the OEM's principle paint process supplier. Accordingly, it is understood that research activities do not constitute an audit of proprietary processes, technologies or performance. Final results will be reported in a normalized format (i.e., employing an appropriate functional unit) and are selected to represent typical North American industry practices. To investigate industry-wide applications and develop corresponding protocols, however, interim results require reporting data in 'raw' format before being normalized. For both the partnered OEM and their associated process material supplier, process-specific details such as marketed product names will be replaced with generic names to ensure confidentiality.

2.0 BACKGROUND

2.1 LCI in the automotive industry

A prominent Life Cycle Inventory (LCI) for a 'generic' North American-based automobile was completed by Sullivan et al. in 1998. This broad study aggregated environmental impacts of a 'generic' mid-size vehicle over its entire life cycle and has been useful in subsequent material innovation and recycling research. LCA studies for a 'generic' automobile have also been completed by Keoleian (1997) and Graedel and Allenby (1998). Vehicle model-specific SLCAs, with aggregate eco-ratings, have been prepared by Dyson (1994) and Thomas and DeCicco (1999); these also resulted in simplified consumer-oriented publications intended to inform environmentally responsible vehicle purchases.

However, detailed and up-to-date LCI data does not exist at this time for the majority of the Manufacturing / Assembly processes associated with the North American-based automotive industry. A comparative LCI for automotive paint has been used to compare competing paint processes but was not intended for general application by LCI practitioners via a publicly available LCI database (Papasavva et al. 2002).

Furthermore, while the need for an LCI on the automotive paint process has been strongly expressed, several challenges have been identified as possibly preventing its completion. These challenges include obtaining industry cooperation in data collection, developing a representative paint formulation, and managing and categorizing the variety of processes (Athena 2001a).

2.2 Life cycle stages of the automobile

There is increasing OEM and consumer interest in 'green' automobiles, driven by growing environmental and social awareness and rising fuel costs. Yet, defining a 'green' automobile is not straightforward. New technologies – such as the hybrid gasoline / electric drive train – or indicators such as high fuel efficiency ratings or low tailpipe emissions cannot entirely define a 'green' automobile because they are limited to one portion of the automobile's life cycle and do not include the environmental impacts associated with its manufacture and assembly.

One way to rationalize the discussion of what constitutes a 'green' automobile is to consider its five key life cycle stages:

1. Pre-Manufacture;
2. Manufacturing / Assembly;
3. Product Delivery;
4. Product Use; and,
5. End-of-Life.

2.2.1 Pre-Manufacture

Pre-manufacture accounts primarily for acquisition and production of the raw materials required in automobile manufacturing (e.g., mining ores for metals production, mining petroleum for plastics production and gasoline / diesel refining, obtaining silica for glass production, etc.).

2.2.2 Manufacturing / Assembly

Manufacture / Assembly accounts for the use of acquired raw materials to manufacture the many subcomponents and components that comprise an automobile – increasingly the responsibility of Tier I and Tier II suppliers – as well as overall assembly of the vehicle itself by the OEM. Throughout this thesis, the generic single term "manufacturing" will be used to denote the manufacturing and assembly processes involved in vehicle production at an OEM vehicle assembly facility.

2.2.3 Product Delivery

Product Delivery includes packaging and shipping the vehicle to point-of-sale dealerships. Packaging is minimal, limited primarily to protective plastic sheeting over a small portion of the vehicle body panels as well as plastic sheeting over the seating areas (Graedel and Allenby 2003). For domestically assembled vehicles, shipment to point-of-sale dealerships is most often by transport trailer over intermediate distances and by rail over longer distances. Vehicles assembled overseas are transported by cargo ship before entering the OEM's transport trailer / rail network.

2.2.4 Product Use

For the automobile, Product Use is driving the vehicle to fulfill its intended transportation purpose. Primary environmental impacts during Product Use are the use of fuel (e.g., gasoline, diesel) as well as the creation of tailpipe emissions (e.g., NO_x, SO_x, HC, CO / CO_2, PM) over the vehicle's long service life. Natural Resources Canada bases their published fuel consumption ratings on an average annual driving distance of 20,000 km and a total vehicle life of 10 years (2005).

2.2.5 End-of-Life

End-of-Life involves retiring the vehicle from service and subsequent dismantling for recycling and/or disposal. European regulations require OEMs to re-claim their products for recycling and disposal, a program termed the End-of-Life Vehicle Directive (ELV). By 2015, ELV requires that 95% of a vehicle be recyclable (UK Environment Agency 2004). At the time of this writing, North American regulations do not include an explicit requirement for end-of-life recycling and disposal and it is unknown if such legislation would be introduced. However, the recovery of metal from a vehicle, which accounts for approximately 75% of its mass, has been quite successful in North America. The remaining 25%, consisting mainly of plastics, fibres, and other remnants, continues to be largely landfilled. (Five Winds 2003, Graedel and Allenby 2003)

Preliminary steps for facilitating increased end-of-life responsibility in North America are currently underway, partly because of the global marketplace many OEMs and suppliers operate in. These include a materials inventory of all automobile components (i.e., using the *International Material Data System*), and the collaborative effort of the North American OEMs to inventory major environmental impacts associated with automobile assembly in North America, including those of the Manufacturing / Assembly life cycle stage as will be demonstrated in this thesis.

2.3 Emerging importance of 'green' automobile manufacturing

The Product Use stage has previously been shown to dominate the overall environmental impact of the automobile, due to its use of non-renewable energy resources (i.e., gasoline or diesel fuel) and emissions of air pollutants over a long duration relative to the other life cycle stages (i.e., on average at least 8 years or 160,000 kms as per Transport Canada's 2000

Canadian Vehicle Survey). This dominance has led the majority of previous researchers conducting environmental impact analyses of the automobile to focus nearly exclusively on the Product Use stage (Graedel and Allenby 2003, Keoleian 1997, DeCicco 1999).

Recently, however, the North American OEMs have committed to assessing the environmental impacts associated with the Manufacturing / Assembly stage (USCAR 2005), with the ultimate goal of 'greening' their manufacturing processes and facilities. There are several compelling reasons for the increasing relevance of 'green' manufacturing and the need to conduct an assessment of environmental impacts for the automobile's Manufacturing / Assembly life cycle stage.

2.3.1 OEM control over environmental impacts in manufacturing

Of all the automobile's life cycle stages, the one where OEMs currently have the most control over environmental impacts is Manufacturing / Assembly. Many of the processes in the Manufacture / Assembly stage are within the OEM's sphere of influence at the vehicle assembly facility. Even outside the vehicle assembly facility, Tier I supplier processes can be affected by OEM component performance specifications, required / preferred materials and processes lists, and component sourcing policies.

In comparison, OEM control in the other life cycle stages is far more limited. Pre-Manufacture, for example, is a temporally and spatially extensive stage with significant associated environmental impacts, yet aside from material selection and supplier sourcing policies, it is typically beyond the reach of an OEM. Similarly, OEM control over the product's environmental performance in the Product Use stage is limited to pre-emptive control through vehicle component / system design that has been durability tested to approximate customer use over the service life and, secondarily, to incorporating diagnostics systems (e.g., OBDII) that assist vehicle servicing, setting OEM-recommended maintenance schedules, and offering comprehensive warranties to encourage prompt replacement of malfunctioning components / systems. OEM control over environmental impacts in the Product Delivery stage can be exercised through optimized assembly facility location but the vast distances that their products must travel for delivery to dealerships across North America (and, in some cases, worldwide), as well as the market and infrastructure-driven choice of transportation mode, limits the possibilities. Finally, OEM control over the automobile's environmental performance is also limited at the End-of-Life stage, although trends towards increased product stewardship are likely to increase OEM responsibility and control.

2.3.2 Increasing relative importance of manufacturing environmental impacts

While OEMs, regulators, and analysts have previously focused primarily on reducing the automobile's environmental impacts in Product Use, it is expected that the relative importance of reducing manufacturing environmental impacts will increase significantly. Somewhat ironically, this is due to technological advances in engine management and exhaust aftertreatment that have greatly reduced vehicle tailpipe emissions, as well as powertrain advances that have created the potential for greatly improved fuel efficiency.

Indeed, trends in tailpipe emission regulation and technologies show orders of magnitude decreases in primary criteria pollutants (e.g., NO_x, CO, PM) over the course of the automobile's current history (Mondt 2000). Tremendous fuel efficiency improvements have also been demonstrated, although a combination of consumer preference, weight increases (i.e., partially due to increased safety equipment content), and compromised fuel efficiency regulation has prevented the realization of significant fleet-wide fuel efficiency improvements. Vehicles using hybrid electric technology (HEV) are a current example of the potential for reduced tailpipe emissions and greater fuel efficiency. As HEVs and other vehicles with 'greener' powertrain technology become more common and come to represent a growing share of the North American market, the relative contribution of manufacturing to the vehicle's overall environmental impact may increase.

One tangible and current example is the increased battery content of HEVs. While most of the vehicles contain similarly sized 12V lead-acid batteries, HEVs contain a much larger on-board nickel metal hydride (Ni-MH) battery pack in addition to the conventional 12V lead-acid battery. This means that HEVs use significantly more metals (i.e., nickel in the on-board battery pack, copper in the windings of the electric motor) than conventional vehicles, to the point where market demand (and prices) for these metals is expected to increase as HEV production increases (Gottliebsen 2004). There are manufacturing environmental impacts associated with the greatly increased battery metals content of HEVs (e.g., battery manufacture, handling of batteries during vehicle assembly, etc.). (In addition to the effect on manufacturing, HEVs' increased battery content also represents increased environmental impact during vehicle disassembly at the End-of-Life stage.)

A large magnitude technological change to more 'green' automobile powertrains, such as the expected long-term development of the hydrogen fuel cell, will most dramatically demonstrate this effect. Hydrogen fuel cells are being aggressively developed by all three of the North American-based OEMs because they have the potential to essentially eliminate current tailpipe emissions (i.e., fuel cell vehicles emit only water vapour). They could also nearly eliminate dependence on non-renewable fossil fuels for the transportation sector. However, fuel cell vehicles would still have significant associated manufacturing environmental impacts, possibly comprising the fuel cell automobile's largest relative environmental burden (i.e., the source of the hydrogen fuel used in the Product Use stage could not be discounted, of course).

An additional point is that it is precisely during the transition and competition between conventional and various types of 'green' powertrain technologies that quantitative comparisons based on environmental impact – including manufacturing impact – will be most needed.

2.3.3 Environmentally responsible material use

Ecological and health and safety principles advocate selecting materials with low environmental impact. Additionally, an established mantra in environmental responsibility is to reduce material use (i.e., the Reduce-Reuse-Recycle hierarchy). A 'green' automobile must therefore consider material use.

The status quo focus on automobiles' Product Use stage, while important, essentially limits environmental responsibility to fuel resource use (i.e., energy) and tailpipe emissions. This is because the majority of the materials used in an automobile's life cycle is accounted for during Manufacturing / Assembly (e.g., type / mass of metal used in engine block casting, type and volume of chemical products used in body-in-white corrosion treatment and painting, type and mass of plastics used in vehicle interior assembly, etc.). Environmentally responsible material selection and use, therefore, demonstrates the importance of assessing the environmental impacts of the automobile's Manufacturing / Assembly life cycle stage.

2.3.4 Corporate citizenship

Canadian consumers have been shown to reward socially and environmentally responsible corporations and "punish" those that they perceive as being poor "corporate citizens" (Beauchesne 2005). Accordingly, North American-based OEMs are increasingly concerned with their corporate image, wanting to project an image to consumers, shareholders, and regulators that they are socially and environmentally responsible (DaimlerChrysler 2005, Ford 2005, General Motors 2005). Concern for a 'green' image makes 'green' manufacturing increasingly important to OEMs. Prominent evidence of this is seen in the substantial investment that one OEM has made to renovate one of their older manufacturing and assembly facilities into a showcase facility. This facility was redesigned using many leading-edge 'green' building technologies such as the use of renewable energy sources (e.g., solar cells, fuel cells), porous paving for storm-water runoff control, phytoremediation of facility grounds, intense landscape greening, and what is currently the world's largest green roof (Ford Motor Company 2005). All three of the North American-based OEMs feature 'green' manufacturing in their annual environmental reports and publicly disclose environmental data such as materials use, energy use, and emissions associated with their manufacturing facilities (DaimlerChrysler 2005, Ford Motor Company 2005, General Motors Corporation 2005). 'Green' success stories in vehicle manufacturing are often featured in the OEMs 'green' marketing campaigns, alongside 'green' automobiles themselves. These investment and marketing efforts are a demonstration that, in addition to reducing environmental impacts from the automobile's Product Use stage (i.e., fuel use, emissions), reducing environmental impacts in the Manufacturing / Assembly stage is also required.

2.3.5 Application to Design-for-Environment (DfE)

Design-for-Environment (DfE) refers to setting as a design objective targeted levels of environmental performance, thereby minimizing or at least reducing environmental impacts. Inclusion of Manufacturing / Assembly data in the DfE process would be useful to industry seeking more 'green' automobiles by providing quantitative product / process design input. As one example, it would allow quantitative characterization of the automobile's dominant life cycle stages that could then assist prioritization of automakers' DfE efforts. As another example, a demonstration that a currently used component material has significant and / or severe environmental impacts (e.g., health and safety concerns for assembly workers, reportable emissions to the environment, energy-intensive assembly) associated with its use in Manufacturing / Assembly would indicate to industry that a replacement material should be sought. This design change would provide a more 'green' Manufacturing / Assembly process and would by extension result in a more 'green' automobile.

2.3.6 Future application to eco-rating / eco-label systems

Consumers, industries, and regulators look increasingly to eco-ratings and eco-labels to identify and promote environmentally responsible products. The potential benefits of an eco-rating and eco-label system for the automobile are extensive: a viable eco-rating and eco-label system could facilitate environmentally informed consumer purchasing, OEM design, and regulator/industry policy decisions.

A recent example of a successful eco-rating and eco-label system in the Canadian market is the Canadian *EnerGuide* home appliance certification label (e.g., *EnergyStar*-rated home appliances). For the automobile, occupant safety has been well represented by the crash safety rating system (e.g., *5 Star Safety Rating*), to the point that recent legislation has proposed including the safety rating on the window stickers of all vehicles sold in the North American market (Rufford 2005).

At this time, however, a viable and comprehensive rating system for the automobile's life cycle environmental impacts (i.e., eco-rating and eco-labeling system) has yet to be developed and accepted. This is at least partially due to the current lack of data for environmental impacts associated with automobile manufacturing. In fact, each of the current attempts at an eco-rating or eco-labeling system has been limited by the exclusion of manufacturing environmental impact data. The yearly US-market publication *ACEEE's Green Book: the Environmental Guide to Cars and Trucks* (DeCicco and Thomas 2003), while perhaps the most visible independent attempt to provide consumers with an environmental impact rating for prospective vehicle purchases, has not been accepted as the standard for automobile consumer-targeted eco-rating and does not include environmental impact data from the Manufacturing / Assembly life cycle stage. The US EPA publishes an even less comprehensive eco-rating system, restricted to even fewer environmental impacts during the vehicle's Product Use life cycle stage (US EPA 2005). In Canada, Natural Resources Canada publishes the *EnerGuide Fuel Consumption Guide*, which is restricted to fuel consumption and CO_2 emissions during the vehicle's Product Use life cycle stage, with 'best in class' vehicle models then awarded recognition and advertised accordingly (Natural Resources Canada 2005). The European market has recently moved closer to an eco-label system yet even this system currently does not attempt to aggregate Manufacturing / Assembly environmental impacts (UK Department for Transport 2005).

As discussed in Section 2.3.2, the sustained status quo focus on reducing the automobile's environmental impacts during Product Use (i.e., fuel use, tailpipe emissions) is expected to increase the relative importance of reducing manufacturing environmental impacts, particularly as 'green' powertrain technologies are implemented more widely across the North American vehicle fleet. Correspondingly, eco-rating and eco-label systems will become increasingly limited if they cannot incorporate environmental impact data from other life cycle stages, including manufacturing. As 'green' manufacturing is increasingly prioritized by the automotive industry, future eco-rating and eco-labeling systems and other environmental metrics will need access to reliable and comprehensive Manufacturing / Assembly environmental impact data.

2.3.7 Application to non-automotive industries

Many automotive manufacturing processes have analogs in other, non-automotive, industries. As an example, the injection molding process used for many underhood engine components is used for a wide variety of consumer and household goods; likewise, the corrosion treatment and painting process used for the automobile's body-in-white is used for household white goods (e.g., refrigerators, washing machines).

Assessing the environmental impacts of the automobile's Manufacturing / Assembly processes can thus provide environmental performance data that can be applied to analog processes in other industries. As well, lessons learned about reducing environmental impacts for 'green' automobile manufacturing can potentially be adapted to allow 'greener' manufacturing of other consumer goods.

2.3.8 Stationary source emissions and health effects

Manufacturing facilities – including automobile manufacturing – create substantial environmental impacts in terms of materials use, energy use, and emissions. In addition to the automobile's mobile source emissions during the Product Use stage, stationary source emissions from automobile manufacturing facilities are consistently identified as significant in the literature (Graedal and Allenby 2003, Bosch Automotive Handbook 2000, Eckerman 2001).

The importance of stationary source emissions is demonstrated by their being regulated by the *National Pollutant Release Inventory* (NPRI) program legislated in Canada under the *Canadian Environmental Protection Act, 1999.* Automobile manufacturing and related facilities must report to the NPRI and are categorized under 'Transportation Equipment Industries' (i.e., 2-digit Standard Industrial Classification code 32). (Environment Canada 2005)

Air emissions from stationary manufacturing sources are particularly problematic as they can affect air quality locally and also regionally through long range transport mechanisms. Windsor, Ontario is an example of this effect. In addition to its local manufacturing facilities, modeling studies have shown that Windsor air quality is often affected by air mass paths traversing Michigan and Ohio, American states acknowledged for their manufacturing concentration (Anastassopoulos et al. 2004). Reliable and comprehensive Manufacturing / Assembly environmental impact data can assist future efforts to source-apportion air emissions to particular industries and even to particular manufacturing facilities.

2.4 Life Cycle Inventory

Life Cycle Analysis (LCA) involves a comprehensive examination of a product's environmental impacts over its complete life cycle. The key step in completing an LCA is the Life Cycle Inventory (LCI), which is essentially an accounting (i.e., inventory) at each of the product's life cycle stages of:

(i) materials use;
(ii) energy use; and,
(iii) pollutant emissions.

LCI can be thought of at an elementary level as a material and energy balance (i.e., input / output analysis) over the product's life cycle (ISO 14040:1997).

Although the LCI methodology itself is fairly well developed, it can be seen that completing a full LCI (i.e., all life cycle stages) would be resource and time-intensive; thus, streamlined LCA (SLCA) methods seek to preserve much of the quantitative detail of an LCA but offer practical improvements by limiting the life cycle stages and environmental impact parameters included in the analysis (Keoleian et al. 1994). SLCA methods typically use scoping to prioritize the life cycle stages that dominate a product's environmental impact (i.e., materials use, energy use, pollutant emissions). In addition to setting the LCI boundaries through scoping, further analysis assumptions and data collection simplifications (e.g., use of surrogate data) are typically used to determine the LCI procedures to be followed for a particular product (Graedel and Allenby 2003).

An LCA framework was first set by the Society for Environmental Toxicology and Chemistry (SETAC) in 1991 (Keoleian et al. 1994). The classical framework suggests that the following steps be followed in completing an LCI (Keoleian et al. 1994):

Step 1: Define purpose and scope of LCI.
Step 2: Define system boundaries.
Step 3: Devise an inventory checklist.
Step 4: Institute a peer review process.
Step 5: Gather data.
Step 6: Develop stand-alone data.

Step 7: Construct a computational model.
Step 8: Present the results.
Step 9: Interpret and communicate the results.

Several of these steps seem self-evident and are intended to ensure that 'best practices' are followed in managing the LCI. Steps 1 and 2 are intended to ensure a focused and achievable LCI process, given the inherent complexity of many products. Steps 3 and 4 are essential if the LCI is to adequately capture the particularities of an individual product and industries associated with its life cycle. Step 5 involves completing the materials use / energy use / pollutant emissions inventory; this is often the most time-intensive step, as it is limited by the reporting realities of the industries associated with the product at each scoped life cycle stage (e.g., manufacturing industry for manufacturing life cycle stage). Step 6 involves normalizing the gathered data over an appropriate functional unit to ensure legitimate and meaningful representation of the environmental impact data for the particular product and the specific life cycle stage. Steps 7 through 9 involve data analysis and development of data protocols for applying the life cycle impact information to other product examples or similar industries. Essentially, it is these data protocols and the subsequent application of the environmental impact data that can enable the LCI process to be a valuable tool to industry (e.g., for improved product design), consumers (e.g., for environmentally-informed product choices), and regulators (e.g., for setting environmentally-informed and industry-sensitive regulation).

2.4.1 LCI Functional Unit

Data collected for an LCI is normalized using a 'functional unit', allowing a reference dataset for comparability of LCA results (ISO 14040:1997) and scalability for broader application. As the name applies, the normalizing unit chosen should reflect the product's primary intended function during the life cycle stages included in the LCI (Graedel and Allenby 2003, Tam 2002).

To illustrate, the most commonly used functional unit for LCIs of the automobile's Product Use stage is *per kilometer*, reflecting the automobile's primary intended function of providing transportation over a distance. Environmental impacts are thus normalized on a *per kilometre* basis (i.e., material used per kilometre driven, energy use per kilometre driven, pollutant emissions per kilometre driven). Natural Resources Canada's published fuel consumption figures, which are expressed as litres of fuel consumed per 100 kilometres driven are in accordance with this functional unit (Natural Resources Canada 2005).

2.4.2 ISO Protocols

Starting with SETAC's classical LCA protocols, the International Standards Organization (ISO) codified the LCI protocols as the series of Environmental Management Standards 14040 through 14043.

ISO 14041 (i.e., Environmental Management – Life cycle assessment – Goal and scope definition and inventory analysis) is of particular relevance to this thesis, as it provides a standardized reference protocol for completing an LCI. This is shown simplified in Figure 2.1; each of the steps is also outlined below (ISO 14041:1998).

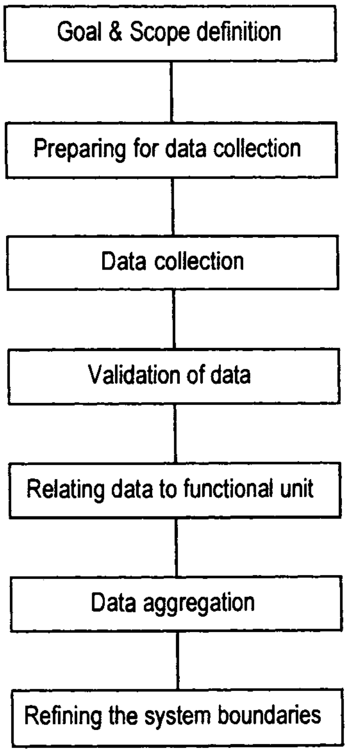


Figure 2.1: Simplified procedure for inventory analysis (adapted from ISO 14041:1998).

2.4.2.1 Goal and Scope definition

Goal definition involves determining and stating the reasons for carrying out the LCI, the intended application of the LCI data, and the LCI's intended audience. Scope definition involves setting the system boundaries for the study, deciding which unit processes to include and at what level of detail to include them. At the macro level, the scoping stage may decide to limit the life cycle stages included (e.g., restricting to Manufacturing / Assembly life cycle stage). At a finer level, scoping may decide which individual environmental impact parameters should be included.

2.4.2.2 Preparing for data collection

This step is intended to ensure that the product system (i.e., product or process) on which the LCI will be carried out is well understood. Recommendations include detailed descriptions of the processes involved (i.e., either through written descriptions or graphical process flow diagrams), specification of units of measurement, and description of data collection techniques.

2.4.2.3 Data collection

This step is often the most resource and time-intensive in the LCI process. It is simplified through the use of data collection sheets that consistently record not only the data (i.e., quantitative amount of material / energy) but also metadata (i.e., data quality indicators such as data source, data age, etc.) that will allow legitimate data analysis and facilitate peer review.

2.4.2.4 Validation of data

Data can be validated with mass / energy balances or similar summation techniques. Data gaps should be clearly identified and, where possible, corrected with appropriate surrogate data values or calculated data values.

2.4.2.5 Relating data to functional unit and data aggregation

Data is related to the functional unit using an appropriate reference flow (e.g., 1 kg of material). Input and output mass / energy flows can be aggregated as indicated by the resolution level required by the system boundaries or by the intended application and users of the LCI information.

2.4.2.6 Refining the system boundaries

Data analysis may show that additional data parameters or a different resolution level should be included in the LCI. Analysis tools such as sensitivity analysis can be used to determine if LCI system boundaries need to be refined and if additional data collection iterations are warranted.

2.4.3 LCI for Manufacturing / Assembly

There are several unique considerations associated with a Manufacturing / Assembly LCI, including the product-process distinction, functional unit, and the principle of process modularity.

2.4.3.1 Product-Process distinction

It is important to note that LCAs typically set out to determine the total environmental impacts associated with a *product* over its entire life cycle. At the Manufacturing / Assembly life cycle stage, however, it is more meaningful to consider that environmental impacts are being determined for a *process* (i.e., the Manufacturing / Assembly process). This distinction is useful in determining the primary intended function of the product or process, which is essential for developing an appropriate functional unit for the LCI. Essentially, for a product-based LCI (e.g., Product Use stage), this is the primary intended function of the product; for a process-based LCI (e.g., Manufacturing / Assembly stage), this is the primary intended function of the process.

ISO chooses inclusive language to simplify the product-process distinction; it terms the subject of an LCI a "product system", defined as "collection of materially and energetically connected unit processes which performs one or more defined functions". (ISO 14040: 1997)

2.4.3.2 Manufacturing / Assembly Functional Unit

For an LCI of the automobile's Manufacturing / Assembly life cycle stage, the primary intended purpose can essentially be stated as 'to manufacture / assemble the product', with 'manufacture / assemble' here serving as a placeholder term for each specific manufacturing and assembly process (e.g., the function of the automobile painting process is to provide a corrosion inhibiting, durable and decorative coating to the vehicle's body surfaces) (Bosch 2000).

2.4.3.3 Manufacturing / Assembly LCI Modules

The manufacture of complex products involves a series of many individual Manufacturing / Assembly processes to form the completed product. The automobile is a good example of complex manufacturing, with a myriad of separate processes taking place within the OEM's facility. An LCI of the automobile's Manufacturing / Assembly life cycle stage, therefore, can be restricted to the OEM's vehicle assembly facility. Such an LCI is termed a 'gate-to-gate' analysis, and is typical of LCIs for manufacturing operations (Graedal and Allenby 2003).

Assuming that consistent scoping is used, each manufacturing process in a gate-to-gate LCI can be viewed as a 'module' and subjected to a separate LCI. The completed LCI modules can then be aggregated to obtain the total (or at least more broadly scoped) LCI for the Manufacturing / Assembly life cycle stage.

In this approach, the total environmental impact incurred during Manufacturing / Assembly is equal to the sum of the environmental impacts incurred during each individual Manufacturing / Assembly process.

As an example for the automobile, the following expression can be written:

$$\begin{aligned}\text{TOTAL}_{\text{enviro impacts of automobile mfg/assy}} = \Sigma\ [&\text{body panel stamping}_{\text{enviro impacts}} \\ &+ \text{body welding}_{\text{enviro impacts}} \\ &+ \text{painting}_{\text{enviro impacts}} \\ &+ \text{drivetrain assembly}_{\text{enviro impacts}} \\ &+ \ldots]\end{aligned} \qquad [1]$$

This principle is scalable and holds for 'sub-modules' within a particular Manufacturing / Assembly process (e.g., automotive paint process is comprised of several sub-module processes, such as Pretreatment, E-coat, Top Coat, etc.).

3.0 NREL LCI DATABASE & AUTOMOTIVE PAINT PROCESS

3.1 NREL Database Project

The use of LCA in North America has been disadvantaged by the lack of widely available, comprehensive, and reliable LCI data. The LCI databases currently available are typically developed by a particular industry group or individual manufacturer, resulting in proprietary restrictions to use of the data and making verification of the data's applicability to other products or processes difficult.

To address these issues, the United States National Renewable Energy Laboratory (NREL), working with the Athena Sustainable Materials Institute (Athena) and several industry and research partners, is developing the United States Life Cycle Inventory Database Project (i.e., hereafter referred to as 'NREL LCI Database'). The NREL LCI database will allow LCA to be used by both the private and public sector in North America for environmentally oriented decision-making. (Athena 2001a)

To achieve this, the NREL LCI Database is intended to be a publicly available database of environmental impact information for materials, products, and processes commonly used by North American-based industries and consumers (NREL 2005). LCI data used to populate the database is developed in accordance with a common research protocol and is critically reviewed before publication in the database. The database, currently in beta, can be found online at *www.nrel.gov/lci* (NREL 2005).

3.1.1 Database Research Protocol

A key requirement of the NREL LCI Database is that all published LCI modules be ISO 14041-compliant. A separate and specific research protocol was developed to facilitate ISO 14041 compliance, as well as to reflect the particular needs of North American industry and the anticipated future use of the LCI database. This was developed in 2001 by Athena in association with Franklin Associates and Sylvatica (Athena 2001b) and was termed the *US LCI Database Project Research Protocol.* The protocol includes specific direction on issues that a North American-based LCI practitioner is likely to face, including scoping and boundaries, data format and communication, and data quality.

A companion document for data collection was also developed, termed the *Franklin Worksheet*. This is intended to facilitate consistent and ISO-compliant data collection and was accordingly adapted for use in this thesis work.

3.1.2 Database Modules

The NREL LCI Database will ultimately encompass nearly every material, product, and process that is relevant to the North American market. As populating this database is a formidable and time-intensive task, 'LCI modules' (i.e., LCI datasets for individual materials, energy sources or processes) were first scoped into several broad categories (adapted from Athena 2001b):

(i) Fuels, Energy, and Transportation;
(ii) Products and Materials (building and construction, automotive and durable goods, commodity chemicals and materials, packaging);
(iii) Transformation Processes; and,
(iv) End-of-Life (recycling, landfill, etc.).

Individual LCI modules were then prioritized in each of the four categories. The automotive painting process was one of three prioritized transformation processes, selected specifically because of its relevance to many other industries (Athena 2001a).

The modular approach of the NREL LCI database is intentional, as it allows modules to be combined and augmented to develop more complex LCIs or even full LCAs (Athena 2001a).

3.1.3 USCAR LCI Contributions

In 1992, the three North American-based OEMs formed an umbrella organization named United States Council for Automotive Research (USCAR). The goal of this organization was to cooperate on 'pre-competitive' issues and technologies, including environmental concerns. There are currently approximately 30 research teams active under USCAR, including a team examining the environmental impacts of vehicle recycling and disposal at the End-of-Life stage (i.e., Vehicle Recycling Partnership or VRP). (USCAR 2005)

The USCAR VRP team has recently agreed to provide LCI modules on several transformation processes in automotive manufacturing / assembly to help populate prioritized sections of the NREL LCI database. Each of the three North American-based OEMs in turn committed to an initial LCI module.

The partnered OEM's chosen commitment is a completed LCI module on the automotive paint process – a key process in vehicle manufacture and assembly and one that is acknowledged as being environmentally significant. Assembly Plant A, operated by the partnered OEM, was selected as the basis for the automotive paint LCI, with results to be reported in a normalized format (i.e., employing an appropriate functional unit) so as to represent typical North American industry practices and allow industry-wide application. The partnered OEM selected the University of Windsor as a research partner for completing the paint process LCI.

3.1.4 Anticipated future uses

The NREL LCI Database will provide a resource base for completing LCAs in North America. Intended users include manufacturers, researchers, and policy analysts and potential uses include environmental impact-based DfE (e.g., manufacturing improvements, materials selection and innovation) and benchmarking, prioritization of research and development, and more effective, industry-informed regulation. A longer-term anticipated use of the LCI data is for quantitative product assessment and 'eco-labeling'. (Athena 2001a)

3.2 Automotive paint process

The function of the automobile painting process is to provide corrosion protection to the vehicle's body structure (i.e., body in white) and a durable and decorative coating to the vehicle's outer body panel surfaces (Bosch 2000). The paint process must accommodate the various metals used in modern automobile architecture (e.g., cold rolled steel, galvaneal, aluminum).

3.2.1 Generic paint process

At its most fundamental level, the automotive paint process can be simplified to two categories of unit processes:

(i) Surface preparation; and,

(ii) Coatings application.

Surface preparation includes unit processes to ensure a clean surface for the coatings to bond to as well as application of a corrosion protection layer to metal surfaces. Coatings application involves applying a paint primer followed by a base paint coat and then finally a clear paint coat. (SBEAP 2002)

The unit process flow for one North American-based OEM is provided in Figure 3.1 (ARDC 2003). Each of the unit processes is summarized generically below (unless specified otherwise, all content adapted from ARDC 2003).

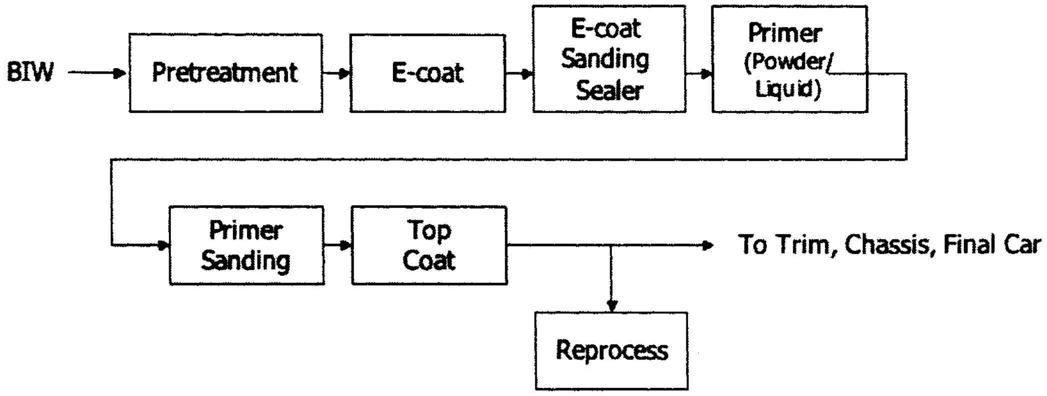


Figure 3.1: Unit process flow for a typical automotive paint process (ARDC 2003).

3.2.1.1 Pretreatment

Pretreatment involves cleansing the body in white's (BIW) metal body panels of metal fabrication residues (e.g., oil or water-based mill oils or drawing compounds from metal stamping, forming, and other metal fabrication processes) and surface corrosion (i.e., uncoated metal oxidizes rapidly with exposure to air). Chemical highlighters are also typically applied to facilitate detection of imperfections in the metal surface.

The resulting clean bare metal surface is essential for successful zinc phosphate coating. The zinc phosphate coating is the key stage in Pretreatment as it provides both corrosion resistance as well as a good surface for subsequent paint adhesion. The importance of phosphating can be summarized by stating that the automotive paint process "paints phosphate, not steel". (PPG 2003)

The materials typically used in Pretreatment (e.g., cleaners, phosphate) are applied by passing the BIW through a series of both spray booths and immersion tanks. Pretreatment is typically concluded with a thorough rinse using deionized water, ensuring that materials applied in the pretreatment unit process are not carried through to the E-coat unit process (i.e., "drag-out").

3.2.1.2 E-coat

Electro-coating (E-coat) involves immersing the phosphated BIW into a tank filled with primer paint in aqueous solution. The primer paint layer is then deposited on the BIW by the principle of electrodeposition, allowing the paint to reach inner panel surfaces and cavities that cannot easily be coated using conventional immersion tanks. In the e-coat tank, the BIW functions as a cathode (i.e., negatively charged electrode) and the surrounding aqueous paint solution functions as an anode (i.e., positively charged electrode). By applying a voltage difference across the two electrodes, the paint is electrically attracted to the BIW, forming a tightly packed coating. As the paint coating thickness increases, the BIW becomes electrically insulated, slowing and finally ending paint deposition at the desired coating thickness.

The purpose of the e-coat layer is to provide further corrosion protection and a uniform paint film. E-coating also provides an adhesion interface for additional coatings to be added in subsequent unit processes (i.e., primer, top coat) and contributes to improved chip resistance.

As mentioned above, the electrodeposition step takes places in an immersion tank (i.e., E-coat tank). Following this, the BIW is rinsed using deionized water to minimize drag-out and then passed through a heated oven to allow the electrodeposited paint coating to cure.

3.2.1.3 E-coat sanding / Sealing

The E-coat Sanding / Sealing unit process begins with sanding any defects that may occur in the BIW's e-coat paint layer. As the E-coat process is inherently highly effective, required corrective sanding is typically minimal.

E-coat sanding is followed by robotic and manual applications of sealer to the BIW's seams and flanges. The purpose of applying sealer to the BIW is to prevent the entry of moisture, thereby further enhancing corrosion inhibition. In addition to the application of sealer, Noise Vibration Harshness (NVH) dampers are also applied as required (e.g., mastic pads).

3.2.1.4 Primer

The Primer unit process involves application of an additional primer paint layer to the BIW (i.e., atop the E-coat primer layer). Similar to the e-coat layer, the primer layer augments corrosion resistance, improves adhesion of the subsequent coatings (i.e., top coat), and promotes chip resistance. Primer is typically applied both robotically and manually in a downdraft paint spray booth and can be either liquid-based or powder-based.

3.2.1.5 Primer sanding

In Primer Sanding, any defects that may occur in the BIW's primer paint layer are sanded out. Required corrective sanding is typically limited.

3.2.1.6 Top coat

The Top Coat unit process comprises a base coat paint layer followed by a clear coat paint layer. It is the base coat that first gives the BIW its intended colour.

Initially, the BIW is prepared by ensuring the primed surface is clean; methods include using air (i.e., either blowing by fan or sucking by vacuum) or mechanical dusters (e.g., feather dusters). This is followed by manual spray application of the base coat paint to areas that are difficult for robotic spray application to reach, such as engine bay walls, door jambs, and the vehicle interior. The base coat is then applied to the exterior surfaces of the vehicle in up to two passes: the first pass is applied using automated multi-axis sprayheads called 'bells', which electrostatically atomize the paint to improve deposition. The second pass is applied using more conventional robotic spray application and is typically reserved for metallic paints.

After the base coat has been applied (i.e., either one pass or two pass system), the BIW is allowed adequate 'flash time' during which water and/or solvents (i.e., dependent on whether water-borne or solvent-borne base coat paint is specified) are volatized from the base coat paint and the base coating becomes largely solid (i.e., 'dries'). Flash time often incorporates a heat / light energy booth to accelerate the drying process. This is followed by an additional flash time during which the now-heated BIW is allowed to cool before the subsequent clear coat application.

The function of the clear coat layer is to provide UV protection to the painted vehicle surfaces and to enhance the paint's decorative function. The clear coat application process is analogous to the base coat process, comprising manual spray application to areas that are difficult for robotic spray application (e.g., engine bay walls, door jambs, vehicle interior), and typically two passes of spray application to exterior surfaces using bells and robotic sprayheads.

The completed base coat and clear coat layers are finally cured in an oven employing both radiant heat and convective heat.

Base coat and clear coat paints can be either liquid-based (i.e., either solvent borne or water borne) or powder-based (PPG 2005). All spray booths in the top coat process use a downdraft design.

3.2.1.7 Reprocessing

Reprocessing introduces the possibility of iteration to the automotive paint process, as BIWs with noted defects are taken off-line and cycled to appropriate preceding unit processes for correction. Reprocessing can require returning an entire BIW to a preceding unit process or can in some instances be expedited by removal of the defective body panel for repainting (e.g., door) and replacement with an inventoried panel.

3.2.2 Automotive paint process environmental impacts

It is generally accepted that, compared with all other automobile manufacturing processes housed at an OEM's assembly facility, the paint process is responsible for the majority of the facility's environmental emissions (Graedal and Allenby 2003, Papasavva et al. 2001).

Significant environmental emissions are released to air (e.g., volatile organic emissions), to wastewater (e.g., pretreatment chemicals and paint overspray in solution), and to land (e.g., waste paint solids from overspray collected from downdraft booths as sludge). Materials used are highly varied (e.g., pretreatment chemicals and solvents, organic coatings, biocides, pH additives, etc.) and processed in large volumes (i.e., immersion tanks must be large enough to adequately submerge a large BIW). Finally, energy use is substantial (e.g., maintaining immersion tank process temperatures, powering curing ovens, powering robotic spray equipment, powering moving assembly line, etc.).

Due to these significant environmental impacts and their relevance to many other industries, the automotive paint process was one of three transformation processes prioritized for the NREL LCI Database (Athena 2001a).

4.0 METHODOLOGY

4.1 Research strategy

Corresponding to the thesis objectives, research activities included:

(i) Completing an LCI for the automotive paint process;

(ii) Developing guidelines for conducting additional manufacturing LCI activities; and,

(iii) Formulating protocols for industry application of the collected paint LCI data.

The research methodology for each of the research activities is detailed below.

4.2 Industry partnership

The research was conducted over a two-year period through a partnership between the University of Windsor (i.e., Department of Civil and Environmental Engineering) and an OEM. An existing research partnership with the Automotive Research and Development Centre (ARDC), located in Windsor, Ontario, was also leveraged. The research also involved reporting to USCAR's Vehicle Recycling Partnership (VRP) team, comprised of representatives from DaimlerChrysler, General Motors, and Ford Motor Company. Subsidiary partnerships were also initiated with two of the partnered OEM's supplier organizations: a paint supplier and an energy provider.

Initially, four graduate students comprised the University of Windsor research team, including this author. LCI data for the Pretreatment sub-module were collected collaboratively by all four graduate students and were partially presented in a Master's thesis (Abdulrahem 2004). LCI data for the E-Coat and Top Coat sub-modules were collected collaboratively by two graduate students, including this author. Throughout the duration of the research, this author was designated as team leader and research partner contact (i.e., client contact), under the supervision of Professor Edwin Tam.

4.2.1 Selection of manufacturing process for LCI research

The LCI research was initially motivated by the partnered OEM's commitment to provide a completed LCI on a key process in automotive manufacturing / assembly for populating the US LCI Database Project to be administered by NREL (i.e., NREL LCI Database). The partnered OEM selected the automotive paint process for their inaugural contributed LCI module. The automotive paint process was specifically selected because it has been classified as a "high priority" transformation process by the US LCI Database advisory group, due to its relevance to many other industries and due to its significant associated environmental impacts (Athena 2001a). The other OEM members of USCAR selected alternate manufacturing processes (e.g., engine block casting).

4.3 LCI & guidelines for automotive manufacturing paint process

Completing a manufacturing LCI for the automotive paint process corresponded to the first thesis objective. Results of the completed LCI dataset are presented in Chapter 5; detailed guidelines for future LCI work are presented in Chapter 6.

4.3.1 Overview

The general LCI project activities followed in the research were to:

- Define research goal and scope;
- Establish industry contacts;
- Obtain process flow information from suppliers;
- View process at assembly facility;
- Conduct LCI process flow mapping;
- Collect LCI data and conduct analysis; and,
- Prepare dataset / reports for the partnered OEM and USCAR.

4.3.2 ISO-compliance

The research ensured compliance with relevant LCI protocols (i.e., ISO 14041) by referencing the LCI protocol developed for the NREL LCI Database project in the "US LCI Database Project Research Protocol" (Athena 2001b) and by referencing the Franklin datasheet (Franklin 2003).

The research methodology sections that follow thus correspond to key activities in these LCI protocols (e.g., see Figure 2.1 for simplified ISO 14041 protocol), including:

(i) LCI goal definition;
(ii) LCI scope definition;
(iii) Data source identification;
(iv) Process flow mapping; and,
(v) Functional unit development.

4.3.3 Research methodology

4.3.3.1 LCI goal definition

The primary goal of the research project was to develop a representative LCI dataset on the automotive paint process for the partnered OEM DfE group's internal LCA database and, with appropriate normalization and aggregation to protect the partnered OEM's proprietary process technologies, for inclusion in NREL's public LCI database. An additional goal was to develop an effective set of guidelines (e.g., processes, contacts with personnel, source documents) to facilitate future additional LCIs on manufacturing / assembly processes.

In addition to contributing to the NREL database, the LCI dataset was expected to lead to future DfE opportunities at the partnered OEM, such as manufacturing process improvements and an improved materials selection process.

4.3.3.2 LCI scope definition

A representative facility was selected for the LCI. The resulting representative paint process was then scoped down to several sub-modules for feasibility and associated assumptions were formulated.

<u>Representative facility</u>

The US LCI Database Project required that example datasets used to populate the database be representative of their respective industry. It was recommended that the partnered OEM's assembly plant A be used for the automotive paint LCI. Assembly plant A was chosen because of its accessibility to the University of Windsor research team as well as for its close coordination with the Automotive Research and Development Centre (ARDC), which operates an experimental paint shop that could be used as a reference automotive paint process. Although there are process variations among the many paint shops in North American-based assembly facilities (e.g., differing technology levels dependent on age of plant and recent paint shop upgrades, use of liquid-based paint compared with use of powder-based paint, etc.), assembly plant A's paint shop and associated processes were accepted as representative of the majority of the North American-based OEM assembly facilities.

Paint process scoping

In accordance with standard LCI practice, it was determined that the automotive paint LCI would include:

- (i) materials use;
- (ii) energy use; and,
- (iii) pollutant emissions.

The environmental parameters scoped for the paint process LCI are shown in Figure 4.1 below.

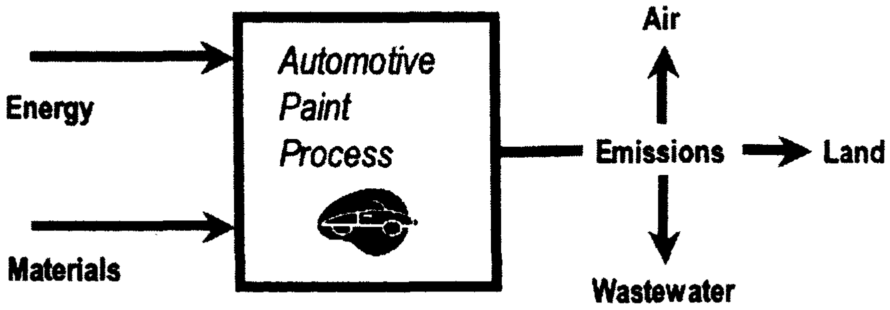


Figure 4.1: Environmental impact parameters scoped for automotive paint process LCI.

The variety in the seven sub-processes that comprise the automotive paint process (e.g., Pretreatment, E-coat, etc.), along with their attendant data collection particularities, was identified as a challenge to completing a true gate-to-gate LCI (Athena 2001a). Project time constraints were an additional concern, as the process mapping (i.e., materials, energy, emissions flows) and data collection for each sub-module was expected to be resource and time intensive.

For this reason, the automotive paint process was scoped down to prioritize the most significant sub-modules for inclusion in the LCI, within project time constraints. The scoping criteria were set as follows:

(i) Select sub-modules that contribute significant quantitative environmental impacts (i.e., material use, energy use, emissions); and,

(ii) Select sub-modules that can serve as surrogates for other sub-modules that are not selected. For example, several Top Coat unit processes are similar to Primer processes.

Using these scoping criteria, three sub-modules were selected for inclusion in the LCI:

(i) Pretreatment;

(ii) E-coat; and,

(iii) Top Coat.

The three scoped sub-modules were agreed to represent a combined majority of the quantitative environmental impacts associated with the automotive paint process. The scoping is summarized in Figure 4.2.

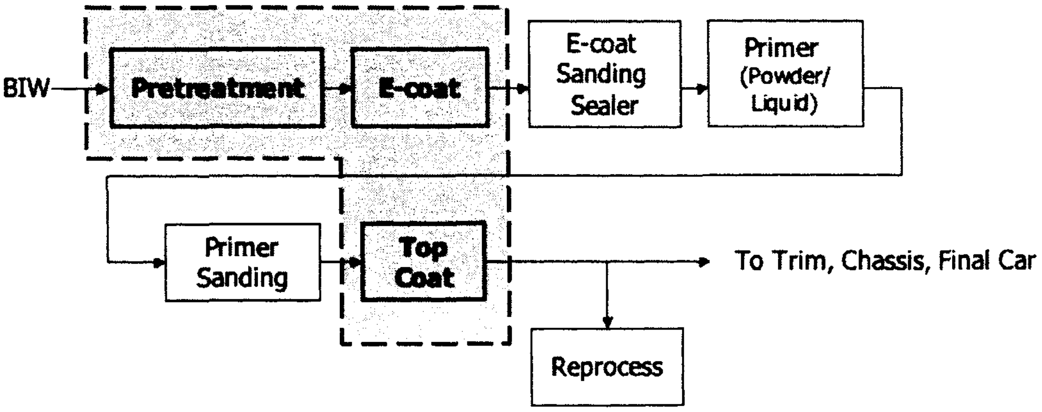


Figure 4.2: LCI system boundaries scoped for paint pretreatment process.

The LCI system boundaries would thus be constrained to the materials use, energy use, and pollutant emissions incurred during the painting process as represented by the three primary scoped sub-modules.

It was decided that the Pretreatment sub-module would be treated as a 'test sub-module', and completed first; lessons learned during completion of the Pretreatment LCI would improve the research team's methods (e.g., use of process flow mapping, efficient data collection) for the remaining sub-modules.

Global assumptions

Several global assumptions were made at the outset of the project, as listed below:

(i) Assembly plant A manufactures two vehicle models, a minivan and a crossover. As the two vehicles share a common vehicle platform design, and to simplify the LCI dataset required for reporting to NREL, model-specific data was aggregated to a single representative vehicle model for assembly plant A. The effects of this assumption were examined during development of LCI application protocols, as detailed in Chapter 7.

(ii) Data types collected on environmental impacts and related parameters (e.g., production volumes) included measured, calculated, and estimated data. Data sources included public and internal reports and documents. Characterization of data quality involved reporting data type and source for all data used in the research.

(iii) LCI analysis was restricted to the primary process border, as depicted in Figure 4.1. (e.g., mass of material input is considered, but environmental impacts incurred during manufacturing and transportation of the material to the automotive paint process are not considered.)

(iv) Environmental impacts of the conveyor assembly used to transport the BIW through the paint process were not included in the LCI.

4.3.3.3 Data source identification

Detailed quantitative information was required on all materials used (e.g., paint, solvents, etc.), energies consumed (e.g., electricity), and emissions created (e.g., atmospheric, wastewater, solid, packaging) for the scoped automotive paint process modules at assembly plant A. Quantitative information on assembly plant A production volumes and BIW surface area were also required for normalization with the developed functional unit.

The data collection targeted the 2003 calendar year as this was the most recent year during which both production of both vehicle models took place and for which complete data was consistently available. Possible data sources were initially identified and are listed in Table 4.1.

Table 4.1: Possible data sources identified for automotive paint process.

Parameter	Records (2003)	Source	Data Type (i.e., Quality)
Materials use	Monthly Pay As Painted Report	Supplier	Measured/Calculated
	VOC Report	OEM	Calculated
	Annual Water Usage Report	OEM	Measured
Energy use	Process energy audit	Energy provider	Calculated
Emissions	NPRI Report	OEM	Calculated
	VOC Report	OEM	Calculated
	Wastewater Report	OEM	Measured
Production volume	Monthly Pay As Painted Report	Supplier	Measured
	Calendar Year Production Report	OEM	Measured
	VOC Report	OEM	Measured
	NPRI Report	OEM	Measured
Surface area of BIW	VOC Report	OEM	Calculated
	CAD model data	OEM	Calculated

Where the identified data sources could not provide data for a particular environmental parameter, additional data sources were sought, including pre-2003 sources.

Although collecting a complete dataset (i.e., quantified materials / energy / emissions) was desired for each sub-module, some environmental impact parameters proved more difficult to obtain. As overall project timelines extended beyond the thesis, it was expected that outstanding data could be collected and prepared for additional reporting to the partnered OEM and NREL.

In addition to completing the LCI dataset for the automotive paint process, an analysis on the data sources was completed and guidelines on 'best practice' data sources for completing similar manufacturing LCIs were developed. Criteria considered included: accessibility, representation, comparability between paint sub-modules (i.e., also facilitating aggregation), and comparability between OEM assembly facilities (i.e., facilitating application of LCI data to other facilities).

4.3.3.4 Process flow mapping

Standardized LCI procedures typically recommend process flow mapping before the data collection process (ISO 14041:1998). It is expected that process flow mapping will provide the LCI practitioner with an improved understanding of the process to be inventoried. This is because, in many instances, an LCI practitioner is outside the industry. Process flow mapping can also ensure a more comprehensive LCI by systematically identifying all possible materials / energy / emissions flows that require data collection. However, process flow mapping can be a resource and time intensive process, particularly for complex and multi-stage manufacturing processes.

LCI process flow maps are analogous to industrial process flows common in manufacturing facility design but are intended to graphically depict materials, energy, and emissions flows in a process. It is important to note that the LCI process flow map does not initially quantify amounts of materials, energy, and emissions involved in the process; the subsequent LCI data collection step is intended to quantify each identified flow. A generic and 'high level' LCI process flow map is shown in Figure 4.3. This is termed a 'high level' process flow map because it does not show the particularities of the bounded automotive manufacturing process.

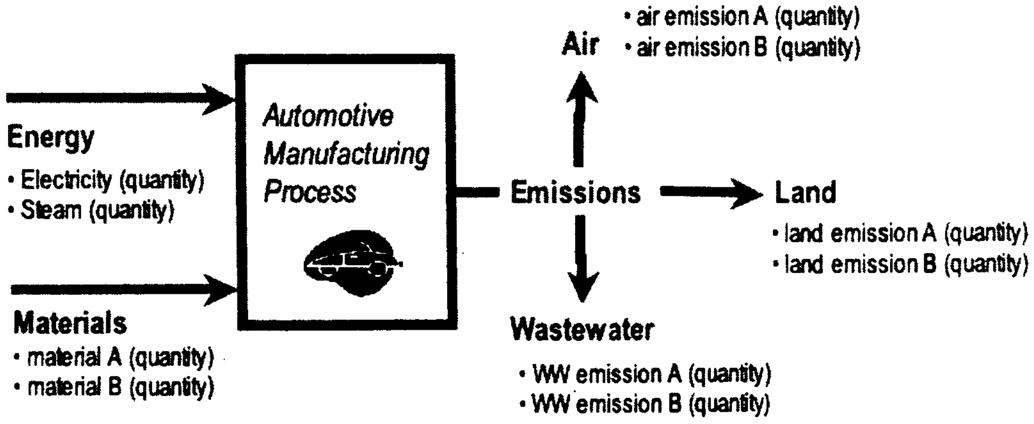


Figure 4.3: High-level LCI process flow map for generic automotive manufacturing process.

LCI process flow mapping would be completed for the Pretreatment sub-module, adapting the technique to the specifics of the automotive paint process. Process flow mapping would not be completed for the E-coat and Top Coat sub-modules, allowing the benefits of process flow mapping in LCI data collection to be evaluated against the associated resource and time demands.

To begin the LCI process flow mapping, a detailed industrial process flow for Pretreatment was obtained from the paint supplier. This provided the initial starting point for depicting the process, as well as the major equipment associated with Pretreatment. It was observed at this point that the Pretreatment sub-module was itself further sub-divided into nine distinct 'stages'. It was decided that LCI process flow maps would be prepared separately for each stage, corresponding to a 'high resolution' process mapping.

To further understand the Pretreatment stages and equipment, a tour of assembly plant A's Pretreatment assembly line was then arranged with OEM and paint supplier personnel. Upon completing the tour, the University of Windsor research team prepared an initial draft of the nine Pretreatment stage LCI process flow maps. This began an iterative review-and-revise process with representatives from the paint supplier and assembly plant A environmental specialists that culminated in agreed upon LCI process flow maps for each of the nine stages comprising Pretreatment. The results of the LCI process flow mapping process are included in Chapter 5.

4.3.3.5 Functional unit development

Selecting a preferred functional unit for normalizing and reporting the final LCI dataset required considering the intended primary function of the automotive paint process. The intended primary function was to 'paint' the BIW with the term 'paint' interpreted specifically at each sub-module: the Pretreatment sub-module 'treats' the BIW and the E-coat and Top Coat processes 'coat' the BIW. Consideration was also given to intended use of the LCI dataset, which is future application of the dataset to different production scenarios or production facilities (i.e., LCI data scaling).

Two candidate functional units were proposed for the paint process LCI:

(i) per vehicle (i.e., per vehicle painted)

(ii) per m^2 painted BIW

The use of each candidate functional unit in reporting and application of the LCI dataset was assessed and a preferred functional unit was selected for reporting to the partnered OEM for internal use and to NREL for use in populating the LCI database.

4.4 Protocols for application of paint process LCI data

Formulating protocols for industry application of the collected paint process LCI data corresponded to the third thesis objective. Results are presented in Chapter 7.

4.4.1 Overview

Applying LCI data involves 'scaling' a reference dataset to predict the environmental impacts of a different vehicle. The LCI data in the NREL LCI database, including the detailed automotive paint process dataset collected in this thesis, is intended to be 'scalable' across a range of North American market vehicle types and assembly facilities, allowing for practical application to new LCI and LCA activities.

To develop protocols for applying paint LCI data (i.e., LCI scaling protocols), the research first analyzed the effects of surface area, vehicle type, paint process, and production period length on LCI scaling. This analysis referenced the controlled conditions of the assembly plant A LCI dataset collected in the research.

Next, a 'test case' was used to represent an LCI practitioner using the NREL LCI database or OEM-selected LCI software (e.g., GaBi) to predict paint process environmental impacts at a different vehicle assembly facility manufacturing a different vehicle type. Using the 'test case', two specific scaling protocols were formulated and assessed.

For protocol development purposes, quantitative analysis was restricted to LCI materials use data and limited to the E-coat and Top Coat sub-modules. This allowed a more manageable dataset while preserving the key automotive paint process types (e.g., E-coat primarily uses an immersion tank process, Top Coat primarily uses spray booth processes).

4.4.2 Development of LCI application protocol

In developing the paint process LCI for the first objective in this thesis, data for the two vehicle models manufactured at assembly plant A were aggregated. The intermediate collection of model-specific LCI data, however, afforded an opportunity to develop scaling protocols. That the two vehicle models are manufactured using identical paint processes at the same facility serves as a desirable control, eliminating many variables that would otherwise be present if considering a different facility.

Several quantitative comparisons were made between the vehicle models with respect to their associated materials use. The data was examined at the sub-process resolution level (e.g., materials use in E-coat, materials use in Top Coat). Vehicle model-specific data was sourced from assembly plant A's *Pay As Painted Reports* and the *VOC Report* from the 2003 calendar year. Four variables were analyzed for their effect on applying reference LCI data: surface area, vehicle type, paint process, and production cycle length.

4.4.2.1 Surface area effect on LCI scaling

The research assessed whether surface area is the dominant vehicle characterization parameter in the paint process, consistent with the *per* m^2 *painted BIW* functional unit and industry's use of surface area-based reporting for painting operations. For the two vehicle models, the percentage difference between painted surface area was compared against the percentage difference between materials use (i.e., E-coat, Top Coat sub-modules). It was expected that a straightforward LCI data application protocol which uses direct linear scaling would be demonstrated by a similar 'scaling ratio' for both painted surface area and materials use. To represent scenarios where the LCI practitioner does not have access to painted surface area, reference values were developed for use as a surrogate surface area; these referenced both vehicle type and vehicle size (i.e., determined from readily available external vehicle dimensions).

4.4.2.2 Vehicle type effect on LCI scaling

The possible effect of vehicle type on LCI scaling protocols was assessed. 'Vehicle type' was used in this research to distinguish the vehicles for sale in the North American marketplace by their basic functional configuration (e.g., minivan, crossover, sedan, pickup truck); it was suggested that vehicle type can be highly simplified for the purposes of LCI scaling.

4.4.2.3 Paint process effect on LCI scaling

The research examined whether LCI data scaling results will differ between paint process sub-modules or process types, representing scenarios where an LCI practitioner selects sub-modules that best apply to their manufacturing process. The E-coat and Top Coat sub-modules were selected to represent the key paint process types, which are immersion tank coating application and spray booth coating application. The analysis compared materials use for both vehicle models, including detailed materials use by colour in the Base Coat unit operation.

4.4.2.4 Production period effect on LCI scaling

The effect of production period on LCI data application was assessed. It was expected that LCI scaling should be limited to a minimum dataset size (i.e., production period length), because the paint process contains unit operations that are relatively independent of vehicle production rates (e.g., immersion tanks).

4.4.3 Test case: application to different facility

The test case represented an LCI practitioner using the NREL LCI Database to predict paint process environmental impacts at a different vehicle assembly facility manufacturing a different vehicle type. The test case also represented the protocols required for future DfE work using OEM-selected LCI software (e.g., GaBi).

The site-specific LCI materials use data collected in this thesis for assembly plant A was applied to a different assembly plant operated by the partnered OEM (i.e., assembly plant B) using two scaling protocols: BIW painted surface area with production volume, and surrogate BIW painted surface area with production volume. The two scaling protocols were selected to represent key situations for LCI practitioners using the NREL database.

For each scaling protocol, site-specific materials use data for assembly plant B were used to verify effectiveness and associated uncertainty of results. Assembly plant B data were sourced from the 2004 calendar year *VOC Report*. In 2004, assembly plant B manufactured sedan models, allowing investigation of LCI scaling to different vehicle types.

4.4.3.1 Scaling protocol I: painted surface area

A scaling equation was formulated based on BIW painted surface area and production volume. Using known painted surface areas for assembly plant B vehicle models, the reference LCI dataset from assembly plant A (i.e., NREL LCI Database) was scaled to predict annual materials use at assembly plant B (i.e., E-coat, Top Coat sub-modules).

4.4.3.2 Scaling protocol II: surrogate painted surface area

A scaling equation was formulated based on production volume and an appropriate surrogate BIW painted surface area for the vehicle models at assembly plant B. Thus, referencing a surrogate painted surface area for a similarly sized sedan vehicle type, the reference LCI dataset from assembly plant A was scaled to predict annual materials use at assembly plant B (i.e., E-coat, Top Coat sub-modules).

5.0 AUTOMOTIVE PAINT LCI RESULTS

5.1 Overview

To develop the manufacturing LCI on the automotive paint process, the research procedure detailed in Chapter 4 - Section 4.3 was followed. This chapter presents the results of this research activity, including:

- LCI process flow maps for the Pretreatment sub-module and analysis of their usefulness to the manufacturing LCI process;
- Functional unit selection appropriate to the paint LCI;
- Data sources and data collection process for the materials, energy, and emissions associated with the Pretreatment, E-coat, and Top Coat sub-modules;
- Completed detailed inventories of materials, energy, and emissions for the Pretreatment, E-coat, and Top Coat sub-modules.
- LCI dataset normalized using selected functional units for submission to the partnered OEM and NREL, in both tabular and graphical formats.

5.2 LCI process flow maps

LCI process flow mapping was developed for the automotive paint process by applying it only to the Pretreatment sub-module; it was not initially used for the other paint sub-modules studied. The intent of selectively applying process flow mapping to the LCI process was to evaluate the benefits of process flow mapping in LCI data collection compared with its associated resource and time demands, as well as to determine the appropriate resolution level at which LCI process flow maps should be constructed.

5.2.1 Pretreatment

Constructing LCI process flow maps for Pretreatment began with obtaining background information on the pretreatment process, including a summary of its major unit operations. This is depicted graphically in Figure 5.1.

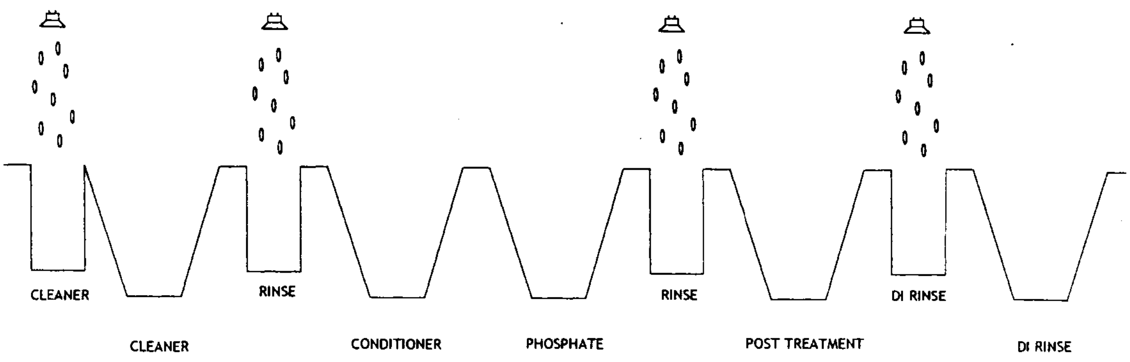


Figure 5.1: Major unit operations comprising the automotive pretreatment process (adapted from ARDC paint shop presentation material, 2003).

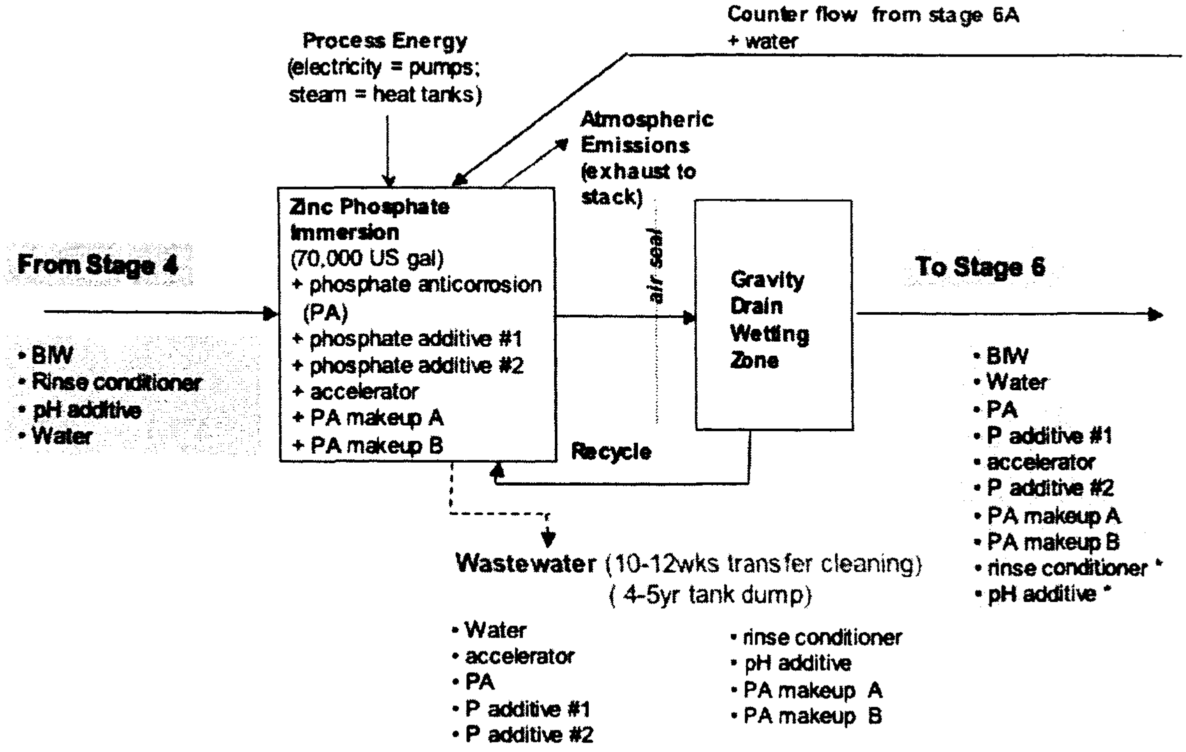
The paint pretreatment itself is subdivided into nine distinct stages. It was decided to prepare separate LCI process flow maps for each of these nine stages, yielding high-resolution process flow maps (i.e., materials / energy / emissions flows at each stage).

The paint supplier, who was responsible for designing, maintaining, and supplying the pretreatment process, provided a detailed industrial process flow for assembly plant A. The industrial process flow included information on major equipment at each pretreatment stage along with quantitative information on equipment capacity, flowrates, maintenance intervals, etc.

The detailed industrial process flow served as the starting point for developing the LCI process flow maps for each Pretreatment stage. Constructing the LCI process flow maps required a more comprehensive understanding of the process, however, so the industrial process flow was supplemented by a tour of the Pretreatment process at assembly plant A, guided by the paint supplier's resident engineer. Had an industrial process flow not been available, the site tour would have served as the next-best starting point for the LCI process flow maps.

From information on the industrial process flow, the plant tour, and several review-and-revise meetings with the paint supplier and environmental specialist personnel at assembly plant A, the LCI process flow maps were finalized as adequately representing the materials / energy /

emissions flows at each Pretreatment stage. Figure 5.2 shows an example LCI process flow map for the phosphating stage, considered the key stage in Pretreatment.



* Materials could still be present from previous stages (trace amounts).
Note: Phosphate anticorrosion makeup A & B are used as needed.

Figure 5.2: LCI process flow map for phosphating stage of Pretreatment.

Constructing the separate process flows for each Pretreatment stage was both time and resource intensive. The time load was estimated at 74 person-hours; the resource load included the need for suitable contacts at assembly plant A (i.e., environmental specialist) and at the paint supplier (i.e., resident paint shop engineer), access to proprietary and detailed process-specific information (e.g., industrial process flow), and access to view the functioning Pretreatment process at assembly plant A. A timeline of activities needed to obtain finalized process flows for the Pretreatment sub-module is presented in Table 5.1.

Table 5.1: Activity timeline for Pretreatment sub-module LCI process flow mapping.

[illegible]	[illegible]	[illegible]	[illegible]
Establish contacts	10	2	At ARDC, then at assembly plant A. Email, phone calls, possible meeting needed.
Plant tour (assembly plant A) and defining scope/objectives	12	4	Includes a tour of all modules, followup, and checks.
Obtain and analyze industrial process flows	12	4 *	*Occurs simultaneously with plant tour.
LCI process flow mapping (iterative)	40	3	9 Pretreatment stages, 3 iterations of mapping
Total	**74**	**9**	

Expected benefits of completing the stage-by-stage LCI process flow maps included providing the LCI practitioners with an enhanced understanding of the Pretreatment process and assisting the data collection process (i.e., quantification of the materials / energy / emissions flows). The LCI process flow maps succeeded in providing a detailed depiction of the unit processes involved at each Pretreatment stage that took into account details such as 'drag through' (i.e., Pretreatment materials that remain on the BIW and are carried through in significant or trace amounts to the next stage) and recycle flows. The stage-by-stage LCI process flow maps also showed where Pretreatment materials are specifically used. For example: phosphate is vital to the Pretreatment process but is applied to the BIW at only one stage; deionized water is vital to Pretreatment but is applied to the BIW in several of the nine stages.

The expected benefit to data collection, however, was not realized. Although the LCI process flow maps depicted the materials / energy / emissions at each stage in Pretreatment, LCI data was generally only available for the entire Pretreatment sub-module as aggregate amounts, a decidedly lower resolution level. Thus, LCI data collection was limited by the resolution of the available data.

For example, material use data was available only as total quantities of Pretreatment materials used. The materials could be partially apportioned, since some were used exclusively in a single stage; often, however, materials appeared in several stages or in more than one type of process operation (e.g., most materials are applied to the BIW by immersion followed by spray application), making it difficult to reliably apportion their usage quantity to the individual stages. Similarly, available emissions data could not be source apportioned to the individual process stages. However, energy data could be compiled at the stage-by-stage resolution level, since it was calculated data based on individual equipment power ratings and time.

As a result of these limitations, the detailed LCI process flow maps were abstracted to a lower resolution LCI process flow map. The system boundary included the entire Pretreatment process and aggregated all nine stages. The lower resolution LCI process flow map now corresponded to the resolution of the available data and could be used effectively for LCI data collection and reporting. It also enabled simplified comparisons between paint process sub-modules (i.e., Pretreatment vs. E-coat vs. Top Coat). The aggregated LCI process flow map for Pretreatment is shown in Figure 5.3 below.

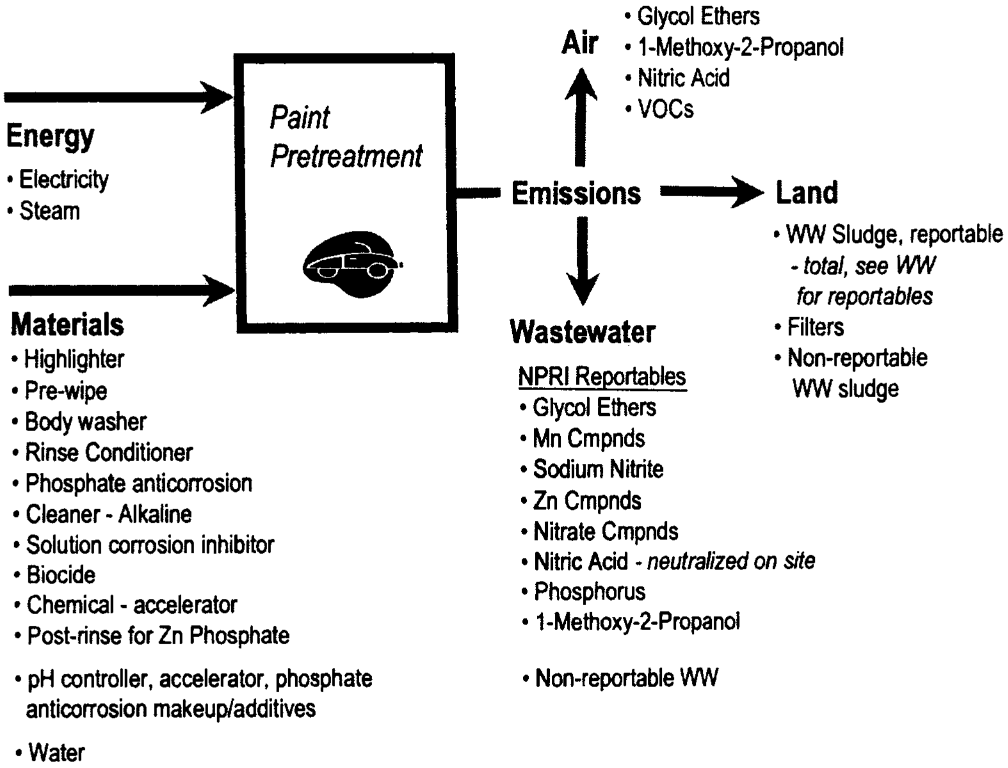


Figure 5.3: Aggregated LCI process flow map for Pretreatment.

5.2.2 E-coat

LCI process flow maps were not constructed for the separate stages of the E-coat sub-module. However, since carrying out the LCI still required knowledge of the E-coat process, a graphical summary of its major unit operations was obtained. This is depicted in Figure 5.4.

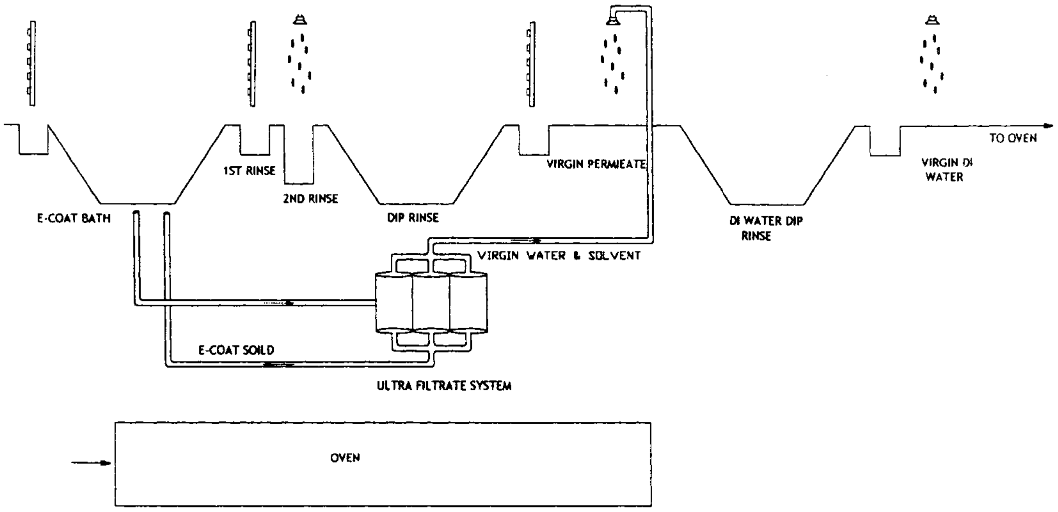


Figure 5.4: Major unit operations comprising the automotive E-coating process (adapted from ARDC paint shop presentation material, 2003).

5.2.3 Top Coat

LCI process flow maps were not constructed for the separate stages of the Top Coat sub-module (i.e., Base Coat, Clear Coat). As well, although summary information on its major unit operations was sourced, a graphical summary of these was not available.

5.3 LCI data collection

5.3.1 Functional unit for normalization

The two functional units proposed for the paint process LCI were:

(i) per vehicle

(ii) per m^2 painted BIW

While both functional units have use in reporting data meaningfully, it was decided that the preferred functional unit is *per m^2 painted BIW*. This was because *per m^2 painted BIW* most closely reflected the stated intended primary function of the automotive paint process (i.e., painting is a surface treatment of the BIW) and the actual paint process mechanism, which involves surface interactions. This preferred functional unit was reviewed at a USCAR VRP meeting and was agreed to by the partnered OEM and the other USCAR VRP team representatives.

The preferred functional unit is also in agreement with environmental reporting already in place at the partnered OEM and other OEMs; internal materials use and VOC emissions reports, for example, use a similar surface area-based normalizing unit.

The *per vehicle* functional unit, however, was deemed to be useful for providing a more intuitive and immediately practical quantification of manufacturing environmental impacts as it is directly based on production volumes. Production volume based reporting reflects typical manufacturing management practice and can be as useful for simplified public reporting. Thus, intermediate LCI results presented to the partnered OEM's management employed both the *per m^2 painted BIW* and the *per vehicle* functional units.

5.3.2 Data sources and data collection process

5.3.2.1 Production volume

Production volumes were required to allow data normalization to the preferred functional unit (i.e., *per m^2 painted BIW* requires quantification of the number of BIWs completing the paint process) as well as to the *per vehicle* functional unit.

Several possible data sources were identified for assembly plant A production volumes, including both public and internal proprietary reports. Table 5.2 lists the combined production volumes at assembly plant A for the 2003 calendar year from three of the available sources (i.e., both vehicle models). Results for the paint supplier's *Monthly Pay as Painted Report* were not made available for the entire 2003 calendar year and are not shown.

Table 5.2: Production volumes for 2003 calendar year (combined vehicle models).

Data Source	Public / Internal	Reporting Period	Publisher	Production Volume
Calendar Year Production Report	Public	Annual	OEM	287,127
NPRI Report	Public	Annual	OEM	287,127
Monthly Pay as Painted Report	Internal	Monthly	Paint supplier	N/A
VOC Report	Internal	Annual	OEM	285,875

The public and internal reported production volumes were in close agreement (i.e., 0.5% difference). Thus, where only publicly available production volume data is available, it can be used with some confidence.

However, in selecting a data source for production volumes, the most accurate quantification of vehicles completing the automotive paint process was desired, corresponding to the preferred functional unit. For the automotive paint LCI project, the internal *VOC Report* was selected as a preferred data source and these production volumes were used to normalize the LCI materials use, energy use and emissions data. Reasons for this include data resolution, data consistency, data availability, and relation to the painting process.

Data resolution

The internal *VOC Report* provides production volume data for both vehicle models. This allows calculation of model-specific parameters (e.g., weighted average BIW painted surface area, as discussed in section 5.3.2.2 below) and production volume comparisons between vehicle models.

Data consistency

The internal *VOC Report* includes a comprehensive reporting of several LCI data parameters needed in the analysis. Specifically, the *VOC Report* provides data for:

- production volume;
- BIW painted surface area;
- materials use; and,
- VOC emissions.

Vehicle model-specific data were available for the production volume and BIW painted surface area. Materials data is taken from paint supplier reporting; thus, although the *VOC Report* is technically a second source document for materials use, it essentially duplicates the less easily obtained supplier materials reporting. VOC emissions data is calculated and represents the bulk of airborne emissions associated with the paint process.

The comprehensive nature of the *VOC Report* ensures consistency among these four data parameters (i.e., production volume, BIW painted surface area, materials use, VOC emissions).

Data availability

Internal reports of production volume are often linked to manufacturing process-specific financial data (e.g., materials sold are billed based on precise usage on painted BIWs). Typical of for-profit enterprise, this results in a precise and closely monitored metric that can benefit auxiliary data collection such as LCI work. However, the financial reporting content also renders them highly proprietary, complicating accessibility even where a confidentiality agreement has been signed, as was experienced in this research.

End-of-line vs. painting process production

Public production volumes provide end-of-line production (i.e., number of complete vehicles exiting the assembly line for shipment to dealers and sale to customers). While these are 'true' production volumes for vehicles exiting the assembly facility system boundary, they may not be a 'true' representation of the number of vehicles undergoing production processes within the assembly facility boundary, due to rework and other in-process redundancies that the end-of-line production volumes ignore. This may lead to under / over-representing the production volumes associated with the manufacturing process. A general LCI recommendation was thus made to use production volume data that most accurately represents the manufacturing process being inventoried. It is also generally noted that this may differ from one manufacturing process to another.

Paint is an example of a manufacturing process where this under / over-representation can occur. Internal reports provide process-specific production volumes that incorporate any rework that occurred (e.g., vehicles are inspected for paint quality at several points in the paint process and those with noted paint flaws may be sent through a second time for re-paint). Taking an extreme example, a vehicle that is deemed to require a complete repaint due to manufacturing or quality issues would be counted correctly as the equivalent of two vehicles in internal paint process reporting, as it was painted twice – once initially and then again in rework. However, the assembly plant's end-of-line public reporting would show only a single vehicle.

Although in this instance the public end-of-line and the internal paint process-specific volumes do not demonstrate this phenomenon (i.e., the internal production figures were slightly lower than the end-of-line figures, within a calculated 0.5% difference), data for other facilities obtained in this research shows that 'reprocess' volumes can be significant. The partnered OEM's data for assembly plant B designates several thousand vehicles as "reprocess" in the *VOC Report* for the 2003 calendar year, associated with a model changeover.

5.3.2.2 BIW painted surface area

As the preferred functional unit selected for the automotive paint LCI is *per m^2 painted BIW*, obtaining data on the BIW painted surface area is vital. Initial consideration was given to using the total BIW surface area from CAD data. However, closer investigation of the paint process and discussions with the partnered OEM's environmental specialists showed that the 'painted' surface area is not necessarily the same as the total surface area. Although the majority of the BIW is treated and coated (i.e., attaining the required corrosion protection), the true 'painted' surface area depends on BIW geometry (e.g., complex body panel shapes, cavities, access / drainage holes) as well as the painting process itself. The proprietary 'painted' surface area is published by the partnered OEM in the *VOC Report* as "vehicle surface area" and this was selected as the data source for BIW painted surface area.

The *VOC Report* shows that the two vehicles assembled at plant A have slightly differing BIW painted surface areas, as would be expected by their differing slightly in size and shape. Corresponding to the *VOC Report*, a weighted average of the two BIW surface areas – based on the production volume for each vehicle model – was used to normalize the aggregated LCI data for the *per m^2 painted BIW* functional unit. Due to data limitations, it was not practical to collect or apportion LCI materials / emissions / energy separately to each vehicle model being manufactured at the facility.

That the BIW painted surface area is a function of the paint process is demonstrated by the *VOC Report's* use of different vehicle surface area figures for the scoped sub-modules. Pretreatment vehicle surface area, specifically, was found to differ for the crossover platform from E-coat and Top Coat vehicle surface area. This can be explained by the differences in the Pretreatment process (e.g., comprised of several immersion stages) and the particularities of the crossover BIW geometry. The minivan platform, in contrast, has the same vehicle surface area for all three scoped sub-modules.

Table 5.3 summarizes the BIW painted surface areas for both vehicle models, as well as the weighted average BIW painted surface area used in the normalization calculations for the preferred functional unit.

Table 5.3: Calculated BIW painted surface area used for *per m^2 painted BIW* functional unit.

Item	CS	RS	Weighted Average BIW Painted Surface Area
Pretreatment	1582 sq.ft.	1631 sq.ft.	1616.705 sq.ft. (150.2 sq.m.)
E-coat, Top Coat	1743 sq.ft.	1631 sq.ft.	1663.675 sq.ft. (154.6 sq.m.)
2003 CY production	83,401 vehicles	202,474 vehicles	--

By way of comparison, normalizing the aggregated LCI data with the *per vehicle* functional unit does not distinguish between the two vehicle models, implicitly assuming a common BIW painted surface area.

5.3.2.3 Materials inventory

The materials inventory sought data on supplied paint process materials (i.e., paint supplier's products) and water use for each of the scoped paint process sub-modules. As the OEM-partnered research project is ongoing and extends beyond the thesis, the materials data collected to date are tabulated below.

Paint process materials use

Paint process materials data were available from two sources: the *Pay As Painted Reports* published monthly by the paint supplier, and the internal *VOC Report* published annually by an environmental specialist at the partnered OEM. For the LCI, the *VOC Report* was selected for paint process materials use data.

The *VOC Report* can be considered secondary source, as it references the paint supplier's monthly reporting for its materials use data. Disadvantages to using the *VOC Report* for a materials inventory are those typical to any secondary source, including the possibility of error having been introduced into the data during its duplication. There are several distinct advantages provided by selecting the *VOC Report* for material use data, including those discussed in section 5.3.2.1.

The *VOC Report* can provide time savings to the LCI practitioner because it is available in electronic form (i.e., Microsoft Excel spreadsheet), eliminating time-consuming and error-prone data entry. Additionally, practice at the partnered OEM is that a single environmental specialist is responsible for preparing the *VOC Report* for several assembly facilities; the consistent report format thus facilitates dataset comparison between assembly facilities (i.e., primary source supplier reports may not use a consistent format for assembly facilities with competing paint suppliers).

Thus, the paint process materials data presented in this thesis are taken from the partnered OEM's *VOC Report*. Although the report provides partial data for individual vehicle models, results reported in this thesis are an aggregated total of the two vehicle models. All data is for the 2003 calendar year.

Paint process water use

Water use data was not available for the individual scoped sub-modules. This is because assembly plant A does not have water meters installed for individual paint process unit operations. Separate water metering is available for assembly plant A's New Paint Shop, however, which houses the Pretreatment, E-coat, and Sealer sub-modules; similarly, separate water metering is available for assembly plant A's Old Paint Shop, which houses the Primer and Top Coat sub-modules (i.e., Base Coat and Clear Coat). Metered water usage is reported by an environmental specialist at assembly plant A via a Microsoft Excel spreadsheet, which was made available to the University research team. Engineering estimates, developed with the environmental specialist at assembly plant A, were then used to apportion water use to the scoped sub-modules.

The calculations used to estimate water use for the Pretreatment and E-coat sub-modules are summarized in Table 5.4 below. The data is for the 2003 calendar year.

Table 5.4: Estimation of water use for Pretreatment and E-coat (2003 calendar year; combined vehicle models).

CALCULATION BASIS	TOTAL QUANTITY [m^3] or [L]
Annual total water use by New Paint Shop	1,346,526 m^3
Estimate: Pretreatment + E-coat	95%
Estimate: Sealer	5%
Annual total water use by Sealer	67,326.3 m^3
Annual total water use by Pretreatment + E-coat	1,279,199.7 m^3
Estimate: Pretreatment	75%
Estimate: E-coat	25%
Annual total water use by Pretreatment (rounded)	**959,400,000 L**
Annual total water use by E-coat (rounded)	**319,800,000 L**

The calculations used to estimate water use for the Top Coat sub-module are summarized in Table 5.5 below. The data is for the 2003 calendar year.

Table 5.5: Estimation of water use for Top Coat (2003 calendar year; combined vehicle models).

CALCULATION BASIS	**TOTAL QUANTITY [m^3] or [L]**
Annual total water use by Old Paint Shop	46,776 m^3
Estimate: Primer	33.3%
Estimate: Top Coat (Base Coat + Top Coat)	66.6%
Annual total water use by Primer	15,576 m^3
Annual total water use by Top Coat (rounded)	**31,153 m^3** **31,152,816 L**

5.3.2.4 Energy inventory

The energy inventory sought data on energy used for each of the scoped paint process sub-modules. Two energy inputs were identified for assembly plant A: electrical and heat energy (i.e., steam).

Electrical Energy

Electricity is used to power the various motors, conveyors and pumps associated with the paint process. The electricity is purchased from the province of Ontario at standard rates. Electricity use is not metered at assembly plant A by manufacturing process and apportioning total electricity use via engineering estimates is not recommended; the expertise to reasonably apportion energy use among the various manufacturing processes by estimation is not available in-house.

As a result, electricity use was based on an audit of equipment associated with the paint process sub-modules and then calculated using audited equipment power ratings. Coincident to the LCI research, assembly plant A had retained an energy consultant to audit various in-plant electrical systems. As part of this contract, a full equipment and electricity usage audit was completed for the Pretreatment and E-coat sub-modules.

Assumptions made in the energy consultant's energy calculations included:

(i) Equipment was assumed to operate at full capacity for 24 hours per day and 273 days per year; exceptions are several pumps in the E-coat process, which are assumed to operate at full capacity for 24 hours per day and 365 days per year.

(ii) Equipment power rating was multiplied by the time of operation to obtain a calculation of electricity use over the course of a specified time interval; and,

(iii) Motor efficiencies and loads are included in the calculations and were also determined by the energy consultant (i.e., expert engineering estimates).

However, the energy consultant was not able to complete a similar audit for the Top Coat sub-module; thus, electricity data is presented only for Pretreatment and E-coat. As the OEM-partnered research project is ongoing and extends beyond the thesis, it was expected that an equipment audit and calculation of electricity use would be completed by the University research team for the Top Coat sub-module at a later date. Due to time constraints and lack of access to in-house OEM expertise comparable to the energy consultant, however, the Top Coat electricity use data is expected to be less detailed than the Pretreatment and E-coat data presented in this thesis.

Heat Energy

Heat energy, in the form of steam, is used to maintain immersion tank temperatures in the scoped sub-modules. This steam is not generated onsite but imported from a nearby facility (i.e., purchased and transported by pipeline). The steam purchased for use by assembly plant A is waste byproduct for the seller and would otherwise be emitted to air. Information on the quantity of steam used by assembly plant A, or engineering estimates needed to apportion it to the scoped paint sub-modules, was not available.

5.3.2.5 Emissions

The emissions inventory sought data on emissions for each of the scoped paint process sub-modules. Relevant emission fates included: emissions to air, emissions to land, and emissions to wastewater.

Air emissions

Air emissions were expected to be significant for the paint process sub-modules, particularly for E-coat and Top Coat. Data sources included the *NPRI Report* and the *VOC Report* for the 2003 calendar year. The *NPRI Report* is prepared for assembly plant A by an external consultant; the *VOC Report* is prepared by an environmental specialist at the partnered OEM. Both documents are essential for the air emissions inventory, as the *NPRI Report* is restricted to regulated compound releases while the *VOC Report* provides calculated VOC emissions associated with the use of all materials subject to volatization.

The format of both reports allows air emissions to be separated by sub-module. While the *VOC Report* calculates VOC emissions based on volatization data for each material used in the scoped paint sub-modules, the reported releases provided by NPRI do not always enable source apportioning to individual materials. If two or more sub-module materials contribute to the same NPRI-reported compound, allocating the proportional contribution of each material is not readily calculated and is not recommended.

Land emissions

Land emissions were also expected to be significant for the paint process sub-modules, primarily due to sludge buildup associated with the immersion tank unit processes and the downdraft spray application booths. The primary data source used for land emissions information is the *NPRI Report* for the 2003 calendar year. Sludge is indicated by the *NPRI Report* as either 'wastewater treatment plant sludge' (e.g., to landfill) or 'paint sludge' (e.g., in Top Coat sub-module). Both wastewater sludge and paint sludge are sent offsite for treatment and disposal to land. The *NPRI Report* also specifies the quantities of regulated compounds that are sent to landfill as part of equipment filter disposal. The format of the *NPRI Report* allows separation of land emissions by sub-module but does not readily enable source apportioning to individual sub-module materials.

The *NPRI Report* is restricted to regulated compounds present as sludge (i.e., reportables); however, total sludge produced typically exceeds the reportable portion. For the Pretreatment sub-module, additional data was obtained for the key phosphating unit process from shipping manifest tracking sheets used to transport the sludge to offsite treatment and disposal.

However, the shipping manifest data employed an average of the 1999 and 2000 calendar years; the older datasets were used because reporting practices at assembly plant A changed as of the 2001 calendar year and sludge shipments are no longer monitored by environmental specialist personnel. The Pretreatment phosphating non-reportable sludge is included in the emissions inventory only to demonstrate the typical magnitude of difference between reportable and non-reportable sludge emissions.

Additionally for the Pretreatment module, a walk-through audit of containers was completed to identify waste containers typically used at assembly plant A in the storage and transport of process materials.

Wastewater emissions

Wastewater is also a significant emission of the paint process, particularly in immersion tank stages but also in the overspray collection system for downdraft spray application booths. The primary data source used for wastewater emissions information is the *NPRI Report* for the 2003 calendar year. Wastewater emissions are indicated by the *NPRI Report* as 'amount discharged to municipal sewage treatment plant'. The format of the *NPRI Report* allows separation of wastewater emissions by sub-module but does not enable source apportioning to individual sub-module materials.

Once again, the *NPRI Report* is restricted to regulated compounds present as wastewater (i.e., reportables) whereas total wastewater produced greatly exceeds the reportable portion. Total wastewater was thus calculated by applying an engineering estimate (i.e., developed with the environmental specialist at assembly plant A) to the total water use at each sub-module; this was calculated during the materials inventory portion of the LCI. This calculation assumed that 95% of water used at each sub-module goes to wastewater. The 95% engineering estimate was determined by comparing total annual water use with total annual wastewater sent for treatment for the entire facility in the 2003 calendar year. The 95% engineering estimate was further corroborated by similar calculations with water usage data for the 2002 and 2004 calendar years.

5.4 LCI data results

5.4.1 Materials inventory

The materials inventory for the scoped sub-modules at assembly plant A is shown in Table 5.6.

Table 5.6: Materials inventory for Pretreatment, E-coat, Top Coat (2003 calendar year; combined vehicle models).

GENERIC NAME	QUANTITY [illegible]	QUANTITY [L] or [kg]
PRETREATMENT		
Process Water [m^3] or [L]	959,400 m^3	959,400,000 L
Process Products		
Pre-cleaner	1,121 GAL	4,243.5 L
Accelerator	82,560 LB	37,448.6 kg
Phosphate	868,608 LB	393,994.0 kg
Phosphate (makeup)	825 LB	374.2 kg
Corrosion Inhibitor	69,281 LB	31,425.3 kg
Body Washer	141,154 LB	64,026.4 kg
Cleaner (alkaline)	167,059 LB	75,776.7 kg
Pre-wipe	228,811 LB	103,786.9 kg
Phosphate Post-rinse	103,204 LB	46,812.6 kg
Rinse Conditioner	49,545 LB	22,473.2 kg
E-COAT		
Process water [m^3] or [L]	319,800 m^3	319,800,000 L
Process Products		
E-coat resin	362,935 GAL	1,373,858 L
E-coat pigment	30,907 GAL	116,996 L
TOP COAT		
Process water [m^3] or [L]	31,184 m^3	31,184,000 L
Process Products		
Base Coat Application		
Almond (Metallic)	50,985 GAL	192,999.2 L
Dark Blue	37,873 GAL	143,364.9 L
White	43,695 GAL	165,403.6 L
Dark Red	5,057 GAL	19,142.8 L
Bright Red	49,681 GAL	188,063.0 L
Silver (Metallic)	85,716 GAL	324,470.4 L
Light Green	34,843 GAL	131,895.1 L
Dark Green (Metallic)	26,031 GAL	98,538.1 L
Light Blue	46,277 GAL	175,177.5 L
Black	31,340 GAL	118,634.8 L
Total Base Coat	*411,498 GAL*	*1,557,689 L*
Clear Coat Application		
Clearcoat	196,445 GAL	743,625.2 L
Tinted Clearcoat	29,605 GAL	112,067.1 L
Total Clear Coat	*226,050 GAL*	*855,692 L*

5.4.2 Energy inventory

The energy inventory for the scoped sub-modules at assembly plant A is shown in Tables 5.7 and 5.8. Energy results are aggregated for key electrically powered equipment (i.e., heat energy is not included). In Table 5.8, items marked with an asterisk denote equipment that was assumed to operate 365 days per year.

Table 5.7: Energy inventory for Pretreatment (2003 calendar year; combined vehicle models).

DESCRIPTION / LOCATION	HP	KW	Qty	kWh/Day	Design kWh/year	Actual kWh/year
Deluge Nozzle-Pump #1	40.0	29.84	1	571	208,563	155,993
Deluge Nozzle-Pump #2	40.0	29.84	1	571	208,563	155,993
Deluge Spray-Pump #1	40.0	29.84	1	571	208,563	155,993
Deluge Spray-Pump #2	40.0	29.84	1	571	208,563	155,993
STAGE SUBTOTAL				**2,286**	**834,250**	**623,973**
Stage #1-Preclean Spray-Pump #1	50.0	37.30	1	714	260,703	194,992
Stage #1-Preclean Spray-Pump #2	50.0	37.30	1	714	260,703	194,992
Stage #1-Preclean Spray-Pump #3	50.0	37.30	1	714	260,703	194,992
Stage #1 Pressure Filter Media Drive	0.5	0.37	1	7	2,607	1,950
Stage #1 Pressure Filter Pump	40.0	29.84	1	571	208,563	155,993
Entrance Air Exhaust Fan	7.5	5.60	1	107	39,105	29,249
Premix Tank Agitator	1.0	0.75	1	14	5,214	3,900
STAGE SUBTOTAL				2,843	1,037,599	191,092
Stage #2 Exhaust Fan	7.5	5.60	1	107	39,105	29,249
Stage #2 Clean Dip Pump #1	75.0	55.95	1	1,071	391,055	292,488
Stage #2 Clean Dip Pump #2	75.0	55.95	1	1,071	391,055	292,488
Stage #2 Clean Dip Pump #3	75.0	55.95	1	1,071	391,055	292,488
STAGE SUBTOTAL				3,321	1,212,270	906,711
Stage #3A Spray Pump	50.0	37.30	1	714	260,703	194,992
Stage #3B Spray Pump	50.0	37.30	1	714	260,703	194,992
Heat Exchanger Clean Tank	5.0	3.73	1	71	26,070	19,499
STAGE SUBTOTAL				1,500	547,477	409,483
Stage #4 Exhaust Fan	7.5	5.60	1	107	39,105	29,249
Stage #4 Conditioner Pump #1	60.0	44.76	1	857	312,844	233,990
Stage #4 Conditioner Pump #2	60.0	44.76	1	857	312,844	233,990
Phosphate Dip Ht Exch Clean TK	60.0	44.76	1	857	312,844	233,990
STAGE SUBTOTAL				2,678	977,637	731,219

Stage #5 Recirc. Pump #1	75.0	55.95	1	1,071	391,055	292,488
Stage #5 Recirc. Pump #2	75.0	55.95	1	1,071	391,055	292,488
Stage #5 Recirc. Pump #3	75.0	55.95	1	1,071	391,055	292,488
Stage #5 Pressure Filter Pump	40.0	29.84	1	571	208,563	155,993
Stage #5 Supply Fan	5.0	3.73	1	71	26,070	19,499
Stage #5 Pressure Filter Media Drive	0.5	0.37	1	7	2,607	1,950
Stage #5 Exhaust Fan	15.0	11.19	1	214	78,211	58,498
Conditioner Pit Sump Pump #1	5.0	3.73	1	71	26,070	19,499
Seal Flush Pump #1	2.0	1.49	1	29	10,428	7,800
Seal Flush Pump #2	2.0	1.49	1	29	10,428	7,800
Stage #5 Hot Water Pump #1	20.0	14.92	1	286	104,281	77,997
Stage #5 Hot Water Pump #2	20.0	14.92	1	286	104,281	77,997
Stage #5 Transfer Pump	50.0	37.30	1	714	260,703	194,992
STAGE SUBTOTAL				5,493	2,004,808	358,785
Stage #6A Spray Pump #1	50.0	37.30	1	714	260,703	194,992
Stage #6A Spray Pump #2	50.0	37.30	1	714	260,703	194,992
Stage #6B Recirc. Pump #1	60.0	44.76	1	857	312,844	233,990
Stage #6B Recirc. Pump #2	60.0	44.76	1	857	312,844	233,990
STAGE SUBTOTAL				3,143	1,147,094	857,963
Stage #7 Exhaust Fan	7.5	5.60	1	107	39,105	29,249
Stage #7 Chromic Dip Pump #1	50.0	37.30	1	714	260,703	194,992
Stage #7 Chromic Dip Pump #2	50.0	37.30	1	714	260,703	194,992
STAGE SUBTOTAL				1,536	560,512	419,232
Stage #8A DI Spray Pump #1	40.0	29.84	1	571	208,563	155,993
Stage #8A DI Spray Pump #2	40.0	29.84	1	571	208,563	155,993
Exit Air Seal Fan	10.0	7.46	1	143	52,141	38,998
Stage #8B DI Dip Pump #1	50.0	37.30	1	714	260,703	194,992
Stage #8B DI Dip Pump #2	50.0	37.30	1	714	260,703	194,992
Dump Tank Pump	50.0	37.30	1	714	260,703	194,992
STAGE SUBTOTAL				3,428	1,251,375	623,973
	PRETREATMENT TOTALS			**23,942**	**8,738,771**	**4,498,459**

Table 5.8: Energy inventory for E-coat (2003 calendar year; combined vehicle models).

DESCRIPTION	[illegible]	[illegible]	[illegible]	[illegible]	kWh/Yr (Design)	kWh/Yr (Actual)
* Stage #1-Circ-Pump #1	75.0	55.95	1	1,071	391,055	391,055
* Stage #1-Circ-Pump #2	75.0	55.95	1	1,071	391,055	391,055
* Stage #1-Circ-Pump #3	75.0	55.95	1	1,071	391,055	391,055
Dump Tank Pump #1	75.0	55.95	1	1,071	292,130	218,498
Dump Tank Pump #2	75.0	55.95	1	1,071	292,130	218,498
Dump Tank Pump #3	75.0	55.95	1	1,071	292,130	218,498
Stage #1 Supply Fan	5.0	3.73	1	71	19,475	14,567
Stage #1 Exhaust Fan	15.0	11.19	1	214	58,426	43,700
Anolyte Pump #1	7.5	5.60	1	107	29,213	21,850
Anolyte Pump #2	7.5	5.60	1	107	29,213	21,850
Pretreatment Additive Tank Agitator	5.0	3.73	1	71	19,475	14,567
Ozone Cenerator	1.0	0.75	1	14	3,895	2,913
* UF Feed Pump #1	100.0	74.60	1	1,429	521,406	521,406
* UF Feed Pump #2	100.0	74.60	1	1,429	521,406	521,406
* UF Feed Pump #3	100.0	74.60	1	1,429	521,406	521,406
UF Cleaner Pump	60.0	44.76	1	857	233,704	174,798
Seal Flush Pump #1	10.0	7.46	1	143	38,951	29,133
* Stage #1 Exit Circ. Pump #4	75.0	55.95	1	1,071	391,055	391,055
* Stage #1 Exit Circ. Pump #5	75.0	55.95	1	1,071	391,055	391,055
* Stage #1 Exit Circ. Pump #6	75.0	55.95	1	1,071	391,055	391,055
Stage #2 UF Rinse Pump #1	50.0	37.30	1	714	194,754	145,665
Stage #2 UF Rinse Pump #2	50.0	37.30	1	714	194,754	145,665
Stage #3 UF Rinse Pump #1	60.0	44.76	1	857	233,704	174,798
Stage #3 UF Rinse Pump #2	60.0	44.76	1	857	233,704	174,798
* Seal Flush Pump #1	10.0	7.46	1	143	52,141	52,141
Seal Flush Pump #2	10.0	7.46	1	143	38,951	29,133
Stage #4 UF Rinse Pump #1	40.0	29.84	1	571	155,803	116,532
Stage #4 UF Rinse Pump #2	40.0	29.84	1	571	155,803	116,532
Stage #5 UF Spray Pump #1	5.0	3.73	1	71	19,475	14,567
Stage #5 UF Spray Pump #2	5.0	3.73	1	71	19,475	14,567
Stage #6 DI Rinse Pump #1	60.0	44.76	1	857	233,704	174,798
Stage #6 DI Rinse Pump #2	60.0	44.76	1	857	233,704	174,798
Stage #6 Exhaust Fan	5.0	3.73	1	71	19,475	14,567
Stage #6 Supply Fan	5.0	3.73	1	71	19,475	14,567
Stage# 7 DI Rinse Pump#1	25.0	18.65	1	357	97,377	72,833
Stage# 7 DI Rinse Pump#2	25.0	18.65	1	357	97,377	72,833
Stage #1 Cleaner Pump#1	60.0	44.76	1	857	233,704	174,798
Stage #1 Cleaner Pump#2	60.0	44.76	1	857	233,704	174,798
Stage #2 Rinse Pump #1	50.0	37.30	1	714	194,754	145,665
Stage #2 Rinse Pump #2	50.0	37.30	1	714	194,754	145,665
Blow Off Supply Fan	20.0	14.92	1	286	77,901	58,266
Air Seal Exhaust Fan	3.0	2.24	1	43	11,685	8,740
Conveyor Shroud Supply Fan	5.0	3.73	1	71	19,475	14,567
E-COAT TOTALS				**26,342**	**8,184,947**	**7,120,706**

5.4.3 Emissions inventory

The emissions inventory is tabulated below for air emissions, land emissions, and wastewater emissions.

5.4.3.1 Air emissions

Reportable compound air emissions (i.e., NPRI air emissions) for the three scoped sub-modules at assembly plant A are presented in Table 5.9; there are no reportable compound air emissions for the E-coat sub-module. VOC air emissions for the three scoped sub-modules are presented in Table 5.10.

Table 5.9: Reportable air emissions for Pretreatment, E-coat, Top Coat (2003 calendar year; combined vehicle models).

Reportable Compound (NPRI)	TOTAL EMISSION (kg)
PRETREATMENT	
Glycol Ether	78
1-Methoxy-2-Propanol	23
Nitric Acid	17
TOTAL (aggregated)	118
E-COAT	
None	0
TOP COAT	
Base Coat	
Carbon Black	9
1-Methoxy-2-Propanol	4,796
Diethylene Glycol Butyl Ether	36
Ferric Oxide	36
Propylene Glycol Butyl Ether	73,148
Copper Compounds	1
Stoddard Solvent	12,568
Light Aromatic Solvent Naptha	2,409
Heavy Alkalide Naptha	37,459
2-Butoxy-Ethanol	231
TOTAL BASECOAT (aggregated)	130,693
Clear Coat	
Acetone	29,778
N-butyl Alcohol	35,054
1,2,4-trimethyl Benzene	25,525
Light Aromatic Solvent Naptha	106,352
TOTAL CLEARCOAT (aggregated)	196,709
TOTAL TOP COAT (aggregated)	327,402

Table 5.10: VOC emissions for Pretreatment, E-coat, Top Coat (2003 calendar year; combined vehicle models).

[illegible]	[illegible]	[illegible]	[illegible]
PRETREATMENT			
Pre-cleaner	1,121 GAL	0.77	391,525
Accelerator	82,560 LB	0	0
Phosphate	868,608 LB	0	0
Phosphate (makeup)	825 LB	0	0
Corrosion Inhibitor	69,281 LB	0	0
Body Washer	141,154 LB	0.04	2,561,033
Cleaner (alkaline)	167,059 LB	0.03	2,273,294
Pre-wipe	228,811 LB	0.0382	3,964,633
Phosphate Post-rinse	103,204 LB	0	0
Rinse Conditioner	49,545 LB	0	0
Total Pretreatment	--	--	**9,190,485**
E-COAT			
E-coat resin	362,936	0.11	18,108,602
E-coat pigment	30,907	0.13	1,822,507
Total E-coat	--	--	**19,931,110**
TOP COAT			
Base Coat Application			
Almond (Metallic)	50,985	1.55	35,845,931
Dark Blue	37,873	1.45	24,909,411
White	43,695	1.65	32,702,536
Dark Red	5,057	1.29	2,959,023
Bright Red	49,681	1.55	34,929,130
Silver (Metallic)	85,716	1.65	64,152,204
Light Green	34,843	1.38	21,810,236
Dark Green (Metallic)	26,031	1.35	15,940,075
Light Blue	46,277	1.6	33,585,431
Black	31,340	1.5	21,323,377
Total Base Coat	--	--	**288,157,354**
Clear Coat Application			
Clearcoat	196,445	3.9	347,513,217
Tinted Clearcoat	29,605	3.9	52,371,548
Total Clear Coat	--	--	**399,884,765**

5.4.3.2 Land emissions

Land emissions for the scoped sub-modules at assembly plant A are presented in Table 5.11. Reportable sludge and filter emissions to landfill were sourced from the *NPRI Report*.

For the Pretreatment sub-module, data sourced from shipping manifests allowed the total sludge to landfill to be calculated. An order of magnitude difference was observed between the mass of reportable sludge and total sludge, with total Pretreatment sludge shipped to landfill approximately ten times the mass of reportable sludge.

Table 5.11: Reportable and total sludge emissions for Pretreatment, E-coat, Top Coat (2003 calendar year; combined vehicle models).

Emissions to landfill	**TOTAL EMISSION [kg]**
PRETREATMENT	
Total sludge (shipping manifests)	**35,525**
Reportable sludge (NPRI)	**3,569**
Glycol Ethers	3
Mn Compounds	3,548
Zn Compounds	3
Phosphorus	14
1-Methoxy-2-Propanol	1
Reportable filters (NPRI)	**515**
Mn Compounds	122
Zn Compounds	391
Phosphorus	2
E-COAT	
Reportable sludge (NPRI)	**576**
Carbon Black	576
Reportable filters (NPRI)	**0**
TOP COAT	
Reportable sludge (NPRI) **– Base Coat Application**	**5,396**
Carbon Black	864
1-Methoxy-2-Propanol	5
Diethylene Glycol Butyl Ether	37
Ferric Oxide	3,611
Propylene Glycol Butyl Ether	739
Copper Compounds	88
Stoddard Solvent	13
Light Aromatic Solvent Naptha	2
Heavy Alkalide Naptha	37
2-Butoxy-Ethanol	0
Reportable sludge (NPRI) **– Clear Coat Application**	**197**
Acetone	30
N-butyl Alcohol	35
1,2,4-trimethyl Benzene	26
Light Aromatic Solvent Naptha	106
Reportable sludge (NPRI) **– Top Coat Application**	**5,593**

For the Pretreatment sub-module, a walk-through audit of packaging waste was completed to identify waste containers typically used at assembly plant A in the storage and transport of process materials. Waste containers were identified as "carboys" (i.e., 20 L containers of HDPE plastic) and filter boxes (i.e., 16" x 18" x 24" cardboard). Carboys are used by the paint supplier to transport biocide and pH buffer solution. Based on the annual use of these two process materials, the number of carboys disposed of annually was estimated at approximately 500 carboys. The annual disposal of filter boxes was not estimated; it should be noted, however, that the filter boxes are recycled by assembly plant A with other clean cardboard. As the packaging waste was shown to represent a small portion of the land emissions inventory, it was not included in the LCI data to be reported to NREL. This was in agreement with the '5% rule', which states that environmental impact quantities less than 5% of the total can be omitted from an LCI except where they represent severe toxicities (Graedal and Allenby 2003, Athena 2001b).

5.4.3.3 Wastewater emissions

Total and reportable wastewater emissions for the scoped sub-modules at assembly plant A are presented in Tables 5.12.

Table 5.12: Total and reportable wastewater for Pretreatment, E-coat, Top Coat (2003 calendar year; combined vehicle models).

[illegible]	[illegible]
PRETREATMENT	
Total wastewater	
Annual total water use by Pretreatment (see Section 5.2.2.3)	959,400 m^3
Annual total wastewater from Pretreatment (estimate 95% of water goes to wastewater)	911,430 m^3
Total reportable wastewater (NPRI)	**57,277 kg**
Glycol Ethers	7,703 kg
Mn Compounds	824 kg
Zn Compounds	790 kg
Nitrate Compounds	7,232 kg
Phosphorus	35,479 kg
1-Methoxy-2-Propanol	2,249 kg
E-COAT	
Total wastewater	
Annual total water use by E-coat (see Section 5.2.2.3)	319,800 m^3
Annual total wastewater from E-coat (estimate 95% of water goes to wastewater)	303,810 m^3
Total reportable wastewater (NPRI)	**1 kg**
Carbon Black	1 kg
TOP COAT	
Total wastewater	
Annual total water use by Top Coat	31,184 m^3
Annual total wastewater from Top Coat (estimate 95% of water goes to wastewater)	29,595,175 L
Total reportable wastewater (NPRI) **– Base Coat Application**	**8 kg**
Copper Compounds	8 kg
Total reportable wastewater (NPRI) **– Clear Coat Application**	**0 kg**
Total reportable wastewater (NPRI) **– Top Coat Application**	**8 kg**

5.5 Normalized LCI data summary

Materials, energy, and emissions data collected and presented in section 5.4 were normalized using the preferred functional unit (i.e., *per* m^2 *painted BIW*). To reflect the numerical range of the data, the preferred functional unit was multiplied by a factor of one thousand (e.g., *per 1000* m^2 *painted BIW*). Additionally, the data was normalized using the *per vehicle* functional unit.

The normalized LCI datasets prepared for submission to the partnered OEM and the NREL LCI Database are presented below. Datasets are presented separately for each of the scoped sub-modules in Tables 5.13 through 5.15.

Table 5.13: LCI data summary for Pretreatment (2003 calendar year; combined vehicle models).

Materials Usage	ANNUAL TOTAL	UNIT	/ 1000 m^2 painted BIW	/ VEHICLE
Pre-cleaner	4,243	L	0.10	0.01
Accelerator	37,448,590	g	872.15	131.00
Phosphate	393,993,960	g	9175.79	1378.20
Phosphate makeup	374,210	g	8.72	1.31
Corrosion Inhibitor	31,425,330	g	731.87	109.93
Body Washer	64,026,380	g	1491.12	223.97
Cleaner - alkaline	75,776,690	g	1764.78	265.07
Pre-wipe	103,786,920	g	2417.11	363.05
Phosphate Post-rinse	46,812,550	g	1090.23	163.75
Rinse Conditioner	22,473,230	g	523.38	78.61
Water Usage	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
Water	959,400,000	L	22343.62	3356.01
Electricity [illegible]	[illegible]	[illegible]	[illegible]	**/ VEHICLE**
Electricity	4,498,459	kWh	104.77	15.74

Emissions To Air	[illegible]	[illegible]	[illegible]	/ VEHICLE
NPRI reportable compounds	**118,000**	g	**2.75**	**0.41**
Glycol Ether	78,000	g	1.82	0.27
1-Methoxy-2-Propanol	23,000	g	0.54	0.08
Nitric Acid	17,000	g	0.40	0.06
VOC emissions	**9,190,485**	g	**214.04**	**32.15**
Pre-cleaner	391,525	g	9.12	1.37
Accelerator	0	g	0	0
Phosphate	0	g	0	0
Phosphate makeup	0	g	0	0
Corrosion Inhibitor	0	g	0	0
Body Washer	2,561,033	g	59.64	8.96
Cleaner - alkaline	2,273,294	g	52.94	7.95
Pre-wipe	3,964,633	g	92.33	13.87
Phosphate Post-rinse	0	g	0	0
Rinse Conditioner	0	g	0	0
Emissions To Water	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
Wastewater to WWTP (NPRI reportable + non-reportable)	**911,430**	m^3	**21.23**	**3.19**
Wastewater to WWTP (NPRI reportable)	**54,277,000**	g	**1264.07**	**189.86**
Glycol Ethers	7,703,000	g	179.40	26.95
Mn Compounds	824,000	g	19.19	2.88
Zn Compounds	790,000	g	18.40	2.76
Nitrate Compounds	7,232,000	g	168.43	25.30
Phosphorus	35,479,000	g	826.28	124.11
1-Methoxy-2-Propanol	2,249,000	g	52.38	7.87
Emissions To Land	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
Sludge to landfill (NPRI reportable + non-reportable)	**35,525,000**	g	**827.35**	**124.27**
Sludge to landfill (NPRI reportable)	**3,572,569**	g	**83.20**	**12.50**
Glycol Ethers	3,000	g	0.07	0.01
Mn Compounds	3,548,000	g	82.63	12.41
Zn Compounds	3,000	g	0.07	0.01
Phosphorus	14,000	g	0.33	0.05
1-Methoxy-2-Propanol	1,000	g	0.02	0.00
Glycol Ethers	3,569	g	0.08	0.01
Filters to landfill (NPRI reportable)	**515,000**	g	**11.99**	**1.80**
(a) Mn compounds	122,000	g	2.84	0.43
(b) Zn compounds	391,000	g	9.11	1.37
(c) Phosphorus	2,000	g	0.05	0.01
[illegible]	**ANNUAL [illegible]**	**[illegible]**	**/ 1000 m^2 [illegible]**	**/ VEHICLE**
Copper compounds	**1,966,000**	g	**45.79**	**6.88**

Table 5.14: LCI data summary for E-Coat (2003 calendar year; combined vehicle models).

Materials Usage	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
E-coat resin	1,373,858	L	31	4.81
E-coat pigment	116,995	L	2.65	0.41
Total paint process materials used	**1,490,854**	**L**	**33.73**	**5.22**
Water Usage	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
Water	**319,800,000**	**L**	**7235.90**	**1118.67**
Electricity Usage	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
Electricity	**7,120,706**	**kWh**	**161.12**	**24.91**
Emissions To Air	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
NPRI reportable compounds				
None	0	g	0	0
VOC emissions				
E-coat resin	18,108,602	g	409.73	63.34
E-coat pigment	1,822,507	g	41.24	6.38
Total VOC to air	**19,931,109**	**g**	**450.97**	**69.72**
Emissions To Water	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
Wastewater to WWTP (NPRI reportable + non-reportable)	**303,810**	**m^3**	**6.87**	**1.06**
Wastewater to WWTP (NPRI reportable)				
Carbon Black	1,000	g	0.02	0.0035
Total reportable compounds to water	**1,000**	**g**	**0.02**	**0.0035**
Emissions To Land	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
Sludge to landfill (NPRI reportable)				
Carbon Black	576,000	g	13.03	2.01
Total reportable compounds to land (sludge)	**576,000**	**g**	**13.03**	**2.01**
Filters to landfill (NPRI reportable)				
Carbon Black	0	g	0	0
Total reportable compounds to land (filters)	**0**	**g**	**0**	**0**

Table 5.15: LCI data summary for Top Coat (2003 calendar year; combined vehicle models).

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BASE COAT APPLICATION				
Almond (Metallic)	192,999	L	4.37	0.68
Dark Blue	143,365	L	3.24	0.50
White	165,404	L	3.74	0.58
Dark Red	19,143	L	0.43	0.07
Bright Red	188,063	L	4.26	0.66
Silver (Metallic)	324,470	L	7.34	1.14
Light Green	131,895	L	2.98	0.46
Dark Green (Metallic)	98,538	L	2.23	0.34
Light Blue	175,178	L	3.96	0.61
Black	118,635	L	2.68	0.41
Total basecoat materials used (all colours)	**1,557,689**	**L**	**35.24**	**5.45**
CLEARCOAT APPLICATION				
Clearcoat	743,625.22	L	16.83	2.60
Tinted Clearcoat	112,067.12	L	2.54	0.39
Total clearcoat materials used	**855,692**	**L**	**19.36**	**2.99**
Total paint process materials used	**2,413,381.72**	**L**	**54.61**	**8.44**
Water Usage	**ANNUAL TOTAL**	**UNIT**	**/1000 m^2 painted BIW**	**/VEHICLE**
Water	31,184,000	L	705.58	109.08
Electricity Usage	**ANNUAL TOTAL**	**UNIT**	**/1000 m^2 painted BIW**	**/VEHICLE**
Electricity	N/A	kWh	N/A	N/A

[illegible]				
NPRI reportable compounds				
BASECOAT				
Carbon Black	9	g	0.00	0.00
1-Methoxy-2-Propanol	4,796	g	0.11	0.02
Diethylene Glycol Butyl Ether	36	g	0.00	0.00
Ferric Oxide	36	g	0.00	0.00
Propylene Glycol Butyl Ether	73,148	g	1.66	0.26
Copper Compounds	1	g	0.00	0.00
Stoddard Solvent	12,568	g	0.28	0.04
Light Aromatic Solvent Naptha	2,409	g	0.05	0.01
Heavy Alkalide Naptha	37,459	g	0.85	0.13
2-Butoxy-Ethanol	231	g	0.01	0.00
Total reportable compounds (Base Coat)	**130,693**	g	**2.96**	**0.46**
CLEAR COAT				
Acetone	29,778	g	0.67	0.10
N-butyl Alcohol	35,054	g	0.79	0.12
1,2,4-trimethyl Benzene	25,525	g	0.58	0.09
Light Aromatic Solvent Naptha	106,352	g	2.41	0.37
Total reportable compounds (Clear Coat)	**196,709**	g	**4.45**	**0.69**
Total reportable compounds to air (Top Coat)	**327,402**	g	**7.41**	**1.15**
VOC emissions				
BASECOAT				
Almond (Metallic)	35,845,931	g	811.06	125.39
Dark Blue	24,909,411	g	563.61	87.13
White	32,702,536	g	739.94	114.39
Dark Red	2,959,023	g	66.95	10.35
Bright Red	34,929,130	g	790.32	122.18
Silver (Metallic)	64,152,204	g	1451.53	224.41
Light Green	21,810,236	g	493.49	76.29
Dark Green (Metallic)	15,940,075	g	360.67	55.76
Light Blue	33,585,431	g	759.92	117.48
Black	21,323,377	g	482.47	74.59
Total VOC (Base Coat)	**288,157,354**	G	**6519.95**	**1007.98**
CLEAR COAT				
Clearcoat	347,513,217	g	7862.95	1215.61
Tinted Clearcoat	52,371,548	g	1184.98	183.20
Total VOC Clear Coat)	**399,884,765**	g	**9047.93**	**1398.81**
Total VOC to air (Top Coat)	**688,042,119**	g	**15567.88**	**2406.79**

[illegible]				
Wastewater to WWTP (NPRI reportable + non-reportable)	**29,595,175**	**L**	**669.63**	**103.52**
Wastewater to WWTP (NPRI reportable)				
BASECOAT				
Copper Compounds	8	g	1.81E-04	2.80E-05
CLEAR COAT				
None	0	g	0	0
Total reportable compounds to water (Clear Coat)	**8**	**g**	**1.81E-04**	**2.80E-05**
Emissions To Land	**ANNUAL TOTAL**	**UNIT**	**/ 1000 m^2 painted BIW**	**/ VEHICLE**
Sludge to landfill (NPRI reportable)				
BASECOAT				
Carbon Black	864000	g	19.55	3.02
1-Methoxy-2-Propanol	5000	g	0.11	0.02
Diethylene Glycol Butyl Ether	37000	g	0.84	0.13
Ferric Oxide	3,611,000	g	81.70	12.63
Propylene Glycol Butyl Ether	739000	g	16.72	2.59
Copper Compounds	88000	g	1.99	0.31
Stoddard Solvent	13000	g	0.29	0.05
Light Aromatic Solvent Naptha	2000	g	0.05	0.01
Heavy Alkalide Naptha	37000	g	0.84	0.13
2-Butoxy-Ethanol	0	g	0.00	0.00
Total reportable sludge compounds (Base Coat)	**5,396,000**	**g**	**122.09**	**18.88**
CLEAR COAT				
Acetone	30000	g	0.68	0.10
N-butyl Alcohol	35000	g	0.79	0.12
1,2,4-trimethyl Benzene	26000	g	0.59	0.09
Light Aromatic Solvent Naptha	106000	g	2.40	0.37
Total reportable sludge compounds (Clear Coat)	**197,000**	**g**	**4.46**	**0.69**
Total reportable sludge compounds (Top Coat)	**11,186,000**	**g**	**253.10**	**39.13**
Filters to landfill (NPRI reportable)	N/A	g	N/A	N/A

For supplementary graphical reporting of the normalized LCI dataset, the LCI process flow maps previously developed can be updated by including detailed LCI parameters and quantities on the material / energy / emissions flows. A sample for the E-coat sub-module is shown in Figure 5.5; comparison can be made with Table 5.14. The advantage of the LCI process flow is the representation of the materials / energy / emissions quantities as flows through the E-coat transformation process, resulting in a more intuitive summary of the environmental impacts for each sub-module. For this reason, LCI process flow maps are recommended as a supplementary summary reporting format, particularly where LCI data is to be presented to management or publicly.

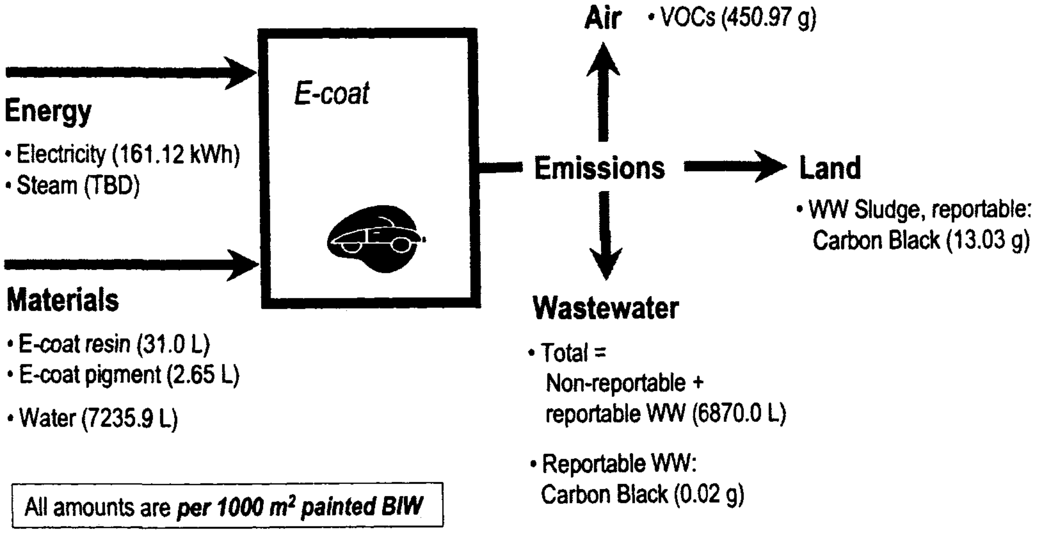


Figure 5.5: Sample LCI process flow for graphical reporting (E-coat).

6.0 GUIDELINES FOR COMPLETING A MANUFACTURING PAINT PROCESS LCI

6.1 Overview

Based on the research and the LCI completed for the Pretreatment, E-coat, and Top Coat sub-modules, a guideline was developed to facilitate future LCIs on the paint process in manufacturing.

The primary intended users of this guideline include:

(i) LCI practitioners completing additional paint sub-modules (e.g., Primer) for augmenting the NREL database on the paint transformation process; and,

(ii) LCI practitioners collecting comparative datasets for other automotive assembly plants or paint operations in other manufacturing industries (e.g., 'white goods' appliance manufacturing).

6.2 Guidelines

6.2.1 LCI project protocol

In conducting the paint LCI on the scoped paint sub-modules, the research adapted the general LCI procedures in ISO 14041 (1998) and Athena's *US LCI Database Research Protocol* (2001b) to reflect the time and resource realities of completing a paint LCI in the automotive manufacturing environment. The thesis research successfully used the following sequence of activities for completing the LCI and managing the LCI project:

1. Goal and Scoping;
2. Functional Unit;
3. LCI process flow mapping;
4. Data source selection;
5. Data collection; and,
6. Reporting.

The LCI activities are similar to the referenced LCI standards (i.e., ISO, Athena). However, specific guidelines that adapt each of the six LCI activities to a manufacturing paint process LCI are provided in the sections below.

6.2.2 Goal and Scoping

Depending on the intended user, the goal can be defined as:

(i) To augment the NREL database on the automotive paint process by completing an LCI for paint sub-modules not currently found in the database (e.g., Primer), providing a complete set of environmental impact data on the paint process for LCI practitioners; or,

(ii) To develop a comparative dataset for other automotive assembly plants or paint operations in other manufacturing industries (e.g., 'white goods' appliance manufacturing), providing LCI practitioners with information on dataset variability in the North American automotive industry and related manufacturing industries.

Scoping should reflect the several distinct unit operations that comprise the paint process. Each unit operation should be scoped as a sub-module, allowing a manageable materials / energy / emissions inventory that yields comprehensive data for that unit operation. Sub-module scoping also allows LCI data to be scaled using a modular approach, whereby an LCI practitioner can select separately the sub-modules that best apply to their process / scenario. As an example, a paint process in a related industry may use a significantly different Pretreatment process, preventing legitimate LCI scaling of this sub-module; E-coat and Top Coat processes, however, may be sufficiently similar to allow LCI scaling.

6.2.3 Functional Unit

The preferred functional unit for an automobile manufacturing paint process LCI is *per* m^2 *painted BIW*. For a non-automotive manufacturing paint process, the preferred functional unit can be more generally written as *per* m^2 *painted surface area.*

This functional unit is recommended because it relates the environmental impact inventory to the function of the paint process, which is to coat the part surface, and to the mechanisms of paint application, which are surface interactions.

A recommended supplementary functional unit for an automobile manufacturing paint process LCI is *per vehicle*. For a non-automotive manufacturing paint process, this can be more generally written as *per manufactured product.*

The supplementary functional unit can be useful for simplified reporting (e.g., public reporting).

6.2.4 LCI Process Flow Mapping

LCI process flow mapping is a useful part of an LCI project protocol only where the resolution of the LCI process flow map is matched to the available data. In most cases, this will be an aggregate LCI process flow map at the sub-module system boundary (e.g., Pretreatment sub-module). Unless intensive data collection (e.g., metering, apportioning) is intended and possible, the effort for a higher resolution stage-by-stage LCI process flow mapping within the sub-module system boundary does not provide value.

LCI process flow maps constructed at the sub-module system boundary may appear relatively generic compared with higher resolution stage-by-stage maps, but they successfully guide data collection to the key expected materials / energy / emission types and also assist the LCI practitioner with data source selection.

Although LCI process flow mapping is recommended at the sub-module resolution level, LCI process flow maps should be constructed based on first-hand understanding of the scoped manufacturing processes, including unit operations / stages inside the sub-module system boundary.

Recommended project activities for successful LCI process flow mapping include: establishing contacts with technical specialists and management, obtaining available industrial process flows, and a detailed walk-through of the manufacturing line, preferably guided by a resident technical specialist.

6.2.5 Data Source Selection

A data source that reports several LCI parameters (i.e., materials, energy, emissions) should be sought. This allows the LCI practitioner to ensure data consistency across the reported LCI parameters. For a paint LCI in North American manufacturing facilities, the internal *VOC Report* should be sourced. This will typically provide data on: production volume, VOC-generating process material use, painted surface area, and of course, VOC emissions.

The *NPRI Report* should also be sourced. Although some aggregate data can be located using the online public NPRI website, the LCI practitioner should obtain the *NPRI Report* prepared by the manufacturing facility for submission to the government environmental agency. This will provide data for all reportable emissions (e.g., to land, to air, to water).

Water use and non-reportable wastewater generation are typically significant manufacturing loads; these can be sourced from internal summary documents showing metered facility water use. Facility metering is unlikely to correspond to the scoped sub-module system boundary, requiring engineering estimates for correct apportioning. Estimates should be derived based on the process / plant expertise of the facility's environmental specialist personnel.

Non-reportable emissions (e.g., total sludge) will require access to additional documents such as shipping manifests or wastewater treatment plant records. The facility's environmental specialist personnel can assist the LCI practitioner in quantifying non-reportable emissions.

Electrical energy use is a significant component of manufacturing and is also unlikely to be metered to correspond to the scoped sub-module system boundary. In lieu of metering, calculations based on equipment power ratings can be used. With this approach, it is essential that a thorough equipment audit be conducted. Assistance from an energy industry technical expert and/or plant mechanical engineer can speed the equipment audit process and improve confidence in the energy use calculations.

For the paint process, packaging materials can be excluded from an LCI due to the predominant use of reusable containers for input materials (e.g., paint products). For other manufacturing LCIs, however, it may be desirable to inventory packaging waste. Although packaging waste to landfill is unlikely to be reported in a document convenient to the LCI, it can be quantified by a walk-through audit at the facility of the scoped sub-module process areas, along with a review of supplier container types used for process material shipments to and from the facility. Recycled packaging waste is often tracked and reported (e.g., clean cardboard), suggesting that recycling shipment records can be used by the LCI practitioner to note absent packaging container types, indicating potential landfilled packaging waste.

6.2.6 Data Collection

For most manufacturing LCIs, the LCI practitioner will be required to enter into a confidentiality agreement with the manufacturer. Source documents can then be obtained from the facility's environmental specialist personnel, or in some cases, from process supplier representatives.

Data should be collected for a suitably long time period to capture normal variations in the manufacturing cycle and allow them to be 'smoothed' in the functional unit normalization. Many manufacturing processes, including the automotive paint process, demonstrate a yearly cycle, as indicated by model year changes, annual preventive maintenance shutdown, etc. Source documents recommended in these guidelines (section 6.2.5 above) typically allow a year's worth of data to be included in the LCI (e.g., *VOC Report*, *NPRI Report*, water usage summaries, etc.).

All engineering estimates required for apportioning environmental impact parameter data to the scoped sub-modules (e.g., water usage, wastewater generation, energy usage) should be developed with the assistance of the facility's environmental specialist personnel.

Data on total emissions (i.e., non-reportable), such as wastewater or sludge, should be collected in the LCI. While non-reportable emissions are classified as lower severity environmental impacts (hence, unregulated by NPRI), they typically are generated in quantities that are orders of magnitude greater than corresponding reportable emissions.

Where possible, the LCI practitioner should use product volumes that quantify the number of products transformed by the manufacturing process (e.g., number of vehicles painted in paint process), and include any reprocessing, rather than more easily sourced end-of-line production volumes. This will typically be found in documents reporting material use and is considered high quality data, particularly where materials suppliers are compensated based on a quantified per unit material use.

Many facilities, both in the automotive industry and other manufacturing industries, produce more than one product model on the same assembly line; this is expected to increase with the growth in flexible manufacturing practices in North America. In the case of the paint process, model variation within a facility can mean differing painted surface areas, requiring a production volume-weighted average of the painted surface area for facility-aggregated LCI data collection and reporting with the preferred *per* m^2 *painted BIW* functional unit. Normalizing data with a *per vehicle* functional unit does not allow distinguishing between models and implicitly assumes a common painted surface area.

LCI data collection sheets like the *Franklin Worksheet* (Athena 2001b) recommended for the NREL database project can be helpful in guiding data collection. However, as these tools are product-based rather than process-based, they will typically require modification to reflect the paint process and for metric units of measure. This research successfully chose to instead adapt the *Franklin Worksheet* to suitable electronic Excel spreadsheets for data collection.

Electronic copies of data source documents are preferred, particularly where these can allow the LCI practitioner to electronically copy/paste data for expedited and less error-prone data entry.

6.2.7 Reporting

LCI data should be normalized for the facility's selected production period (e.g., annual) using the *per* m^2 *painted BIW* as well as the *per vehicle* functional units. The units may need to be adjusted by a multiple of ten to suit the numerical range of the data.

LCI data intended for inclusion in the NREL database should be reported for each scoped sub-module separately rather than aggregated for the entire process. This modular reporting approach will enable other LCI practitioners to select separately the sub-modules that best apply to a manufacturing process / scenario.

The completed LCI dataset should be reported in tabular format. For supplementary graphical reporting, the LCI process flows previously developed can be updated by including detailed LCI parameters and quantities on the material / energy / emissions flows.

Facility details and metadata (e.g., data sources, quality, age, limitations, etc.) are needed for NREL to peer review the LCI dataset before online publication in the database. This information will also assist LCI practitioners who wish to correctly apply the LCI data to other manufacturing facilities, industries, or scenarios (i.e., LCI scaling).

Table 6.1: Summary of guidelines for completing a manufacturing paint process LCI.

LCI ACTIVITY	GUIDELINES
Goal	• Add new manufacturing paint process sub-module to NREL database or OEM-selected LCI software (e.g., GaBi) • Comparative dataset for other automotive assembly plants or paint operations in other industries (e.g., 'white goods' manufacturing)
Scoping	• Scope each unit operation as sub-module (e.g., E-coat) • Sub-module LCI datasets can be referenced individually by LCI practitioners
Functional unit	• Preferred = per m^2 painted BIW; represents manufacturing transformation process (i.e., painting product's surface) • Secondary = per vehicle; may be suitable for simplified reporting
LCI process flow mapping	• Match resolution to available data; typically choose system boundary for process flow at scoped sub-module (e.g., E-coat) • Map materials / energy / emissions flows entering / leaving system boundary • Obtain industrial process flows where available
Data source selection	• Seek data sources that report several LCI parameters for dataset consistency (e.g., VOC Report) • Internal NPRI Report = reportable emissions • VOC Report = paint process materials use, production volumes, painted surface area, VOC emissions • Water usage summary = water use, wastewater generation (requires estimates/apportioning) • Sludge shipment manifests, Wastewater Treatment Plant records = total sludge (non-reportable) • Electrical equipment audit = electrical energy use (requires power rating calculations) • Packaging waste typically minimal for manufacturing paint process; use walk-through audit to assess and quantify
Data collection	• Secure confidentiality agreement with OEM, suppliers for access to internal process info, data • Collect data for time period representing regular production cycle to 'smooth' production variations; typically annual • Develop process-apportionment engineering estimates with facility environmental specialist • Do no restrict emissions data collection to regulated reportables; collect total emissions data • Collect production volume data incorporating reprocessing, rather than end-of-line data • Collect model-specific painted surface area and production volumes for multiple product manufacturing facilities (e.g., flexible manufacturing) • Obtain electronic copies of data source documents where possible
Reporting	• For NREL, normalize dataset using preferred functional unit (per m^2 painted BIW); for internal reporting, also normalize using per vehicle functional unit • Report normalized dataset by sub-module • Report normalized dataset in tabular format • Report normalized dataset with supplementary graphical format (LCI process flow map) • Report metadata (e.g., sources, quality, age, limitations)

7.0 PROTOCOLS FOR APPLICATION OF PAINT PROCESS LCI DATA

7.1 Overview

To develop practical protocols for applying the paint LCI dataset collected in this thesis and presented in Chapter 5, the research first analyzed the effects of surface area, vehicle type, paint process, and production period length on LCI scaling. This analysis referenced the controlled conditions of the LCI dataset collected in this research for assembly plant A.

Next, a 'test case' was used to represent an LCI practitioner using the NREL LCI database or OEM-selected software (e.g., GaBi) to predict paint process environmental impacts at a different vehicle assembly facility manufacturing a different vehicle type. Using the 'test case', two specific scaling protocols were formulated and assessed.

7.2 Formulation of LCI application protocols

For LCI protocol formulation, model-specific materials use and production volume data for the two vehicle models painted at assembly plant A were used along with the LCI data collected in this thesis. Model-specific data was available from the paint supplier's monthly reporting for the third and fourth quarters of the 2003 calendar year (i.e., July through December). This reduced dataset was not felt to compromise the analysis as it represented typical quarterly production volumes for both vehicle models, consistent with the annual volumes of both vehicle models. The model-specific materials use data are aggregated in Tables 7.1 and 7.2.

Table 7.1: Model-specific production volumes at assembly plant A (Q3, Q4 of 2003 calendar year).

NUMBER OF VEHICLES	[illegible]	[illegible]	TOTAL (Q3+Q4)
Model A	23,481	22,186	45,667
Model B	42,767	44,373	87,140

Table 7.2: Model-specific material use at assembly plant A for E-coat and Top Coat (Q3, Q4 of 2003 calendar year).

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Model A					
E-COAT (ALL MATERIALS)	37,502	33,438	70,940	268,537	5.88
BASE COAT (ALL PAINT COLOURS)	35,243	38,374	73,617	278,669	6.10
CLEARCOAT (ALL MATERIALS)	18,682	18,920	37,601	142,335	3.12
TOTAL (E-COAT + TOP COAT)	91,427	90,732	182,158	689,542	15.10
Model B					
E-COAT (ALL MATERIALS)	69,236	69,133	138,369	523,782	6.01
BASE COAT (ALL PAINT COLOURS)	59,708	71,366	131,074	496,168	5.69
CLEARCOAT (ALL MATERIALS)	33,064	38,165	71,229	269,631	3.09
TOTAL (E-COAT + TOP COAT)	162,008	178,664	340,672	1,289,581	14.80

The two vehicle models share the assembly line at assembly plant A and are manufactured using identical paint processes and identical paint process materials. This situation functions as a desirable control in the analysis, eliminating many variables that would be present if applying LCI data to a different assembly facility. For this idealized case, model-specific materials data for assembly plant A were used to examine the effect of four possible differences between facilities or production scenarios:

(i) painted surface area;
(ii) vehicle type;
(iii) paint process; and,
(iv) production period length.

7.2.1 Painted surface area differences

7.2.1.1 Materials use difference

It was noted from the model-specific materials use data that slight differences existed between the two vehicle models for the materials use per painted vehicle (i.e., see Table 7.2 above). The difference was quantified by calculating the percentage difference in materials use between vehicle models for each of the paint processes. These results are shown in Table 7.3.

Table 7.3: Percentage difference in materials use by vehicle model at assembly plant A (Q3, Q4 of 2003 calendar year).

	[illegible]	[illegible]	[illegible]	[illegible]
E-COAT	5.88	6.01	0.13	2.2%
TOP COAT	9.22	8.78	0.44	4.8 %
Base Coat	6.10	5.69	0.41	6.7%
Clear Coat	3.12	3.09	0.02	0.7%
TOTAL (E-coat + Top Coat)	15.10	14.80	0.30	2.0%

In reviewing the scoped sub-modules, vehicle model-specific paint process materials were in close agreement and within a 5% difference (i.e., E-coat = 2.22%; Top Coat = 4.78%). As well, total materials use (i.e., E-coat + Top Coat), which would be used by an LCI practitioner interested in LCI scaling for the more inclusive automotive paint process, was within a 2% difference. These differences indicate that the well known '5% rule' can be applied, which states that environmental impact quantities less than 5% of the total can be omitted from an LCI except where they represent severe toxicities (Graedal and Allenby 2003, Athena 2001b). The results support the LCI research's assumption that the two vehicle models assembled at plant A can be aggregated for the purposes of LCI data collection and reporting to the NREL LCI database.

7.2.1.2 BIW surface area and materials use difference

Due to the differing as-reported BIW painted surface areas of the two vehicle models (i.e., 161.925 m^2, 151.520 m^2), a corresponding difference in materials use was expected. However, it was desired to see if the vehicle model difference in materials use (i.e., per vehicle) was comparable with the vehicle model difference in BIW surface area. This was examined using a ratio of the materials use and comparing with the ratio of the BIW painted surface areas, shown in Table 7.4.

Table 7.4: Vehicle product ratio for material use and surface area at assembly plant A (Q3, Q4 of 2003 calendar year).

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] BIW Surf Area
E-COAT	5.88	6.01	0.98	1.07	8.4 %
TOP COAT	9.22	8.78	1.05	1.07	1.9 %
Base Coat	6.10	5.69	1.07	1.07	0 %
Clear Coat	3.12	3.09	1.01	1.07	5.6 %
TOTAL (E-coat + Top Coat)	15.10	14.80	1.02	1.07	4.7 %

A vehicle model materials use ratio that equals the vehicle model BIW painted surface area ratio <u>exactly</u> would indicate that the differences in material use between the two vehicle models could be explained entirely by their painted surface area differences. An examination of the results in Table 7.4 show that the Base Coat vehicle model materials use ratio did equal the vehicle model BIW surface area ratio exactly; as well, the Top Coat vehicle model materials use ratio was within 2% difference of the vehicle model BIW surface area ratio. These results suggest that, for the two quarters of production for which model-specific materials data was available, Base Coat and Top Coat materials use can be scaled based on BIW painted surface area with minimal uncertainty in results.

E-coat and Clear Coat, however, had vehicle model materials use ratios that differed more compared with the vehicle model BIW surface area ratio (i.e., E-coat = 8.4% difference; Clear Coat = 5.6% difference). This suggests that LCI scaling based on painted surface area would have a larger results uncertainty for E-coat and Clear Coat materials use relative to Base Coat and Top Coat. Similarly, since E-coat is a significant component of total materials use (i.e., E-coat + Top Coat), the resulting vehicle model total materials use ratio (i.e., 1.02; 4.7% difference) also suggests that LCI scaling based on painted surface area would have a larger results uncertainty for total materials use relative to Base Coat and Top Coat.

Overall, since all vehicle model materials use ratios were within 8.5% of the vehicle model BIW surface area ratio, it can be suggested that painted surface area is a dominant vehicle characterization parameter in the paint process. This is consistent with the choice of preferred functional unit (i.e., *per m^2 painted BIW*) in results to be presented to the partnered OEM and to the NREL LCI Database.

7.2.1.3 Surrogate painted surface area

An LCI practitioner interested in scaling a reference LCI dataset to a new vehicle may not always have access to its BIW painted surface area data. Thus, a surrogate for the painted surface area was desired (SSA). Since they are readily available for all vehicles sold in North America, OEM-published major vehicle dimensions can be sourced from marketing specifications, selecting overall exterior dimensions for length, width, and height. The major exterior dimensions can then be used to reference a surrogate BIW painted surface area for a vehicle that is similarly sized and the same vehicle type (i.e., sedan, minivan, etc.). Surrogate BIW painted surface area values (e.g., assembly plant A data acquired in this thesis) can be provided as reference values to LCI practitioners wishing to apply reference LCI data to a new vehicle model for which the true BIW painted surface area is not known.

7.2.2 Vehicle type differences

It can be proposed that a single surrogate BIW painted surface area would not be sufficient for LCI practitioners wishing to conduct LCI scaling for various vehicle types. Two vehicles may even have identical exterior dimensions and yet have quite different painted surface areas due to differences in vehicle shape, complex body contours, or the number and geometry of structural members. For this analysis, vehicle types were simplified to:

(i) minivan / crossover; and,
(ii) sedan.

The proposed vehicle types are limited to OEM-marketed vehicle types that are based on car platforms (i.e., uni-body construction). (Pickup trucks represent an additional vehicle type but they also introduce additional variables to the surface area characterization since they typically use body-on-frame construction so they are omitted from this analysis.)

The decision to simplify the minivan and crossover as a single vehicle type was based on analysis of the BIW painted surface area and major vehicle dimensions for the two vehicle models. Major vehicle dimensions for the two vehicle models at assembly plant A are presented in Table 7.5 below. A comparison of the major external dimensions revealed less than 1% difference in length and width and less than 4% difference in height.

Table 7.5: Major exterior dimensions for vehicle models at assembly plant A (2003 calendar year vehicle models).

DIMENSION	Model A	Model B	% Diff = $\lvert B - A \rvert / A$
Overall length, L [mm]	5052	5093	0.8%
Overall width, W [mm]	2013	1996	0.8%
Overall height, H [mm]	1688	1750	3.7%

A comparison of the BIW painted surface areas showed less than 7% difference (i.e., E-coat, Top Coat sub-modules), as shown in Table 7.6.

Table 7.6: BIW painted surface areas for vehicle models at assembly plant A (2003 calendar year vehicle models).

[illegible]	[illegible]	[illegible]
Model A	161.925	6.9 %
Model B	151.52	6.4 %

This suggested that the two vehicle models could be considered the same vehicle type for the purposes of LCI scaling, despite being marketed as different vehicle types (i.e., model A is a crossover, model B is a minivan).

A surrogate BIW painted surface area for the 'minivan / crossover' vehicle type (i.e., $SSA_{MINIVAN}$) could then be calculated as the weighted average BIW painted surface area, referencing the data for assembly plant A. Production volume and BIW painted surface area data are from the *VOC Report*.

Table 7.7: Surrogate painted surface area for minivan/crossover (2003 calendar year data).

DIMENSION	[illegible]	[illegible]
2003 Production [vehicles]	83,401	202,474
BIW surface area [m^2]	161.9	151.5
Weighted average BIW Surface Area [$SSA_{MINIVAN}$]	$154.6\ m^2$	

To verify the effect of vehicle type, it was expected that a sedan would have a different SSA value. To provide a surrogate painted surface area for the analysis, data was used from the partnered OEM's assembly plant B, which in 2003 assembled the two sedan models (i.e., SSA_{SEDAN}). This is shown in Table 7.8.

Table 7.8: Surrogate surface area for sedan (2003 calendar year data, January – August inclusive).

DIMENSION	Model A	Model B
2003 Production [vehicles]	108623	24120
BIW surface area [m^2]	131.9	133.5
Weighted average BIW Surface Area [SSA_{SEDAN}]	$132.2\ m^2$	

It was thus observed that the surrogate surface area differed for the two vehicle types (i.e., $SSA_{MINIVAN} = 154.6\ m^2$, $SSA_{SEDAN} = 132.2\ m^2$), suggesting that the surrogate surface area should ideally be matched to the vehicle type. An LCI practitioner seeking to apply LCI data to a facility or production scenario would thus select a surrogate surface area that most closely matches the vehicle of interest (e.g., SSA_{SEDAN} , $SSA_{MINIVAN}$).

Based on this preliminary analysis, it is recommended that future research develop a range of surrogate painted surface area values for reference by LCI practitioners. In addition to depending on vehicle type, the surrogate painted surface area will also depend on vehicle size, requiring further distinction when preparing reference values for SSA (e.g., $SSA_{COMPACT\ SEDAN}$, $SSA_{MIDSIZE\ SEDAN}$, $SSA_{LARGE\ SEDAN}$). Such an analysis is outside the scope of this thesis, however, and is left for future research.

7.2.3 Paint process differences

It is expected that an LCI practitioner will most typically perform an LCI scaling on the entire automotive paint process (i.e., inclusive of all sub-modules). However, an LCI practitioner may wish to separately select the sub-modules that best apply to a manufacturing scenario. Thus, the effect of individual paint sub-modules on the resultant LCI data was analyzed. The model-specific materials use dataset from assembly plant A was again used to examine the differences between specific sub-modules and is reproduced in Table 7.9.

Table 7.9: Percentage difference in materials use by vehicle model at assembly plant A (Q3, Q4 of 2003 calendar year).

	Model A MATERIALS USE (L/VEHICLE)	Model B MATERIALS USE (L/VEHICLE)	Diff = |B – A|	% Diff = |B - A| / A
E-COAT	5.88	6.01	0.13	2.2%
TOP COAT	9.22	8.78	0.44	4.8 %
Base Coat	6.10	5.69	0.41	6.7%
Clear Coat	3.12	3.09	0.02	0.7%
TOTAL (E-coat + Top Coat)	15.10	14.80	0.30	2.0%

As mentioned previously, it was noted that the difference in vehicle model materials use was not consistent across the three assessed paint processes. Paint process materials use for the two vehicle models was very similar for the Clear Coat process (i.e., 0.7% difference) and most different for the Base Coat process (i.e., 6.7% difference); materials use for the E-coat process was within 2.5%. This suggests that LCI scaling is to some extent dependent on the paint process under consideration, with some sub-module operations carrying greater associated uncertainty in the results (e.g., Base Coat).

Examining the specific paint process materials applied in each of the sub-modules is useful for understanding why some processes show larger percentage differences in usage quantities (e.g., Base Coat) than others (i.e., Clear Coat, E-coat). The first indicator considered in the analysis was the number of process products involved in each of the sub-module operations. As inventoried in Chapter 5, the E-coat and Clear Coat operations each apply two paint products to every BIW. The Base Coat operation, however, applies one of nine different paint products (i.e., Base Coat colours) to the BIW, depending on the colour intended for each vehicle manufactured.

If the same quantity of Base Coat were applied to each BIW, regardless of colour, the number of available Base Coat colours would not be a factor in the LCI scaling. However, it was noticed in the paint supplier's monthly reporting that the quantity applied per vehicle was slightly different for each colour. To illustrate, the paint supplier's monthly report data for the first quarter of 2003 is shown in Table 7.10. The *per vehicle* normalization is here used differently than it is for the aggregated LCI dataset prepared for reporting to USCAR (i.e., Chapter 5): the material quantity of each Base Coat colour is divided by the number of vehicles painted that colour, not by the total number of vehicles produced in the reporting period.

Table 7.10: Paint materials use for assembly plant A by Base Coat colour (combined vehicle models, Q1 of 2003 calendar year).

BASE COAT COLOUR [illegible]	No. Vehicles	Quantity (L)	L/VEH
Dark Blue	4,196	23,284.0	5.6
Light Green	4,675	27,610.7	5.9
Light Blue	8,214	40,276.7	4.9
Dark Green (metallic)	3,947	22,500.4	5.7
Silver (metallic)	14,177	72,524.5	5.1
Almond (metallic)	9,632	46,450.6	4.8
Bright Red	4,989	31,623.2	6.3
Black	2,201	14,706.3	6.7
White	6,430	31,384.8	4.9

It can be seen from Table 7.10 that the quantity of Base Coat applied to vehicles varies depending on the colour. As an example, each vehicle painted 'Black' received 6.7 L of base coat; each vehicle painted 'Almond' received only 4.8 L of base coat, etc. This variation in materials use depending on paint colour introduces greater variability to the LCI materials use data for the Base Coat operation, and by extension to the Top Coat sub-module (i.e., Top Coat = Base Coat + Clear Coat).

Further complicating matters is the fact that assembly plant A does not produce equal numbers of each colour vehicle; 'Silver Metallic' was the most popular colour in 2003 production, whereas comparatively few 'Black' vehicles were painted. The production ratio of vehicle model A to vehicle model B further affects the Base Coat materials use (i.e., model B production is much higher than model A production; 'Black' is one of the more popular colours for model A but is relatively rare for model B). This adds further variability to the LCI materials use data and also explains the larger percentage difference shown between vehicle model materials use for the Base Coat operation and Top Coat sub-module.

Thus, LCI materials data for the paint process exhibits process-dependency. There would be greater uncertainty for LCI scaling the Top Coat sub-module than for the E-coat sub-module.

Consideration was also given to the broad classification of paint processes as either immersion processes (e.g., E-coat application) or spray processes (e.g., Top Coat application). It can be observed that materials use in immersion processes is relatively independent of production volume compared with materials use in spray processes; as an example, immersion tanks must be sized to accommodate the BIW and must be kept filled regardless of BIW throughput. This is discussed further in Section 7.2.4.

7.2.4 Production period differences

The research assumed that a dataset aggregating a larger period of time would be preferable to one aggregating a smaller period of time. The paint process, in particular, contains some operations that are relatively independent of vehicle production rates.

Some paint process equipment must be operated continuously rather than only when a BIW is present. As an example, immersion tanks for Pretreatment must be kept at an elevated operating temperature; since attaining the operating temperature requires time, their operation cannot be dependent on the presence or absence of a BIW on the moving assembly line. For this reason, the paint shop at most assembly facilities is kept running through weekends, even where no vehicles are scheduled for assembly. Other equipment that runs essentially continuously in an automotive paint shop includes fans, blowers, and drying ovens.

Scheduled shutdowns for equipment maintenance and process changes / model year changes are typically annual events and so require a suitable time period in data collection to ensure that they are quantitatively represented in the LCI.

It should also be noted that the effect of production period length on an LCI dataset may vary depending on which environmental impact parameter is examined. Materials, for example, largely tend to scale with vehicle production rates (e.g., spray equipment only applies paint when a BIW is present to be painted; immersion tanks are depleted due at least partially to 'dragout' as a BIW passes through them; etc.). The exception is water use, which runs continuously in systems such as the spray booth overspray collection system and so would not scale as directly with vehicle production rates as other materials. Since the bulk of paint shop emissions are created as a result of paint process materials use (e.g., VOCs from paint or solvents), emissions can be said to largely scale directly with vehicle production rates. Energy, however, is relatively independent of vehicle production rates, since much of the aforementioned equipment requiring continuous operation is electrically powered (e.g., fans, blowers, drying ovens) or steam powered (e.g., immersion tank heating).

This analysis suggests that LCI scaling to another facility or production scenario should be limited to a production period that is at least the period length of the source data (i.e., one year's production for use of the paint LCI data collected from assembly plant A). This allows 'smoothing' of the operations that are relatively independent of vehicle production rates, such as continuously operated equipment or scheduled production shutdowns.

7.3 Test case: application of NREL LCI data to different facility

The test case represented an LCI practitioner applying the paint LCI dataset using the NREL LCI database or OEM-selected LCI software (e.g., GaBi). This tested several LCI scaling protocols by applying the site-specific materials data from assembly plant A (i.e., reference dataset collected in this thesis, to be supplied to the NREL LCI Database) to assembly plant B as surrogate data. The scaling protocols used to apply the NREL data (i.e., assembly plant A data) were then verified with materials data collected at assembly plant B from the OEM-published *VOC Report* (2004 calendar year).

7.3.1 Scaling protocol I: painted surface area

The first scaling protocol is based on the preferred functional unit (i.e., *per m^2 painted BIW*) and uses painted surface area and production volume for scaling. Predicted assembly plant B data was based on aggregate production of both vehicle models, January through August 2004 (i.e., nine months of data).

Since assembly plant B is a facility operated by the partnered OEM, it uses a similar paint shop facility and also sources materials from the same paint supplier. Production volumes for the assembly plant B in the selected nine-month period were a combined 142,303 vehicles. Furthermore, it was assumed that the LCI practitioner had access to the BIW painted surface area for the vehicle models at assembly plant B. Using the production volume and BIW painted surface area information, the production volume weighted BIW painted surface area was calculated, thereby aggregating the two vehicle models into a single representative model for assembly plant B. (This is analogous to what was done in preparing the paint LCI dataset for NREL and the partnered OEM in Chapter 5.)

The scaling protocol for predicting the annual assembly plant B LCI data from the reference NREL LCI dataset used the following general equation:

$$\text{LCI}_{\text{PREDICT}} = \text{LCI}_{\text{NREL}} * [\text{BIW Painted Surface Area}_{\text{PREDICT}} * \text{Annual Vehicle Production}_{\text{PREDICT}}] \quad \textbf{[2]}$$

Equation [2] was used to predict the annual materials use at assembly plant B for the E-coat and Top Coat (i.e., Base Coat, Clear Coat) sub-modules. A comparison could then be made to the 'true' annual materials use data at assembly plant B (i.e., sourced from *VOC Report*) and the percentage difference calculated. The results are shown in Table 7.11.

Table 7.11: Predicted materials using NREL dataset and painted surface area (combined vehicle models, 2004 calendar year).

[illegible]	[illegible]	[illegible]	[illegible]	% DIFF (PREDICT - ACTUAL)/ ACTUAL [%]
E-COAT	**33.7**	**728,492**	**824,186**	**-12%**
E-coat resin	31.1	672,288	747,078	-10%
E-coat pigment	2.6	56,204	77,109	-27%
BASE COAT	**35.2**	**760,917**	**661,319**	**15%**
All colours aggregated	35.2	760,917	661,319	15%
CLEAR COAT	**19.4**	**419,369**	**385,472**	**9%**
Clearcoat	16.8	363,165	367,560	-1%
Tinted Clearcoat	2.5	54,042	17,913	202%
TOP COAT (Base Coat + Clear Coat)	**54.6**	**1,180,286**	**1,046,791**	**13%**
TOTAL (E-coat + Top Coat)	**88.3**	**1,908,778**	**1,870,978**	**2%**

For the E-coat sub-module, total materials use was underpredicted by approximately 12%; for the Top Coat sub-module, total materials use was overpredicted by approximately 13%. The net effect of the two differences, however, yielded a total materials use (i.e., E-coat + Top Coat) that came very close to the true value, overpredicting it by only 2%.

Additionally, the E-coat sub-module, which is essentially an immersion process, underpredicted assembly plant B results for each E-coat material; the Top Coat process, which is essentially a spray process, overpredicted assembly plant B results for most materials.

These results may be explained by several factors, including:

- The percentage difference in the E-coat materials use (i.e., -12%) can possibly be explained by the reference LCI dataset being scaled down to a smaller predicted production scenario and by the observation that E-coat is primarily an immersion process with the total materials use relatively independent of production rates. Thus, immersion processes such as E-coat will approach a 'lower limit' of materials use, corresponding to the reality of maintaining full tanks. The predicted materials use for assembly plant B, representing a significantly lower production volume than the reference data (i.e., assembly plant B = 142,303 vehicles; NREL/assembly plant A =

285,875), is likely to have scaled results below this 'lower asymptote', resulting in an underprediction.

- The percentage difference in the Base Coat materials use (i.e., + 15%) can be explained by considering the effect of aggregating the different colours. Although some Base Coat colours are common with the vehicle product colours used at assembly plant A in 2003, assembly plant B used several different colours for the 2004 sedan models; as well, the production ratio for the vehicle colours at assembly plant B is likely to differ significantly from that at assembly plant A. As was shown in Section 7.2.3, this can introduce uncertainty to the Base Coat scaling compared with the Clear Coat scaling. This is confirmed by the observed percentage difference in the predicted assembly plant B results of approximately +15% for Base Coat compared with only +9% for Clear Coat.

- A final factor in the observed percentage differences was that, since assembly plant B data was aggregated from only nine months, it may have missed or inadequately represented factors such as scheduled production shutdowns or continuously operating equipment, as discussed in Section 7.2.4.

7.3.2 Scaling protocol II: surrogate painted surface area (SSA)

Although the BIW painted surface area-based scaling protocol has been shown to provide useful LCI application results, it is anticipated that an LCI practitioner may not always be able to obtain proprietary BIW painted surface area data for the vehicle for which the environmental impacts are being predicted. Protocol II will thus apply a surrogate for the predicted vehicle's BIW painted surface area that references the vehicle type and size (i.e., determined from OEM-published vehicle exterior dimensions).

For the example of applying the reference NREL dataset to predict assembly plant B results (i.e., combined vehicle models), the specific equation was modified to:

$$\text{LCI}_{\text{PREDICT}} = \text{LCI}_{\text{NREL}} * [\text{Surrogate BIW Painted Surface Area}_{\text{PREDICT}} * \text{Annual Vehicle Production}_{\text{PREDICT}}] \qquad [3]$$

Equation [3] required a surrogate painted surface area for a sedan vehicle type (i.e., SSA_{SEDAN}) of similar size. In this analysis, the surrogate painted surface area developed earlier for the sedan manufactured at assembly plant B in 2003 was used (i.e., SSA_{SEDAN} = 132.2 m²).

Similar to the calculations in scaling protocol I, equation [3] was used to predict the materials use at assembly plant B for the E-coat and Top Coat sub-modules and comparison was made to the 'true' materials use data at assembly plant B. Results are shown in Table 7.12.

Table 7.12: Predicted materials using NREL dataset and surrogate painted surface area (combined vehicle models, 2004 calendar year).

Paint Process Materials	NREL [illegible] Painted [illegible]	PREDICTED (assy plant B) (L)	ACTUAL (assy plant B) (L)	% DIFF = (PREDICT - ACTUAL)/ ACTUAL [%]
E-COAT	**33.7**	**633,980**	**824,186**	**-23%**
E-coat resin	31.1	585,067	747,078	-22%
E-coat pigment	2.6	48,912	77,109	-37%
BASE COAT	**35.2**	**662,198**	**661,319**	**0%**
All colours aggregated	35.2	662,198	661,319	0%
CLEAR COAT	**19.4**	**364,962**	**385,472**	**-5%**
Clearcoat	16.8	316,049	367,560	-14%
Tinted Clearcoat	2.5	47,031	17,913	163%
TOP COAT (Base Coat + Clear Coat)	**54.6**	**1,027,160**	**1,046,791**	**-2%**
TOTAL (E-coat + Top Coat)	**88.3**	**1,661,140**	**1,870,978**	**-11%**

The surrogate painted surface area-based protocol provided a relatively close prediction of the materials use at assembly plant B, yielding a total materials use that underpredicted the true value by approximately 11%. These results were limited by the reference data for a BIW painted surface area representative of a similarly sized vehicle type (i.e., SSA_{SEDAN}).

A side-by-side comparison of the percentage difference results from protocols I and II illustrates that an LCI practitioner who does not have access to the BIW painted surface area of the vehicle being predicted can use an appropriate surrogate painted surface area to obtain results that are reasonably close to the ideal case where the BIW painted surface area is known (i.e., within 13%, in this example). Compared with actual painted surface area-based protocol I, the prediction quality of surrogate painted surface area-based protocol II will of course depend on the reference value used for a surrogate surface area. A surrogate painted surface area that more closely represented the sedan manufactured at assembly plant B would result in predicted LCI results that approached the optimal prediction of protocol I. Results are shown in Table 7.13.

Table 7.13: Results comparison of scaling protocols I and II.

Paint Process Materials	Protocol I % DIFF	Protocol II % DIFF
E-COAT	-12%	-23%
BASE COAT	15%	0%
CLEAR COAT	9%	-5%
TOP COAT (Base Coat + Clear Coat)	13%	-2%
TOTAL (E-coat + Top Coat)	2%	-11%

7.3.3 Reference surrogate painted surface area values for future LCI scaling

In a real-world application the LCI practitioner may not know the BIW painted surface area of the vehicle for which they wish to predict materials use, requiring use of scaling protocol II with an appropriate surrogate BIW painted surface area (SSA) value. For such an application, the LCI practitioner could reference a surrogate painted surface area from a dataset with a similarly sized vehicle type for which the BIW surface area is known. As an initial contribution to future LCI data scaling scenarios, this author submits surrogate painted surface areas as derived in this research for the 'minivan/crossover' vehicle type and the 'sedan' vehicle type. To accommodate an LCI practitioner wishing to determine applicability of the surrogate painted surface area values to their particular vehicle, reference should also be made to the vehicle dimensions for each painted surface area value. A reference table is provided in Table 7.14.

Table 7.14: Reference surface area values for use as surrogate in scaling protocol II.

[illegible]	[illegible]	[illegible]
Sedan (large)	L = 5.3 W = 1. 9 H = 1.4	132.2 m^2
Sedan (large)	L = 5.0 W = 1.9 H = 1.5	151.9 m^2
Minivan/crossover	L = 5.1 W = 2.0 H = 1.7	154.6 m^2

To accommodate the diversity of vehicle types and sizes in the North American market, it is recommended that a range of reference surrogate painted surface areas be developed and made available as part of the NREL LCI Database.

8.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

With an OEM industry partner's commitment to the NREL LCI Database Project, a representative North American assembly facility was selected for completion of an automotive paint process LCI. Three principle unit processes in the automotive paint process were scoped as LCI sub-modules: Pretreatment, E-coat, and Top Coat. The following key activities and deliverables summarize the thesis research:

1. A detailed LCI reference dataset was developed to include the materials, energy, and emissions associated with the scoped paint process. The LCI reference dataset will be provided to the industry partner for internal DfE use and submitted to the NREL LCI Database for use by LCI practitioners.

2. The challenges and industry realities of completing the LCI enabled a detailed set of guidelines to be developed. The "Guidelines for completing a paint LCI" adapt existing protocols (e.g., ISO, Athena) to the specifics of the manufacturing paint process. The guidelines developed in this thesis are intended to assist LCI practitioners augmenting the NREL database with additional paint LCI sub-modules (e.g., Primer) or preparing comparative LCIs for other automotive manufacturing facilities or other industries (e.g., 'white goods' manufacturing).

3. Protocols were developed for industry application of the manufacturing paint LCI dataset (i.e., scaling protocols). The application of a manufacturing paint process LCI was shown to depend primarily on BIW painted surface area. Additional dependencies were shown for vehicle type, paint process type, and production period. Two distinct protocols were formulated to allow an LCI practitioner to scale the reference LCI dataset to a different facility or production scenario:
    a. Scaling protocol I: scaling uses BIW painted surface area and production volume of predicted vehicle manufacturing scenario.

    b. Scaling protocol II: scaling uses production volume of predicted vehicle manufacturing scenario with surrogate for BIW painted surface area; surrogate painted surface area is referenced from a vehicle of similar type and similar size (i.e., based on readily available external vehicle dimensions – overall length, overall width, overall height).

4. The two scaling protocols were assessed using a 'test case'. The 'test case' applied the NREL LCI dataset (i.e., collected at assembly plant A for a minivan / crossover) to predict LCI materials use at assembly plant B for a large sedan and verified results against actual materials use at assembly plant B. Assessed results revealed two recommended protocols for LCI practitioners intending to apply the paint LCI dataset to industry:
    a. Scaling protocol I was shown to provide the least percentage difference between predicted and 'true' results (i.e., 2%) and is considered optimal. It is limited, however, by the requirement that the LCI practitioner obtain the BIW painted surface area of the predicted vehicle.

    b. Scaling protocol II was shown to provide predicted results within 11% of 'true' results and to be acceptable for situations where the LCI practitioner must approximate BIW painted surface area using a surrogate. Quality of the predicted results was shown to depend on the surrogate painted surface area value referenced. Reference BIW painted surface areas were provided for examples of the 'sedan' and 'minivan / crossover' vehicle types.

8.2 Conclusions

8.2.1 Completing future manufacturing LCIs

1. Standard LCI protocols are largely product based and may need to be adapted for successful completion of manufacturing LCIs, which are process-based.

2. Challenges in completing a manufacturing LCI primarily involve data collection. This includes potential lengthy time allowances for establishing appropriate contacts and securing access to internal and confidential data. Further, a manufacturing facility's existing data measurement and reporting is unlikely to be at a resolution corresponding to the scoped LCI system boundaries, requiring engineering estimates to apportion data appropriately.

3. Due to limitations in available / measured data resolution, time and resource demands of stage-by-stage LCI process flow maps exceed their benefits to the LCI process with respect to data collection. A lower resolution LCI process flow map should instead be constructed, achieved by placing the system boundary around the LCI sub-module in consideration and aggregating the material / energy / emissions flows within the sub-module boundary. Such aggregated LCI process flow maps are useful in data source identification and also provide a good graphical representation of the normalized LCI results. LCI process flow maps are recommended as a supplementary summary reporting format, particularly where LCI data is to be presented to management or publicly.

4. Manufacturing LCIs should be based on a parameter that best represents the function and mechanisms of the transformation process; the selected parameter should be used for the functional unit and as the basis of data scaling. For the paint process, the LCI should be based on the painted surface area.

8.2.2 Industry application of manufacturing LCI data

1. LCI application protocols can be formulated to allow site-specific reference data, such as will be available from the NREL LCI Database, to be used for predicting LCI results for a different manufacturing facility / scenario.

2. If the selected functional unit is consistent with LCI principles in representing the function of the manufacturing transformation process, it will form the basis for scaling a reference LCI dataset to a different production facility or production scenario.

3. Data limitations in LCI application can be overcome through the use of surrogate painted surface area based on vehicle type and vehicle size, as determined by publicly available external vehicle dimensions.

4. LCI data is likely to exhibit process dependency. As an example, energy use in the paint process can be relatively independent of production rates due to the contributions of continuously operating equipment. The uncertainty of predicted results from a reference dataset will relate to any demonstrated process dependency, with materials / energy / emissions data representing some processes more reliably than others.

5. Automotive assembly facilities used in this research were very similar (i.e., same OEM, same paint process layout, same paint materials supplier, etc.), serving as a useful control in the analysis for developing and assessing scaling protocols. However, it is expected that while the reference dataset is generally representative of North American-based OEM assembly facilities, applying the LCI data to other facilities, particularly for differing OEMs or significantly differing vehicle types, will exhibit differences in paint process layout, paint formulation, etc. that will introduce additional uncertainty to predicted results. Expansion of this research to a facility that differs more greatly from the facility studied in this research can provide additional useful conclusions.

6. The NREL LCI paint dataset developed in this research should generally not be applied to another facility directly as a surrogate dataset. Aside from process differences between any two manufacturing facilities, differences in painted BIW surface area and differences in annual production volumes will affect results. For this reason, industry application of

the NREL LCI database should use an appropriate scaling protocol, similar to those developed in this thesis.

8.3 Recommendations

1. The key remaining sub-module in the automotive paint process is Primer. Completion of this LCI sub-module by an LCI practitioner will allow a more comprehensive representation of the paint process as a whole.

2. Variations between automotive manufacturing facilities and their effect on results predicted by scaling the NREL LCI Database can be investigated by expanding this research to a facility that differs more greatly from the facility studied in this research and used in the NREL dataset. A 'survey LCI' can be completed on the differing facility, similar to a comparative LCI and requiring basic data collection to characterize the facility and note any differences that may affect LCI scaling or otherwise limit use of the NREL LCI Database. The data can also be scaled to a non-automotive industry with a related paint process (e.g., 'white goods') and the predicted results assessed with a 'survey LCI'.

3. Develop a suite of surrogate BIW painted surface area (SSA) values for reference by LCI practitioners interested in applying the NREL LCI Database results to different vehicle manufacturing scenarios. In addition to depending on vehicle type, the surrogate painted surface area will also depend on vehicle size, requiring further distinction when preparing reference values for SSA (e.g., $SSA_{\text{COMPACT SEDAN}}$, $SSA_{\text{MIDSIZE SEDAN}}$, $SSA_{\text{LARGE SEDAN}}$); overall external dimensions for the reference SSA values should be provided to allow an LCI practitioner to select a surrogate BIW painted surface area value correctly.

4. Incorporate data to example of OEM-selected LCI software for future in-house analysis and DfE activities (e.g., the partnered OEM has sourced GaBi) and summarize reference dataset in terms of equivalent 'eco-indicators' (i.e., primary environmental stressors, such as global warming potential, acidification potential, etc.). This will advance the LCI towards LCA by introducing environmental impact severity concepts and is consistent with near-term initiatives at the partnered OEM.

5. Assess whether resolution of reference dataset is amenable to specific DfE activities such as the revised “Paint Selection Process” currently under investigation by the partnered OEM, which aims to introduce environmental impact criteria to current economic, performance, timing, and industry regulatory criteria.

6. Perform a ‘survey LCI’ (i.e., comparative LCI) on proposed paint processes in research and development. The near-term recommendation is to compare the environmental impacts of the current Top Coat application process to a powder-based Top Coat process (i.e., powder Base Coat + powder Clear Coat).

7. Assess the feasibility and methods for manufacturing LCI data to distinguish between vehicle types, or ideally individual vehicle models. This research would enable manufacturing data to be incorporated into future eco-rating and eco-labeling systems, which are currently limited to Product Use data (e.g., fuel use, tailpipe emissions).

8. Install additional electricity and water metering at manufacturing facility for the paint shop facility processes. Construction or renovation of paint shop facilities are a cost-effective opportunity to incorporate additional metering.

9. Due to the observed process dependency of LCI data and the corresponding observation that a portion of total annual materials use is ‘constant’ (i.e., relatively independent of production rate, such as the need to maintain filled immersion tanks), an alternate LCI approach could attempt to determine the marginal quantity of materials / energy / emissions associated with the paint process. This alternate approach, while differing from conventional LCI practice, may allow improved scaling to differing production facilities or DfE comparison of competing manufacturing scenarios.

REFERENCES

Abdulrahem, F.I. 2004. The effectiveness of life cycle inventories: conceptual data versus site-specific data. University of Windsor Press.

Anastassopoulos, A., Nguyen, S., and Xu, X. 2004. On the use of HYSPLIT model to study air quality in Windsor, Ontario, Canada. Environmental Informatics Archives. Vol. 2: 375-383

ARDC. 2003. Paint shop process overview. (presentation material)

Athena Sustainable Materials Institute. 2001a. US LCI database project research protocol. Athena Institute.

Athena Sustainable Materials Institute. 2001b. Final phase I report. Athena Institute.

Beauchesne. 2005. Responsible firms rewarded in Canada. Windsor Star. 21 April 2005. CanWest Global Communications Corporation.

Bosch, A.G. 2000. Automotive handbook. Robert Bosch GmBH.

DaimlerChrysler. 2005. Our responsibility for sustainable activities. Accessed 15 July 2005. Available online: http://www.daimlerchrysler.com/dccom/0,,0-5-502930-1-511986-1-0-0-0-0-0-8-220714-0-0-0-0-0-0-0,00.html

DeCicco, J.M., M. Thomas. 2003. ACEEE's green book: the environmental guide to cars and trucks. American Council for an Energy-Efficient Economy.

DeCicco, J.M., M. Thomas. 1999. A method for green rating of automobiles. Journal of Industrial Ecology. Vol. 3:1 pp 55-75.

Dyson, C., B. Magavern, J. Shah, and T. Stephens. 1994. The green buyer's car book. Public Citizen.

Eckerman, E. 2001. World history of the automobile. Society of Automotive Engineers, Inc.

Environment Canada, 2005. National Pollutant Release Inventory. Accessed 26 August 2005. Available online: http://www.ec.gc.ca/pdb/npri/npri_home_e.cfm

Five Winds. 2003. Product stewardship opportunities within the automotive industry. Five Winds International.

Ford Motor Company. 2005. Corporate citizenship report (for 2003-2004). Accessed 15 July 2005. Available online: http://www.ford.com/en/company/about/corporateCitizenship/report/tools.htm

General Motors Corporation. 2005. Corporate responsibility report (for 2004). Accessed 15 July 2005. Available online: http://www.gm.com/company/gmability/sustainability/reports/04/index.html

Gottliebsen, R. 2004. Petrol price drives copper bonanza for resources chief [online]. The Australian, July 16, 2004. Available from www.theaustralian.news.com.au [cited 16 July 16 2004].

Graedel, T.E., B.R. Allenby. 2003. Industrial ecology, 2nd Edition, Prentice-Hall.

Graedel, T.E., B.R. Allenby. 1998. Industrial ecology and the Automobile. Prentice-Hall.

ISO. 2000. Environmental management – life cycle assessment – life cycle interpretation (ISO 14043). International Organization for Standardization.

ISO. 2000. Environmental management – life cycle assessment – life cycle impact assessment (ISO 14042). International Organization for Standardization.

ISO. 1998. Environmental management – life cycle assessment – goal and scope definition and inventory analysis (ISO 14041). International Organization for Standardization.

ISO. 1997. Environmental management – life cycle assessment – principles and framework (ISO 14040). International Organization for Standardization.

Keoleian, G.A., K. Kar, M.M. Manion, and J.W. Bulkley. 1997. Industrial ecology of the automobile: a life cycle perspective. Society of Automotive Engineers, Inc.

Keoleian, G.A., Menerey, D. 1994. Product Life Cycle Assesment to Reduce Health Risks and Environmental Impacts. Noyes Publications.

Mondt, Robert J. 2000. Cleaner cars: the history and technology of emission control since the 1960s. Society of Automotive Engineers, Inc.

Natural Resources Canada, 2005. Fuel Consumption Guide. Natural Resources Canada, Government of Canada.

NREL. 2005. Life Cycle Inventory database project. Accessed 5 August 2005. Available online: www.nrel.gov/lci

Papasavva, S., Kia, S., Claya, J., Gunther, R. 2002. Life Cycle Environmental Assessment of paint processes. The Journal of Coatings Technology. Vol. 74:925 pp 65-79.

Papasavva, S., Kia, S., Claya, J., Gunther, R. 2001. Characterization of automotive paints: an environmental impact analysis. Progress In Organic Coatings. Vol. 43. pp 193-206.

PPG. 2003. Automotive paint boot camp. (training material) PPG Industries, Inc.

PPG. 2005. Automotive coatings: products and services. Accessed 27 July 2005. Available at: http://www.ppg.com/car_autocoat/products.htm

Rufford, Nick. 2005. "Named and shamed on the ecolabel." Times Online. Published 13 February 2005. (online) http://www.timesonline.co.uk/

SBEAP. 2002. Industrial Painting and Coating. (Small Business Environmental Assistance Program) Kansas State University's Pollution Prevention Institute. Available online at http://www.sbeap.org/ppi/publications/Paintbook.pdf

Sullivan, J., et al. (1998) "Life Cycle Inventory of a Generic US Family Sedan Overview of Results USCAR AMP Project," Society of Automotive Engineers, 982160.

Tam, E. 2002. Challenges in using environmental indicators for measuring sustainability practices. Journal of Environmental Engineering Science. Vol. 1: 417-425. NRC Canada.

Thomas, M., J.M. DeCicco. 1999. Integrated approach to environmental rating for light vehicles. Transportation Research Record. No. 1664, 1999, pp 68-78.

Transport Canada. 2000. Canadian vehicle survey. Transport Canada, Government of Canada.

UK Department for Transport. 2005. Green car labels go live. (Department for Transport news release 2005/0074) 1 July 2005. Accessed 27 July 2005. Available at: http://www.dft.gov.uk/pns/displaypn.cgi?pn_id=2005_0074

UK Environment Agency. 2004. End-of-Life vehicles directive. Accessed 28 March 2004. Available at: www.environment-agency.gov.uk

US EPA. 2005. Green Vehicle Guide. Accessed 10 June 2005. Available at: http://www.epa.gov/greenvehicles/

USCAR. Teams. 2005. Accessed 10 August 2005. Available at: http://www.uscar.org/consortia&teams/consortiahomepages/cons&ttINDEX.htm

APPENDIX:
Franklin Worksheet

FRANKLIN ASSOCIATE LCI PROCESS DATA WORKSHEET

Please complete this worksheet on the basis of 1,000 Kg of
If process output is a specific part, specify the weight/finished part (or the distribution of part weights on which the data are based): Spray Virgin DI Water & Drain / Observation Deck

GENERAL INFORMATION

Prepared by:	LCI Team	Phone Number:	
Company Name:	U of W	Fax Number:	
Facility Location(s)	Windsor	Date Prepared:	1-Oct-03

MATERIAL INPUTS None

Inputs that become part of the product

Material #1:		Quantity Used:		Kg
Material #2:		Quantity Used:		Kg
Material #3:		Quantity Used:		Kg
Material #4:		Quantity Used:		Kg
Material #5:		Quantity Used:		Kg

Ancillary materials that do not become part of the product but are consumed in the process and must be replaced (examples: machining oil, shot blast, etc.)

Material #1:	Virgin DI Water ?	Quantity Used:	?	Kg
Material #2:		Quantity Used:		Kg
Material #3:		Quantity Used:		Kg
Material #4:		Quantity Used:		Kg
Material #5:		Quantity Used:		Kg

CO-PRODUCT PRODUCED None

Co-Product #1:		Quantity Produced:		Kg
Co-Product #2:		Quantity Produced:		Kg
Co-Product #3:		Quantity Produced:		Kg
Co-Product #4:		Quantity Produced:		Kg
Co-Product #5:		Quantity Produced:		Kg

NET WATER USED

Water Intake:	?	liters	Primary Source of Water:*	?
Water Output:	?	liters	Primary Receiver of Water:*	?

*Please name river, lake, reservoir, or ground water

PROCESS ENERGY

Electricity

Purchased	?	kilowatts-hours		
Fuel			Fuel	
Natural gas		cu.m.	Wood	Kg
Coal		Kg	Distillate Oil	liters
Residual Oil		liters	Other (Specify)	
Steam	_____ Kg	_____ Pascal	Type of fuel used:	

(Note: If fuel used to produce steam has already been shown above, do not fill out the steam data.)
Do these energy requirements include functions (for example office heating/cooling) not specifically related to the process(es) of interest ?

TRANSPORTATION N/A

Primary mode(s) of shipping finished products to customers (percent)
Truck_____ Rail_____ Ship_____ Air _________ Pipeline________
Empty backhaul? (yes or no)______
Average shipping distance to customers (km)
Truck_____ Rail_____ Ship_____ Air _________ Pipeline________
Weight of product (Kg) per shipping container ________
Packaging Material(s) Kg per shipping container

Please complete this worksheet on the basis of 1,000 Kg of
(If basis other than 1,000 Kg used, describe here:)

WASTE MATERIALS (see instructions; do not include internally recycled materials)

		Indicate fate of material				
		land filled	Sold for recycling or reuse	Burned	Waste to energy	Other (describe)
Off-spec. Product	Kg					
Trim or Scrap	Kg					
Ancillary Materials (by material type)	Kg					
	Kg					
	Kg					
	Kg					
Wastewater Sludge	Kg					
(% moisture in sludge)	%					
Hazardous Waste	Kg					
Other (specify) **filters, nozzles etc.**	Kg	?	?	?	?	?

ATMOSPHERIC EMISSIONS (controlled PROCESS emissions only, if possible)

Particulates*	Kg	Odorous Sulfur	Kg
Nitrogen Oxides	Kg	Ammonia	Kg
Hydrocarbons*	Kg	Hydrogen Fluoride	Kg
Sulfur Oxides	Kg	Lead	Kg
Carbon Monoxide	Kg	Mercury	Kg
Aldehydes	Kg	Chlorine	Kg
Other Organics*	Kg	Other (Specify)	Kg
Methane	Kg	Other (Specify)	Kg

Indicate whether reported emissions include boiler emissions that cannot be separated from process emissions: ?

Particulates Describe the chemical composition of particulates as much as possible

Size distribution of particulate emissions, if known.

* Hydrocarbons Describe the chemical composition of this category as much as possible.

* Other Organics Describe the chemical composition of this category as much as possible.

WATERBORNE WASTE (controlled PROCESS wastes only)

Fluorides	?	Kg	Chromium	?	Kg
Dissolved Solids	?	Kg	Iron	?	Kg
BOD	?	Kg	Aluminum	?	Kg
COD	?	Kg	Nickel	?	Kg
Phenol	?	Kg	Mercury	?	Kg
Sulfides	?	Kg	Lead	?	Kg
Oil	?	Kg	Phosphate	?	Kg
Suspended Solids	?	Kg	Zink	?	Kg
Acid	?	Kg	Ammonia	?	Kg
Metal Ion	?	Kg	Other (Specify	?	Kg
Cyanide	?	Kg	Other (Specify	?	Kg

Describe on-site wastewater treatment, if any. Also, if discharging to treatment plant, please indicate. ?

VITA AUCTORIS

Angelos Anastassopoulos was born in 1972 in Ottawa, Ontario, Canada. He graduated from the University of Western Ontario in London, Ontario in 1997 with a Bachelor's degree in English Literature and from Carleton University in Ottawa, Ontario in 2000 with a Bachelor's degree in Environmental Engineering. Upon completion of his undergraduate studies, he moved to Windsor, Ontario and worked as an engineer in Canada's automotive industry. He joined the University of Windsor in fall 2003 to pursue graduate studies in Environmental Engineering and successfully obtained his Master of Applied Science degree in September 2005.