Life Cycle Inventory of the Automotive Paint Processes

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Automotive coating processes contribute significantly to the environmental burden of vehicle manufacturing, with significant emissions released to air, water, and land, and consumption of substantial amounts of energy and raw materials. In North America, the automotive industry is currently quantifying the environmental impacts incurred during an automobile's manufacturing processes. Detailed and up-to-date life cycle inventory (LCI) data does not exist at this time for the majority of the vehicle painting processes associated with the North American-based automotive industry. The complexity of the contemporary automobile and the numerous 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. This article presents the findings from a major LCI research project conducted in order to populate a newly emerging North American LCI database. Typical data from selected processes within a representative vehicle painting facility are discussed, as well as the challenges faced and lessons learned from completing the study.

INTRODUCTION

The automotive manufacturing industry is one of the largest industrial sectors in North America. Millions of cars, of sizes ranging from small economy cars to large commercial vehicles, are manufactured every year. These millions of cars supply not only the demand in North American markets, but also worldwide.

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In North America, the automotive industry is currently attempting to quantify and inventory the environmental impacts incurred during the automobile manufacturing processes. This data is being used to populate a public database of environmental impacts intended to enable both the private and public sector in North America to use life cycle assessment (LCA) techniques for environmentally oriented decision-making.[1]

The complexity of the contemporary automobile and the many different processes in its manufacture and assembly, however, poses a significant set of challenges for completing a manufacturing life cycle inventory (LCI). Consequently, 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.

This article will develop an LCI for automotive paint pretreatment, the first portion of the automotive paint process. Pretreatment is an ideal candidate for an LCI because of the complexity of the process stages and the resources involved, and their interrelationships with the environment. To date, a complete life cycle inventory of the pretreatment process has not been reported in literature. Previous studies have instead been comparative in nature (e.g., waterborne versus solvent paints,[2] powder coating[3]) and so discuss relative differences, rather than focusing on absolute performance levels. This article will thus contribute valuable environmental impact information for an environmentally significant manufacturing process, and will furthermore be relevant to other industries beyond vehicle manufacture (e.g., white goods manufacturing).

BACKGROUND

Life Cycle Inventory in the Automotive Industry

One method used to evaluate the environmental impacts of a product or process is life cycle assessment (LCA). This technique quantifies the environmental impacts associated with a product or process at its various life cycle stages and can identify stages that are most significant.[3] It also identifies the stages where trade-offs between alternatives chosen arise.[4] As recognized by many authors, the most difficult part of the LCA is data collection, the part of the LCA known as the life cycle inventory (LCI).[5] This resource-intensive process is a careful inventory of a product's or process' associated materials use, energy use, and emissions, thereby yielding a quantifiable measure of the overall environmental impact.

It is common in LCA studies to use data from different sources such as real plant data, engineering calculations, patents, etc. As reported by Tam and Abdulrahem,[5] this can lead to uncertainties of the LCA results. The authors found that theoretical LCI data for materials, compositions, and emissions were different than site-specific data and the need arose for scaling factors (i.e., correction factors). However, due to the inconsistent differences between theoretical and real values, there was no single scaling factor that could be assigned for the conversion of theoretical LCI data to real plant data.[5] Yet, very few studies have been conducted to assess the life cycle material use, energy use, and emissions of these paint processes.

NREL LCI Database Project

The United States Life Cycle Inventory Database Project (hereafter referred to as NREL LCI Database) is being developed by the United States National Renewable Energy Laboratory (NREL), working with the Athena Sustainable Materials Institute and several industry and academic research partners.

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.[6] 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 stage, can be found online.[7]

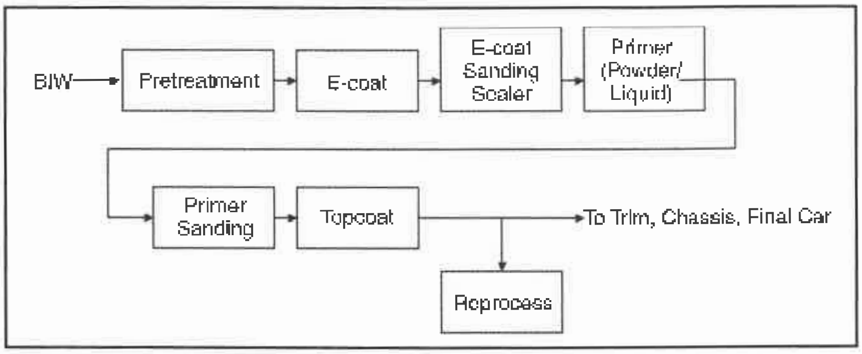
The NREL LCI Database will provide a resource base for completing LCAs in North America and will ultimately encompass nearly every material, product, and process relevant to the North American market.

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 scoped and prioritized. Representing the automotive industry, the North American-based automobile manufacturers agreed to develop LCI modules on several prioritized processes in automotive manufacturing/assembly. The automotive painting process was one such prioritized process, selected due to its significant associated environmental impacts and their relevance to other industries besides automobile manufacture.[1]

Automotive Paint Process and Paint Pretreatment

Automotive Paint Process—The function of the automobile painting process is to provide corrosion protection to a vehicle's body structure (i.e., body in white) and a durable and decorative coating to a vehicle's outer body panel surfaces.[8] Automotive paint process involves the following unit processes: pretreatment, e-coat, basecoat, and clearcoat (*Figure* 1).

Figure 1—Unit process flow for a typical automotive paint process.



As an assembly line process, pretreatment is comprised of 13 substages. Each substage of pretreating the BIW has a significant impact on the quality and quantity of the final product, and also potential effects on the environment.

The paint application process has been found to have a significant effect on the environment, when compared to other processes in automobile manufacturing.[3] 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). Plus, energy use is substantial: maintaining immersion tank process temperatures, powering curing ovens, powering robotic spray equipment, powering moving assembly line, etc.

Pretreatment Paint Process—In this article we will specifically develop an LCI for the pretreatment process because of the complexity of its stages, the vast amount of energy and materials used, and the significant wastes generated.

Pretreatment involves cleansing the body in white (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.[10] 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 that follows (i.e., "drag-out").

METHODOLOGY

Industry Partnership

The research in this project was conducted over a two-year period through a partnership between the University of Windsor and a North American-based vehicle manufacturer. Subsidiary partnerships were also initiated with two of the partnered vehicle manufacturer's supplier organizations: a paint supplier and an energy provider.

ISO Compliance

The research complied with relevant LCI protocols (i.e., ISO 14041) by referencing the LCI protocol developed for the NREL LCI Database project in the "U.S. LCI Database Project Research Protocol"[1] and by referencing a standardized LCI data collection sheet.[1] Consistent with these LCI protocols, the research followed several key activities, including:

(1) LCI goal definition
(2) LCI scope definition
(3) Data source identification
(4) Process flow mapping
(5) Functional unit development

LCI Goal Definition—The primary goal of the research project was to develop a representative LCI dataset on the automotive paint process for inclusion in NREL's public LCI database. In addition to contributing to the NREL database, the LCI dataset was expected to lead to future Design for the Environment (DfE) opportunities at the partnered OEM, such as manufacturing process improvements and an improved materials selection process.

LCI Scope Definition—The U.S. LCI Database Project[1] requires that datasets populating the database represent their respective industries. 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), the paint processes and facilities were selected to represent the majority of the North American-based assembly facilities.

The paint process was then scoped down to several sub-modules for feasibility, including the pretreatment

Table 1—Data Sources Identified for Automotive Paint Process

Parameter	Records (2003)	Source	Data Type
Materials use	Pay-as-painted reporting (monthly)	Supplier	Measured/Calculated
	VOC emissions reporting	OEM	Calculated
	Annual water usage reporting	OEM	Measured
Energy use	Process energy audit	Energy provider	Calculated
Emissions	NPRI reporting	OEM	Calculated
	VOC emissions reporting	OEM	Calculated
	Wastewater reporting	OEM	Measured
Production volume	Pay-as-painted reporting (monthly)	Supplier	Measured
	Calendar year production reporting	OEM	Measured
	VOC emissions reporting	OEM	Measured
	NPRI reporting	OEM	Measured
Surface area of BIW	VOC emissions reporting	OEM	Calculated

process presented in this article. Two additional paint processes scoped for LCI were e coat and topcoat. These three paint processes represent the bulk of the environmental impact associated with the automotive paint process.

The environmental impact parameters scoped for the automotive paint pretreatment process LCI include materials use, energy use, and pollutant emissions. These are shown in *Figure* 2. The LCI employed several simplifying assumptions:

- The assembly plant used in this study manufactures two vehicle models that share a common vehicle platform design, allowing for model-specific data to be aggregated and reported as a single representative vehicle model.
- Environmental impacts and related parameters used (e.g., production volumes) measured, calculated, and estimated data from both public and internal sources.
- The LCI analysis was restricted to primary processes within the facility. For example, the mass of the material input is considered, but environmental impacts incurred during manufacturing and transportation of the material to the automotive facility are excluded. Essentially, the LCI represents only the "gate-to-gate" analysis scenario.
- Environmental impacts of the conveyor assembly used to transport the BIW through the paint process are not included.

Data Sources—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 processes. Quantitative information on production volumes and BIW surface area were also required for normalization with the developed functional unit (i.e., per m² painted BIW). Since the partnered assembly facility manufactures two different models, a weighted average BIW painted surface area was calculated, weighted by the respective production volumes of the two vehicle models.

The data collection targeted the 2003 calendar year as this was the most recent year during which production of both vehicle models took place at the facility and for which complete data was consistently available. Where the identified data sources could not provide data for a particular environmental parameter, additional data sources were sought, including pre-2003 sources. Data sources used are summarized in *Table* 1.

Process Flow Mapping—Standardized LCI procedures typically recommend process flow mapping before the data collection process (ISO 14041:1998). It is

Figure 2—High-level LCI process flow map for generic paint pretreatment process.

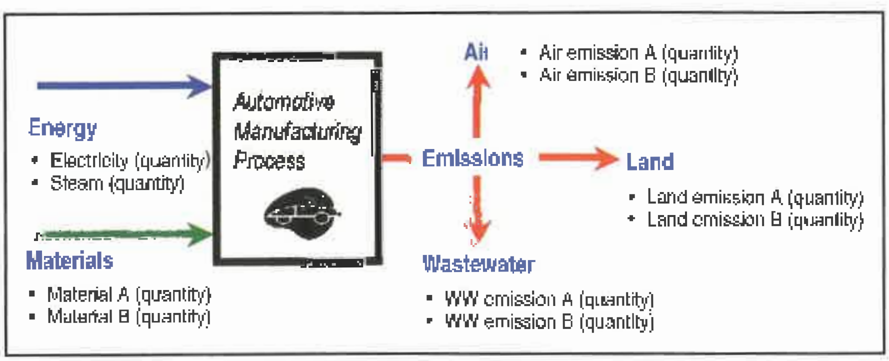


Table 2—Estimation of Water Use for Pretreatment

Calculation Basis	/1000 m² Painted BIW
Annual total water use by New Paint Shop	31,359
Estimate: pretreatment + e-coat	95%
Estimate: sealer	5%
Annual total water use by sealer	1,567
Annual total water use by pretreatment + e-coat	29,791
Estimate: pretreatment	75%
Estimate: e-coat	25%
Annual total water use by pretreatment (rounded)	**22,344**

(2003 Calendar Year; Combined Vehicle Models)

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* 2. This is termed a "high level" process flow map because it does not show the particularities of the bounded automotive manufacturing process.

Table 3—Summary of Materials and Energy Usage

Materials Use (Generic Industry Name)	/1000 m² Painted BIW
Precleaner	0.10
Accelerator	872
Phosphate	9176
Phosphate makeup	9
Corrosion inhibitor	732
Body washer	1491
Cleaner—alkaline	1765
Pre-wipe	2417
Phosphate post-rinse	1090
Rinse conditioner	523
Highlighter	302
Biocide	222
Phosphate anti-corrosion makeup	164
Water	22344
Energy Use	
Electricity	105

LCI process flow mapping was completed for the pretreatment sub module, adapting the technique to the specifics of the automotive paint process. 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. 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 the pretreatment assembly line at the partnered assembly facility was 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 environmental specialists at the assembly plant that culminated in LCI process flow maps for each of the nine stages comprising pretreatment.

Functional Unit Development—The choice of a good functional unit is very important for the validity and interpretation of LCA results. A meaningful functional unit allows comparisons between facilities with similar painting processes and helps overcome the differences between plants due to production rates and vehicle sizes.

Selection of a preferred functional unit for normalizing and reporting the final LCI dataset required consideration of the intended primary function of the process under study. For the automotive paint process, the intended primary function is to treat and coat the BIW.

The selected "best practice" functional unit used for the paint process LCI and reported to the NREL LCI Database is "per m² painted BIW." This functional unit is consistent with current industry environmental reporting practices (e.g., internal materials and VOC emission reports use a similar surface area-based normalizing unit). The chosen functional unit also allows the NREL dataset to be applied to different production scenarios or production facilities.

LIFE CYCLE INVENTORY OF PAINT PRETREATMENT

Materials Inventory

The materials inventory sought data on supplied paint process materials (i.e., paint supplier's products) and water use for the pretreatment automotive paint process.

Water use data were not available for the individual paint processes (e.g., pretreatment, e-coat, topcoat) because the selected assembly plant does not have water meters installed for individual unit operations. Metered water usage is reported by an environmental specialist at the assembly plant via a Microsoft Excel spreadsheet, which was made available. Engineering estimates, developed with the plant's environmental specialist, were then used to apportion water use to the pretreatment process. The calculations used to estimate water use for the pretreatment process are summarized in *Table* 2.

Pretreatment materials data were available from internal volatile organic compound (VOC) emissions reporting published annually by an environmental specialist at the facility (*Table* 3). VOC emission reporting references the paint supplier's monthly reporting for its material use data. Although VOC reporting provided partial data for individual vehicle models, the results reported here used an aggregated total of the vehicle models produced at the plant.

Energy Inventory

The energy inventory sought data on energy used for the pretreatment paint process. Two energy inputs were identified for the selected assembly plant: 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 specifically for each stage of pretreatment, but for pretreatment and e-coat processes together. As a result, it was decided to measure electricity use based on an audit of equipment associated with the pretreatment process, and then calculated using audited equipment power ratings.

Assumptions made in the energy calculations include:

- The equipment was assumed to operate at full capacity for 24 hours per day and 273 days per year
- The 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
- A 94% motor efficiency and a 75% load factor are included in the electricity usage calculations

As per the above assumptions, the calculated estimate of total annual electricity use for the pretreatment process is 105 per 1000 m² painted BIW (*Table* 3). In order to compare the metered and calculated energy values, the calculations were done for the e-coat process as well.

It was found that metered and estimated values for total annual electricity usage were significantly different. The reason for this discrepancy might stand on the assumptions made for energy calculations, and as a result they may need to be revisited.

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. Thus, the recommended "best practice" for reliable energy data collection is to have a metering system in the plant.

Heat Energy—Heat energy, in the form of steam, is used to maintain immersion tank temperatures in the pretreatment process. 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 the plant is waste byproduct for the seller and would otherwise be emitted to air. Information on the quantity of steam used by the plant, or engineering estimates needed to apportion it to the pretreatment process, were not available.

Emissions Inventory

The emissions inventory sought data on emissions for the pretreatment paint process. The relevant emission pathways included: emissions to air, emissions to land, and emissions to wastewater. The weighted average BIW painted surface area was calculated as 150 m².

Emissions to Air—Data sources included National Pollutant Release Inventory (NPRI) reporting and VOC emission reporting for the 2003 calendar year. Emissions are summarized in *Table* 4. NPRI reporting is pre-

Table 4—Emissions to Air

Emissions	/1000 m² Painted BIW
To Air (NPRI reportable compounds)	
Glycol ether	1.82
1-Methoxy-2-propanol	0.54
Nitric acid	0.40
Total reportable compounds to air	2.75
To Air (VOC)	
Precleaner	9
Accelerator	0.00
Phosphate	0.00
Phosphate makeup	0.00
Corrosion inhibitor	0.00
Body washer	60
Cleaner—alkaline	53
Pre-wipe	92
Phosphate post-rinse	0.00
Rinse conditioner	0.00
Total VOC to air	214

Table 5—Emissions to Water

Emissions	/1000 m^2 Painted BIW
Wastewater to WWTP (NPRI reportable + non-reportable)	**21**
To Water (NPRI reportable compounds)	
Wastewater to WWTP:	
Glycol ethers	179
Mn compounds	19
Zn compounds	19
Nitrate compounds	169
Phosphorus	826
1-Methoxy-2-propanol	53
Total reportable compounds to water	**1264**

pared for the assembly plant by an external consultant; VOC emission reporting is prepared by an in-house environmental specialist. Both reporting documents are essential for the air emissions inventory, as NPRI reporting is restricted to regulated compound releases while VOC emission reporting provides calculated VOC emissions associated with the use of all materials subject to volatization (i.e., including non-regulated compounds).

The format of both reports allows air emissions to be separated by paint process (e.g., pretreatment, e-coat, topcoat). While VOC reporting 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 pretreatment materials contribute to the same NPRI-reported compound, allocating the proportional contribution of each material is not readily calculated and is not recommended.

Emissions to Water— Wastewater emissions from pretreatment are also significant, 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 facility's NPRI reporting for 2003, which indicates wastewater emissions as "amount discharged to municipal sewage treatment plant." The format of the NPRI reporting allowed separation of wastewater emissions by paint process but did not enable source apportioning to individual process materials. LCI results for emissions to water are summarized in *Table* 5.

Once again, NPRI reporting 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 assembly plant's environmental specialist) to the total water use in pretreatment; this was calculated during the materials inventory portion of the LCI. This calculation assumed that 95% of water used goes to wastewater. The 95% engineering estimate was determined by comparing total annual water use with total annual wastewater sent for treatment from the entire facility in 2003. The 95% engineering estimate was further corroborated by similar calculations with water usage data for the 2002 and 2004 calendar years.

Solid Emissions—Land emissions were also expected to be significant for the pretreatment paint process, 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 was the assembly plant's NPRI reporting for 2003 (*Table* 6). Sludge was therein indicated as either "wastewater treatment plant sludge" (e.g., to landfill) or "paint sludge" (e.g., for topcoat). Both wastewater sludge and paint sludge are sent offsite for treatment and disposal to land. The NPRI reporting also specified the quantities of regulated compounds that are sent to a landfill as part of equipment filter disposal. The format of the NPRI reporting allows separation of land emissions by paint process but does not readily enable source apportioning to individual process materials.

Finally, the NPRI reporting 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 used an

Table 6—Solid Emissions

Emissions	/1000 m^2 Painted BIW
Sludge to landfill (NPRI reportable + non-reportable)	.828
Sludge to landfill (NPRI reportable)	
Glycol Ethers	0.07
Mn compounds	83
Zn compounds	0.07
Phosphorus	0.33
1-Methoxy-2-propanol	0.02
Glycol ethers	0.08
Total reportable compounds to land (sludge)	**83**
Filters to landfill (NPRI reportable)	
(a) Mn compounds	2.84
(b) Zn compounds	9.11
(c) Phosphorus	0.05
Total reportable compounds to land (filters)	**12**
Non-Reportable Metals Emissions	
Copper compounds	46

average of the 1999 and 2000 calendar years; the older datasets were used because reporting practices at the selected assembly plant 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 the assembly plant for the storage and transport of process materials.

CONCLUSIONS AND RECOMMENDATIONS

Completing Future Manufacturing LCIs

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

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, thus requiring engineering estimates to apportion data.

Due to limitations in available/measured data resolution and time and resource demands of stage-by-stage, the effort to develop high resolution LCI process flow maps outweighs 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.

Aggregated material/energy/emissions LCI process flow maps are useful in data source identification and also graphically represent 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 in a public forum.

Manufacturing LCIs should be based on a data collection and reporting 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 "best practice" LCI data collection and reporting parameter should be the painted surface area.

Where the opportunity exists, the installation of additional electricity and water metering for paint shop facility processes can facilitate and improve LCI data collection. Additional metering is likely to be most cost-effectively added during the construction or renovation of any particular industrial facility.

Industry Application of Manufacturing LCI Data

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.

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.

The NREL LCI paint dataset developed in this research should generally not be applied directly to another facility 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 the results. As a result, it will likely be necessary to use an appropriate scaling protocol when adapting one set of data to an independent facility. CT

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